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Table of contents

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Sustainability indicators of the Brazil nut tree management

Indicadores de sustentabilidade do manejo da castanha-da-amazônia

Fernanda Lopes da Fonseca[1], *Oscar José Rover*[2], *Lucia Helena de Oliveira Wadt*[3], *Cleisa Brasil da Cunha Cartaxo*[1]

ABSTRACT

Brazil nut tree (*Bertholletia excelsa* Bonpl) management, is a traditional activity that plays a key role in the economy of forest-based Amazon communities and in the conservation of forests. Nevertheless, some threats and critical points related to sustainability indicate to the need for establishment of monitoring procedures that can assist in the management of this natural resource. The overall aim of the research was to evaluate the MESMIS method as a tool to support the participatory definition of sustainability indicators to monitor Brazil nut management, and the viability of Brazil nut harvest over time. For that, we carried out a case study in the Porvir Community, RESEX Chico Mendes, Acre State (Brazil), aiming to integrate the perceptions of Brazil nut harvesters, researchers, managers, and technicians to define the indicators. The result was the generation of 18 strategic indicators to assess sustainability in the environmental, technical-economic and social dimensions. Assessment parameters, representing conditions that must be achieved for system sustainability, were collectively defined for each indicator. The main critical values attributed in the evaluation of the indicators are related to Brazil nut commercialization to intermediaries and oscillation in the annual fruit production. The use of the MESMIS method was considered appropriate to the studied context and can be recommended to similar non-timber forest product management systems.

Keywords: extractivism; sustainability indicators; community management; mesmis method.

RESUMO

O manejo da castanheira-da-amazônia (*Bertholletia excelsa* Bonpl.) é uma atividade tradicional, chave para a economia de milhares de famílias extrativistas da Amazônia e para a conservação das florestas. Algumas ameaças e pontos críticos relacionados à sustentabilidade da atividade apontam para a necessidade de se estabelecerem procedimentos de monitoramento que possam auxiliar na gestão desse recurso natural. O objetivo deste trabalho foi avaliar o método Marco para a Avaliação de sistemas de Manejo de Recursos Naturais Incorporando Indicadores de Sustentabilidade (MESMIS) como ferramenta de apoio à definição participativa de indicadores para a avaliação da sustentabilidade do manejo de castanhais nativos e da viabilidade do extrativismo da castanha ao longo do tempo. Para tanto, realizou-se um estudo de caso na Comunidade Porvir, Reserva Extrativista Chico Mendes, Acre, onde se buscou integrar as percepções de extrativistas, pesquisadores, gestores e técnicos sobre o assunto. O resultado foi a geração de 18 indicadores estratégicos para a avaliação da sustentabilidade nas dimensões ambiental, técnico-econômica e social, definindo-se coletivamente parâmetros de avaliação para cada indicador. Os principais valores críticos atribuídos na avaliação do estudo de caso foram relacionados à questão da comercialização da castanha para atravessadores e à oscilação na produção anual de frutos. O emprego do método MESMIS foi considerado adequado ao contexto estudado, de modo que pode ser recomendado e adaptado ao manejo de outros produtos florestais não madeireiros.

Palavras-chave: extrativismo; indicadores de sustentabilidade; método mesmis; manejo comunitário.

[1]Empresa Brasileira de Pesquisa Agropecuária – Rio Branco (AC), Brazil.

[2]Universidade Federal de Santa Catarina – Florianópolis (SC), Brazil.

[3]Empresa Brasileira de Pesquisa Agropecuária – Porto Velho (RO), Brazil.

Correspondence address: Fernanda Lopeas da Fonseca – Rodovia BR-364 – Km 14 (Rio Branco/Porto Velho) – Caixa Postal: 321 – CEP: 69900-970 – Rio Branco (AC), Brazil. E-mail: fernanda.fonseca@embrapa.br

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Introduction

The Amazon rainforest is the world's largest tropical forest, with about 52% of its territory protected as conservation units or indigenous lands. These areas act as a buffer for external pressures of deforestation and expansion of the agricultural frontier, contributing significantly to ensuring biodiversity, reducing carbon emissions, and mitigating climate change. The Brazilian Amazon alone fixes roughly 30% of all carbon stored in protected natural areas and indigenous lands throughout the biome (Walker et al., 2020).

The production of Brazil nuts is directly related to the conservation of the Amazon Forest. The species *Bertholletia excelsa* is an imposing tree in tropical forests and produces Brazil nuts, which is collected almost exclusively in native forests. Currently, Brazil nuts is considered one of the most important non-timber forest products in the world (Gardner and Costi, 2014).

Most Brazil nuts are produced in conservation units, primarily by traditional peoples and communities, including extractivists, indigenous people, and *quilombolas*, combining income generation and biodiversity conservation (Picanço and Costa, 2019; Silva et al., 2020).

Over the past three decades, Brazil nuts have emerged as a key product in the Amazonian extractive economy, promoting food security and ensuring the livelihoods of traditional populations (Kainer et al., 2018).

In the state of Acre, Brazil, despite the well-structured production chain and the valorization of Brazil nuts in the market, the sustainable management of the activity faces threats and critical points, which require studies for a better understanding. Some of these challenges concern the socio-environmental crisis, climate change, constant threats of deforestation, and forest fires, as well as the conversion of forest areas into pastures in the Amazon. Other concerns refer to oscillations in fruit production of Brazil nut trees in critical years, price fluctuations, and market speculations, deficiency of public policies for the sector, as well as the fragility of the social and governance dynamics that involve these management systems (Brose, 2016; Cartaxo et al., 2016; Wadt et al., 2016; EMBRAPA, 2017; Mascarenhas et al., 2018).

These socioeconomic and productive challenges for Brazil nut harvests by traditional populations require community management strategies to assess and monitor the sustainability of these production systems. These strategies allow understanding interrelationships, predicting risks, and proposing improvements for the resilience of the system.

This work evaluated the *Marco para la Evaluación de Sistemas de Manejo de los Recursos Naturales Incorporando Indicadores de Sustentabilidad* method (MESMIS) as a support tool for the participatory definition of indicators to assess and monitor sustainability in Brazil nut stands management, based on a case study carried out at RESEX Chico Mendes in the state of Acre.

General aspects of sustainability indicators in natural resource management

Since the United Nations Conference on Environment and Development "Rio 92" and the elaboration of Agenda 21, the need to develop indicators capable of assessing sustainability has been discussed in the political and academic spheres. According to Caporal et al. (2010), based on the institutionalization and popularization of the sustainable development discourse, the search for methodologies that allow measuring sustainability and, consequently, indicating ways to minimize social problems intensifies on the scientific, ecological, and economic agenda promoted by anthropic action in agroecosystems and by unequal sociopolitical relations regarding the appropriation of nature.

In general, "sustainability indicators intend to inform concisely about a certain state or a certain condition of a system of interest (an agroecosystem, for example). Sustainability indicators are taken, therefore, as decision-making instruments to improve the use of the environment" (Schlindwein, 2010, p. 88).

Gallopín (1996) states that the most important characteristic of an indicator is its relevance to policies and the decision-making process, and social actors involved in the process have considered the indicator's relevance to be representative.

Sustainability indicators are defined as the synthesis and interpretation of a set of information that indicate trends in behavior and help in the development of strategies to improve the human-nature relationship. These indicators allow quantifying, analyzing, and transmitting information in a simple way, as well as informing about the achievement of sustainability in different dimensions. Therefore, it is possible to monitor progress toward achieving the goals set, preventing economic, environmental, and social losses (Hammond et al., 1995; Bellen, 2006; Melane-Lavado and Álvarez-Herranz, 2018).

In this context, sustainability indicators can and should be widely used as a management tool in projects and processes linked to the management of natural resources, as they allow diagnosing, monitoring, evaluating, and planning methods, guiding new actions and investments for local development and for the creation of public policies (Vivan and Floriani, 2001; Steenbock et al., 2013).

However, Schlindwein (2010) states that the adoption of sustainability indicators in the management of natural resources only provides concrete changes if the indicators are developed through processes that involve social learning and joined actions between the different social actors.

According to Marques et al. (2003), indicators should:

- be applicable to many systems;
- be sensitive to system changes;
- be measurable and easy to measure;
- be easy to obtain and low cost;
- allow cross-checking with other indicators;
- be conceived with the participation of local population, at least at a property level of measurements.

The use of the MESMIS method is highlighted in agroecology and small-scale natural resource management, mainly because this method has a flexible operational structure, allowing a "*bottom-up*" approach (involving different social actors, especially farmers) in the sustainability assessment process and proposing a cyclical assessment process (Cândido et al., 2015; Loureiro et al., 2020). These differentials allow using the method in different social and productive realities. According to Loureiro et al. (2020), over a hundred scientific papers on MESMIS have already been published, which document case studies applied to different productive activities (mainly agriculture and livestock) in different parts of the world.

Material and Methods

The MESMIS method for evaluating natural resource management systems

The MESMIS method was developed in Mexico during the 1990s and has been extensively tested in different geographic areas, mainly in South America, North America, and Europe. MESMIS presents a path to determine, read, and interpret sustainability indicators with a systemic focus. It also provides practical and flexible orientation for adaptations in different contexts, based on a participatory and interdisciplinary approach (Masera and López-Ridaura, 2000; López-Ridaura et al., 2002; Astier and Hollands, 2007; Astier et al., 2012).

The MESMIS framework (Figure 1) was developed by critically integrating concepts on sustainable development, sustainability, systemic approaches, natural resource management, sustainability assessment, and sustainability indicators (Masera et al., 1999; López-Ridaura et al., 2002).

Table 1 presents the definition of Masera et al. (1999) for the general attributes, which were theoretically conceived from fundamental systemic properties linked to different aspects for a management system to be considered sustainable.

Case study at RESEX Chico Mendes

Study site

The study was carried out in the municipality of Epitaciolândia, Chico Mendes Extractive Reserve (RESEX), Acre State, Brazil, in partnership with the community of Wilson Pinheiro Base Center (Community Porvir) (Figure 2). The nucleus aggregates 36 families and the total area of the community comprises 11,500 ha (Acre, 2012). The exploratory stage of the research began in January 2019 and data was collected between May and June 2019.

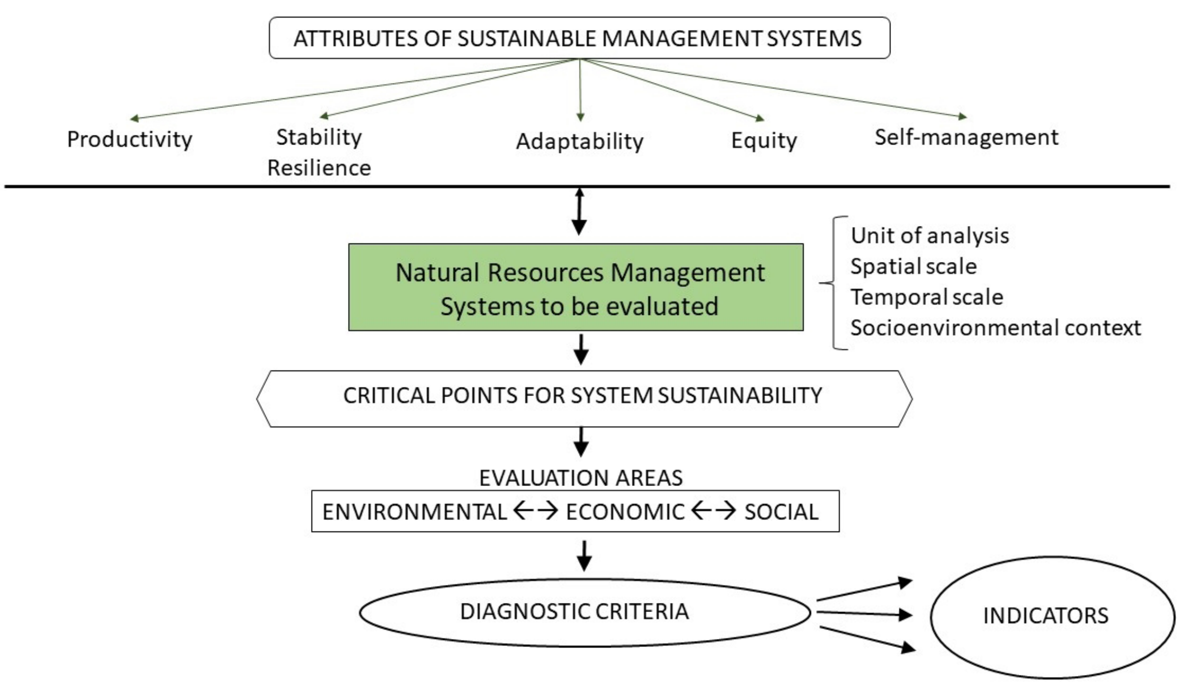

Figure 1 – The MESMIS method framework: linking sustainability attributes to indicators.
Source: translated from Masera et al. (1999).

Table 1 – General attributes for sustainable management systems.

Productivity	Agroecosystem capacity to provide the required level of goods and services. Represents the attribute value (income, earnings, etc.) at a given time.
Stability and Resilience	Interconnected attributes relate to the system's ability to ensure a state of dynamic equilibrium, maintaining its productive capacity in face of normal environmental changes (stability) or after suffering severe or extreme disturbances (resilience).
Adaptability or Flexibility	System's ability to find new levels of balance and to continue offering its benefits in the face of long-term changes in the environment (such as new economic or biophysical conditions). This attribute also refers to the ability to actively search for new levels or production strategies. This concept ranges from aspects related to the diversification of activities or technological options to processes of social organization and training of human resources.
Equity	System's ability to fairly distribute, both intra and intergenerationally, the benefits and costs related to the management of natural resources.
Self-management	System's ability to regulate and control its interactions with the outside world. It includes the organizational processes and mechanisms of the socio-environmental system to endogenously define its own objectives, priorities, identity, and values.

Source: translated from Masera et al. (1999).

Data collection

The research had a descriptive and analytical methodological character, with a quali-quantitative approach, prioritizing the participation of extractivists (López-Ridaura et al., 2002; Gomes, 2010). The premise for constructing the indicators was based on a "bottom-up" approach. After obtaining the necessary authorizations to conduct the research, the field trips were carried out. This research was approved by the Ethics Committee for Research with Human Beings of *Universidade Federal de Santa Catarina* (CEPSH-UFSC) through process No. 3.344.855/2019, as well as by ICMBio through the project submission on the platform of the System of Authorization and Information on Biodiversity (SISBIO – authorization No. 68144-1, issuing date 03/29/2019).

The sustainability criteria and indicators were defined by the evaluation cycle proposed by MESMIS (Figure 3), with adaptations to the studied context inspired by other studies involving the generation and use of indicators with agro-extractivists (Vivan and Floriani, 2001; Steenbock et al., 2013).

The study was conducted according to the following steps:

- Step 1) Characterization of the management system studied, with its main socioeconomic aspects, based on a literature review and document analysis;
- Step 2) Participatory diagnostic workshop at the community aimed at: understanding the harvesters' perception on sustainability and aspects that define a "good" Brazil nut management system, from production to marketing; critical points of the management system, that is, aspects that limit or strengthen the production system capacity to sustain itself over time;
- Step 3) Systematization of an initial list of indicators from the following sources: aspects that define a good Brazil nut management system, according to the knowledge of harvesters; matrix of critical points; MESMIS framework (Figure 1); and information collected in step 1;
- Stage 4) Semi-structured interviews with different social actors interested in the management of native Brazil nut trees (researchers, RESEX manager, technicians, and harvesters), aimed at selecting strategic indicators from the initial list of indicators defined in stage 3. During the interviews, parameters were also defined to evaluate each indicator, according to the knowledge of the interviewees, assigning scores from 1 (one) to 10 (ten), where 10 represents the ideal condition for system sustainability; 5 represents an acceptable condition; and 1 represents an undesirable condition. The parameters constructed allowed evaluating indicators through the scores. In the end, 18 strategic indicators were selected to assess sustainability in the environmental, technical-economic, and social dimensions;
- Step 5) Assessment workshop in the community participating in the study. In this step, four Brazil nut stands were selected to apply the indicators, based on the scores defined in step 4;
- Step 6) Systematization and integration of data obtained in the field, using radial type graphics, examining the relationships between indicators (synergies and trade-offs).

The data collected and analyzed were used to describe conclusions and recommendations upon completion of the first evaluation cycle.

A volunteer group of 10 harvesters participated in the workshops, belonging to four different Brazil nut stands (productive units): Boa Água, Morada Nova, São José, and Encontro.

Results and Discussion

Characterization of the management system studied

Residents of the Community Porvir traditionally harvest Brazil nuts, rubber, açaí, bacaba, patoá, vegetable oils, as well as hunt, fish, and plant crops for subsistence. Some crops grown are rice, beans, corn, cassava (for flour production), banana, and other fruits. They also raise animals such as dairy and beef cattle, chicken, duck, pigs, fish, sheep, buffaloes, and horses. The main products commercialized are:

- Brazil nuts and latex;
- cassava, banana, rice, and corn;
- chicken, beef cattle, and swine. Income to the community is generated from extractivist activities, followed by agriculture and livestock (Acre, 2012).

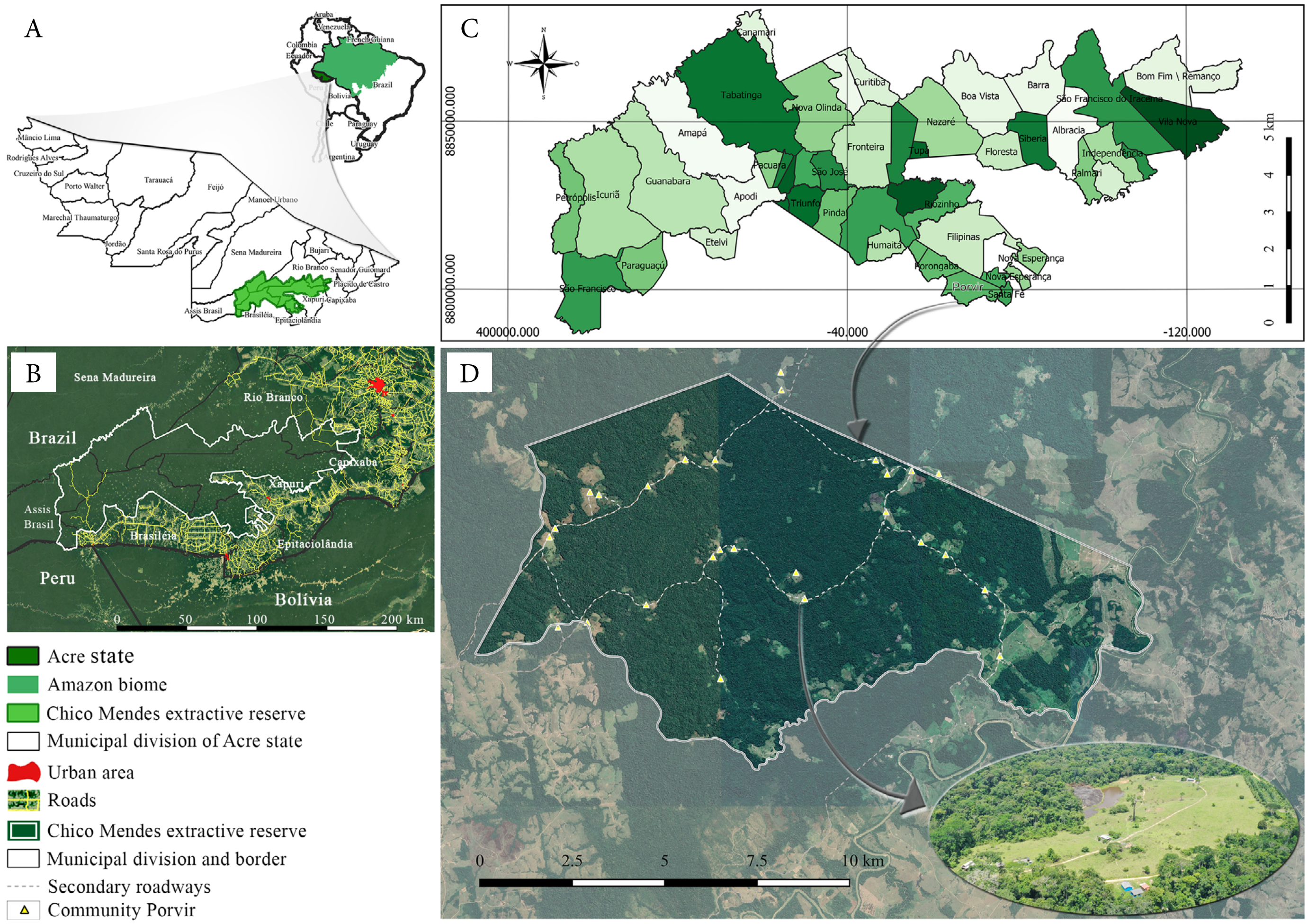

Figure 2 – Study site. (A) location of the Acre State and RESEX Chico Mendes; (B) area of RESEX Chico Mendes and municipalities included; (C) geopolitical division of rubber plantations of RESEX Chico Mendes; (D) highlight of Seringal Porvir area with a satellite image superimposed on the map with an aerial photo of the Boa Água site, location of the Wilson Pinheiro base nucleus.
Source: own data. Graphic design at Embrapa Acre. Google Satellite Images, 2017.

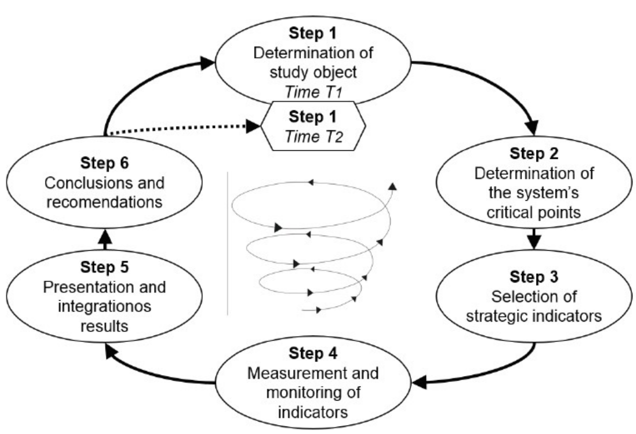

Figure 3 – MESMIS method evaluation cycle.
Source: translated from Masera et al. (1999).

The field research showed that the income from the Brazil nut management constitutes the main financial source of families in the community, accounting for more than 40% of the annual income of the harvester's families participating in this study.

This result corroborates the study of Duchelle et al. (2014), who reported that the Brazil nut harvest accounts for 45% of the net income of families in the Western Amazon.

Figure 4 shows the traditional agro-extractivist management system of community residents, similar to practices at RESEX Chico Mendes, where production units include various components and subsystems (forest, agricultural, and animal). The dynamic nature of agroecosystems, which are constantly responding to internal and external changes, are highlighted (Masera et al., 1999).

Figure 5 shows the main timeframes that somehow affected the management of Brazil nut in the community, according to the harvesters participating in the diagnostic workshop held during the field phase of this research.

Community residents emphasized the foundation in 1993 and bankruptcy in 2004 of the Agroextractive Cooperative of Epitaciolândia and Brasileia Producers (*Cooperativa Agropecuária de Epitaciolândia e Brasileia* – CAPEB).

CAPEB was founded with strong participation from the social movement of rubber tappers and even operated a nut processing plant in Brasiléia, provided by the state government of Acre in 2006. Due to internal management problems, the cooperative was unable to sustain the plant operation and cooperative producers, including those from the Community Porvir, had to pay the debt with the production of Brazil nuts at the time, which has been a factor of resistance to an initiative of a new community in cooperativism (Simoni, 2009).

More recently, in 2017, harvesters highlighted the construction of two community warehouses for Brazil nuts, with resources from the State Government, through an agreement with the Inter-American Development Bank (IDB).

Another milestone for the community was the approval of the Project "Castanhal – sustainable use of sociobiodiversity", with resources from the Amazon Fund, managed by the Banco do Brasil Foundation (*Fundação Banco do Brasil* – FBB), approved in the Ecoforte Extractivismo public selection for associations of extractive activities in federal protected areas. This was the first project of this type managed by the local association, representing a new experience for the community, which also relies on the Bem Diverso Project as a partner for administrative and operational support. This project develops actions for the conservation of biodiversity and sustainable management of natural resources in forest landscapes and agroforestry systems in three Brazilian biomes (Amazon, Cerrado, and Caatinga) in partnership between the Brazilian Agricultural Research Corporation (*Empresa Brasileira de Pesquisa Agropecuária* — Embrapa) and the United Nations Development Program (UNDP), with resources from the Global Environment Facility (GEF).

Unveiling sustainability with harvesters: descriptors of a "good" management system

Table 2 presents the descriptors of a "good" Brazil nut management system according to the perspectives of harvesters. The values in parentheses represent the number of answers given by the participants in the diagnostic workshop for the same descriptor, relativized as a percentage, and the total grouped by the sustainability attribute.

There is a prioritization of descriptors related to the attributes of adaptability and self-management, although the descriptor "good production" was the most cited among the total responses. The existence of very objective descriptors characterizes a good management system,

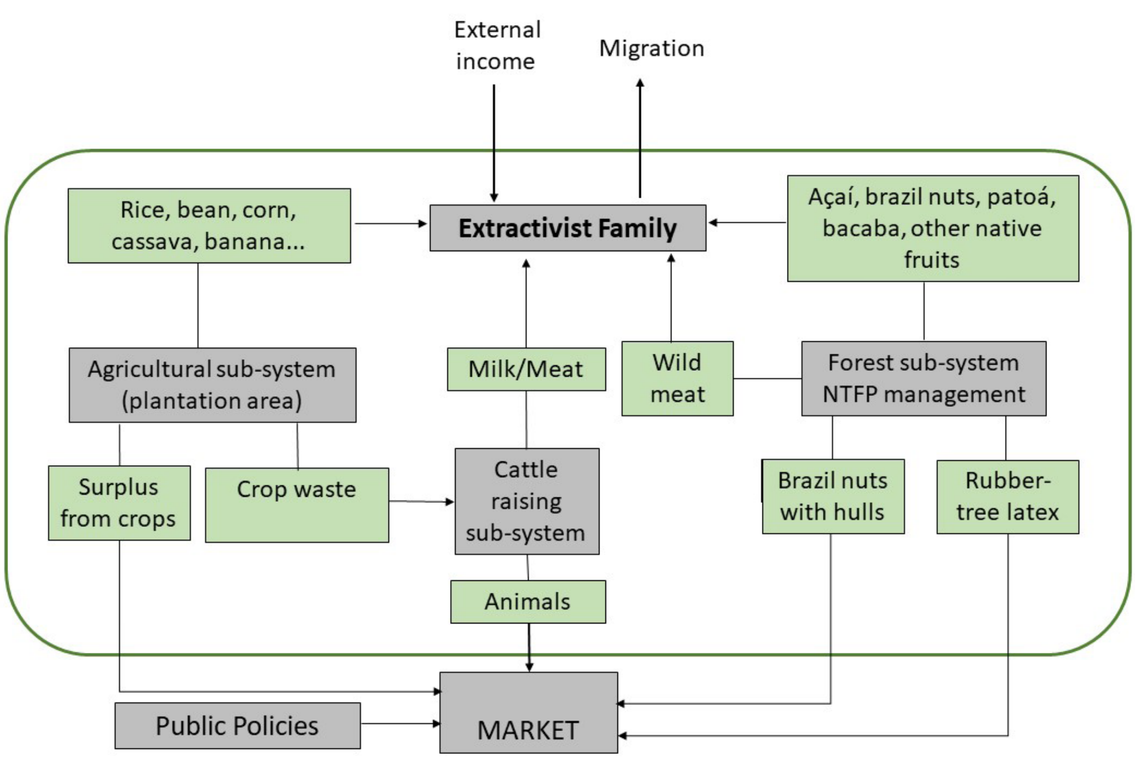

Figure 4 – Flowchart of the traditional agro-extractivist system in the Community Porvir, RESEX Chico Mendes, Acre State, Brazil.
Source: prepared by the author based on the Community Development Plan (Plano de Desenvolvimento Comunitário – PDC) (Acre, 2012) and Masera et al. (1999).

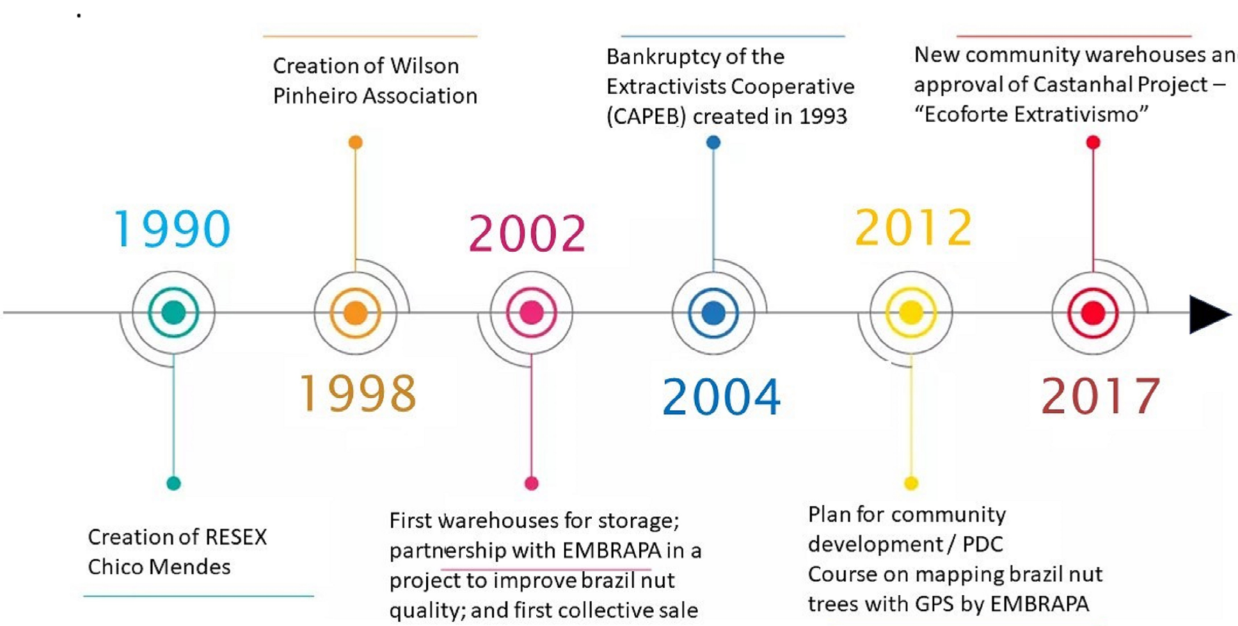

Figure 5 – Brazil nut Management timeline, Community Porvir, RESEX Chico Mendes – Acre State, Brazil.
Source: prepared by the author based on data collected in the research.

even when observed from the logic of scientific knowledge. In addition, the ecological knowledge of harvesters is evidenced by the high relevance of descriptors for the stability of Brazil nut tree populations, such as the presence of dispersers and pollinators, for example bumble bees (*Xylocopa spp.*), as well as the existence of regeneration (young Brazil nut trees). This knowledge is also expressed in the social and economic dimensions, demonstrating a capacity for systemic vision.

Table 3 shows the matrix of limiting and strengthening points built from the diagnostic workshop.

The low productivity of Brazil nuts trees in recent years is one of the main limiting points pointed out by harvesters, due to ecological and climatic factors, such as the perception of the senescence of Brazil nut trees and the great droughts in Acre State in 2005 and 2017.

In recent decades, several studies have investigated the impacts of the intensity of Brazil nut harvest on the stability of managed populations. Peres et al. (2003) studied 23 populations of the Brazil nut species in the Brazilian, Peruvian, and Bolivian Amazon and concluded that the hunting of natural dispersers (such as agouti) and overexploitation of fruits in some regions directly reduced the natural regeneration of *B. excelsa* species.

Recent studies (Wadt et al., 2005, 2008) have challenged some of the hypotheses presented by Peres et al. (2003) in Acre. These investigations demonstrated a condition of dynamic equilibrium in the pop-

Table 2 – Descriptors of a "good" Brazil nut management system cited by harvesters grouped by general sustainability attributes according to the MESMIS Method framework.

Attributes	Descriptors
Adaptability (41)	Nut transport tracks (4); well-kept Brazil nut trees (5); access facilities (2); cleaning nut trees and removing vines (7); cleaning peaks (4); mapping Brazil nut trees (9); differentiated market (2); national and international markets (2); partnerships (2); harvest planning (2); use of good management practices (4)
Self-management (21)	Family warehouse for storage (2); good communication (2); good organization (4); know production of Brazil nuts (2); quality nuts for good sales (9); vehicle to transport the nut (2); direct sales (2).
Productivity (18)	Good production (11); good income to the producer (4); production monitoring (2); quantity and quality of nut trees (2)
Equity (11)	Women participating in harvest and income (2); fair price and financial return (9)
Stability and resilience (9)	Absence of use of poisonous chemicals in Brazil nut stands and surrounding areas (2); presence of agouti - *Dascyprocta spp*. (2); presence of bumble bees (4); presence of young Brazil nut trees (2)

Source: elaborated by the authors from data collected in the research.

RBCIAMB | v.56 | n.4 | Dec 2021 | 551-563 - ISSN 2176-9478

Table 3 – Matrix of limiting and strengthening points in the Brazil nut management, Community Porvir, RESEX Chico Mendes – Acre State, Brazil.

Dimension	Limiting points	Strengthening points
Environmental	Many old Brazil nut trees (end of the production cycle)	Conserved Forest
	Use of pesticides around RESEX	Biodiversity richness
	Deforestation	Presence of agouti and other rodents (nut dispersers) – fauna richness
	Weaknesses in RESEX management system	
Technical-economic	Low productivity of Brazil nuts in recent years	Good price
	Sale to intermediaries (no commitment to the community)	High market demand
		Mastery of Best management practices for Brazil nut
		Partnerships: Embrapa, Bem Diverso Project/UNDP, Ecoforte Extractivism
Social (cultural and political)	Lack of training – knowledge of the proper use of RESEX	Extractive Culture
	Weaknesses in the performance of the concessionaire association	Women participation
	Lack of local organization for joint selling	

Source: elaborated by the authors from data collected in the research.

ulations studied, according to the reverse-J pattern, in the frequency distribution of Brazil nut trees by diameter class. According to the authors, this structure suggests healthy demographic populations with capacity for self-regeneration.

Ribeiro et al. (2014) also demonstrated a positive correlation between nut extraction by traditional populations and the stability of managed tree populations. The authors studied Brazil nut trees under different harvesting intensities in southern Pará. Scoles and Gribel (2011, 2015) studied population ecology and regeneration of Brazil nut trees in the Madeira and Trombetas River basins. These studies showed that the regeneration rates of Brazil nut trees are higher in managed forest environments.

Zuidema and Boot (2002) used matrix models and concluded that two populations of Brazil nut trees managed in Bolivia remain stable, even under a harvest intensity of 93% of fruits. Bertwell et al. (2018) conducted a population modeling study based on data from 14 years of research in two managed areas in Acre State (Brazil) and concluded that, instead of concentrating on the fate of most of the seeds produced, the most pressing risk to *B. excelsa* populations is the survival of existing trees, particularly those nearing reproductive size and those that are already producing.

Sustainability indicators of the environmental dimension

Table 4 shows the environmental indicators and the assessment results for four Brazil nut stands in Boa Água (I), Morada Nova (II), São José (III), and Encontro (IV).

For the four Brazil nut stands, the environmental indicator with the lowest score was "annual variation in the production of Brazil nuts", due to a 30% drop in the production of the crop evaluated in relation to the average for the region. Therefore, this indicator represents an undesirable condition for the sustainability of the activity.

Although the annual fluctuations in fruit production are characteristic of the species already well known by harvesters, production drops in recent years were discrepant and never experienced even by older harvesters, especially in the 2016/2017 harvest.

Brazil nut harvesters attribute these drops to changes in the frequency of rains, hindering nut formation.

Extreme weather events have become more frequent in southwestern Amazon and the years 2005, 2010, and 2016 registered the most severe droughts, causing forest fires in thousands of hectares, increasing air pollution and causing significant economic losses (Oliveira et al., 2017).

Staudhammer et al. (2021) state that the variation in Brazil nut fruit production in Acre State has also been affected by aspects related to soil characteristics, vegetative competition, higher temperatures in the dry season, and pressure deficit of water vapor in the air.

The population dynamics of Brazil nut trees and interactions with pollinators and dispersers showed favorable results, rated between "acceptable" and "ideal" conditions, demonstrating a positive correlation regarding the attributes of stability, resilience, and reliability for the management system studied.

In relation to the "deforestation" indicator, two sites evaluated are within the limit of 10% of areas open for agricultural use, according to the regulations for use of RESEX Chico Mendes (acceptable condition), while the others are configured as an "ideal" condition with less than 10% of deforested area. In this community, deforestation is not a critical problem as in other regions of this RESEX, with a tendency toward “pecuarization” (Gomes et al., 2012; Fittipaldy, 2017; Mascarenhas et al., 2018).

Comparison to other case studies carried out in tropical forest areas using the MESMIS method shows that the indicators defined for the environmental dimension are aligned with aspects generally monitored in studies on forest management systems and family agroecosystems (Silva et al., 2013; Proença and Massaroto, 2018; Roboredo et al., 2018).

Sustainability indicators of the technical-economic dimension

The indicators related to “Best management practices for Brazil nut” were considered strategic by all interviewees, as nut quality depends on the adoption of this set of actions. Having a product free from aflatoxins contamination is a matter of food safety, which is strongly related to the sustainability of the activity. Since the main challenge related to the quality of Brazil nuts is the high presence of contamination levels by aflatoxins, a mycotoxin produced by fungi of the genus *Aspergillus*.

Most indicators evaluated in the technical-economic dimension received scores from 5 to 10, representing reference values between “acceptable” and “ideal” conditions. Only the indicator “marketing channels” revealed an undesirable situation for the good management of Brazil nut trees. Table 5 presents the results for the four Brazil nut trees studied.

Most indicators evaluated are related to the theme of best management practices (BMP) in Brazil nut harvests, representing the set of techniques adopted in the pre-harvest, harvest, and post-harvest stages to ensure production quality, species conservation, and maintenance of productive activity over time.

The scores from these indicators demonstrate that the stands evaluated almost entirely adopt the guidelines proposed in the manuals of best management practices, showing that the harvest stage still needs improvement.

Studies carried out at RESEX show that, despite the ease of appropriating BMP, the little adoption of these practices in the harvest and post-harvest stages is due to factors such as the non-differentiation of price for the managed product, the high competition from buyers in the triple border region (Brazil, Bolivia and Peru), the low management capacity of local associations to seek differentiated markets, and insufficient technical assistance to guide the BMP adoption and support product quality monitoring (Wadt et al., 2016; Fonseca et al., 2019).

Therefore, the aspects that limit the full adoption of BMP are directly related to marketing issues, except for the factor related to technical assistance aimed at product quality.

Conversely, points that favor the BMP adoption in the Community Porvir refer to the existence of two community warehouses and a series of family warehouses (built with resources from the Ecoforte Extrativismo project). In addition, the support of Embrapa Acre is paramount in promoting the training of several families in the community in the participatory mapping of Brazil nut trees, as well as the use of GPS in

Table 4 – Scores attributed to sustainability indicators in the environmental dimension in four Brazil nut stands in the Community Porvir, RESEX Chico Mendes – Acre State, Brazil.

Nº	Indicators – Environmental Dimension	Brazil nut stands evaluated			
		I	II	III	V
1	Annual variation in Brazil nut tree fruit production	1	1	1	1
2	Distribution in size classes	10	5	5	5
3	Occurrence of native bees and pollinators	5	10	5	5
4	Occurrence of Brazil nuts dispersers	5	10	10	10
5	Deforestation	10	5	10	5
6	Regeneration of Brazil nut tree	10	10	10	10
	Final average	6.83	6.83	6.83	6.00

Source: elaborated by the authors from data collected in the research.

Table 5 – Scores attributed to the sustainability indicators of the technical-economic dimension in four Brazil nut stands evaluated in Community Porvir, RESEX Chico Mendes, Acre State, Brazil.

Nº	Indicators – Technical-Economic Dimension	Brazil nut stands evaluated			
		I	II	III	V
7	Best pre-harvest practices: mapping Brazil nut trees and production estimation.	10	10	10	10
8	Best harvest practices: harvest planning, recording annual production of trees.	5	10	10	5
9	Best post-harvest practices: storage conditions	10	10	10	10
10	Brazil nut trees maintenance	10	10	10	10
11	Marketing channels	5	5	1	1
12	Income from nuts	10	10	10	10
	Final average	8.33	9.17	8.50	7.67

Source: elaborated by the authors from data collected in the research.

the inventory of trees, and in best practices of collecting, storing, and transporting the nut.

The assessment of sales channels revealed a critical situation, configured as non-favorable for the activity sustainability, as it reflects the dependence of the community on intermediaries. According to harvesters, access to differentiated markets through the adoption of new marketing strategies and the organization of production is positive for the community, as this access could provide opportunities for new social gains, such as work and income generation for young people and women in the processing of nut-based products.

Over the past two years, association members and the community have received training in marketing and institutional markets, as well as participated in exchanges with other cooperatives. These actions stimulated reflection and discussion about new collective alternatives for marketing and adding value to the product.

The evaluation of the indicator "income from nuts" obtained the highest score, justified by the fact that the financial income obtained from the product sale accounts for more than 40% of the annual income of harvesters' families participating in the study. This reinforces the important role that Brazil nut management plays in supporting the livelihood of thousands of Amazonian residents.

Sustainability indicators of the social dimension

Table 6 shows that most indicators evaluated for the social dimension are situated between "acceptable" and "ideal" conditions, with the exception of the indicator "presence of support institutions", which had the lowest reference score for one of the participating families. For this dimension, the group represented in the evaluation workshop reflects the sample of families most involved with the association and the collective activities as a whole.

All families considered an "acceptable" level for the "access to information" indicator, since the community already has mobile telephones through a rural antenna and TV signal, although radio continues to be the main means of communication. The community has also benefited from several training courses in recent years.

The sharing of work and family income was considered "ideal" for three families and "acceptable" for one. Women participation is considered a strength for this community. The information is confirmed by the PDC (Acre, 2012), which indicated the engagement of women in decision-making, production tasks, and community activities.

Table 6 – Scores attributed to sustainability indicators for Social Dimension in four Brazil nut stands evaluated in Community Porvir, RESEX Chico Mendes, Acre State, Brazil.

Nº	Indicators - Social Dimension	Brazil nut stands evaluated			
		I	II	III	V
13	Access to information	5	5	5	5
14	Sharing work and family income	10	10	5	10
15	Social Organization	5	10	10	10
16	Knowledge about the proper use of RESEX	5	5	10	5
17	Fair price	10	5	5	5
18	Presence of support institutions	5	5	1	5
	Final average	6.67	6.67	6.00	6.67

Source: elaborated by the authors from data collected in the research.

Likewise, the indicator "social organization" was considered "ideal" for three families and "acceptable" for one, revealing the active engagement of the harvesters participating in the study, both in the association and in other community activities. The survey carried out during the PDC (Acre, 2012) showed that 28 of the 36 families in the community were members of the association, equivalent to 77.7%.

As for "knowledge about the proper use of the RESEX", only one family claimed to know all the existing regulations and management instruments, while three families claimed to know only one of the regulations (Use Plan). Farias (2013) reported a similar situation in a study carried out with representatives of 23 base centers of the RESEX, which revealed that 96% of respondents knew about the Use Plan for this Conservation Unit while 87% said they did not know the Management Plan nor the difference between this regulation and the Use Plan.

The indicator "fair price" was considered "acceptable" (price that remunerates only the labor and cost for extracting the nut) by three families and ideal for one family (price that pays environmental service and role of harvesters in addition to labor and production cost). This result demonstrates that most harvesters consider that the price paid for Brazil nuts still does not remunerate other socio-environmental services associated to forest conservation. According to Angelo et al. (2013), the price of Brazil nuts in the domestic market is determined by a series of variables, namely nut production, income, exchange rate, road network, and deforestation rate. However, Acre State has no governmental program for the payment of environmental services or state subsidies, as observed for latex production. Rubber tappers in Acre receive incentives via a government subsidy paid per kg of rubber produced (Law Chico Mendes No. 1.277 of January 13th, 1999) and also an additional amount via international payment for environmental service programs linked to the reduction of emissions by avoided deforestation (REDD).

The indicator "presence of support institutions" received scores between "undesirable" and "acceptable" conditions. There is no ongoing technical assistance for families at RESEX. Some services in Technical, Social, and Environmental Assistance (*Assistência Técnica, Social e Ambiental* – ATES) have already been provided with Brazilian Colonization and Land Reform Agency (*Instituto Nacional de Colonização e Reforma Agrária* – INCRA) resources, but in a discontinued manner.

Radial graphics have been widely used to integrate results of research involving participatory evaluation, as they allow an easy-to-understand presentation of results (Masera et al., 1999; Comin et al., 2016). This type of graphical representation shows the problems and potentialities of the management system in an integrated manner, considering each axis where the indicators selected for evaluation are found. Values closer to the outside of the graph represent aspects closer to the ideal condition.

Figure 6 presents a radial chart with the results of all indicators and dimensions evaluated for native Brazil nut trees in the Community Porvir.

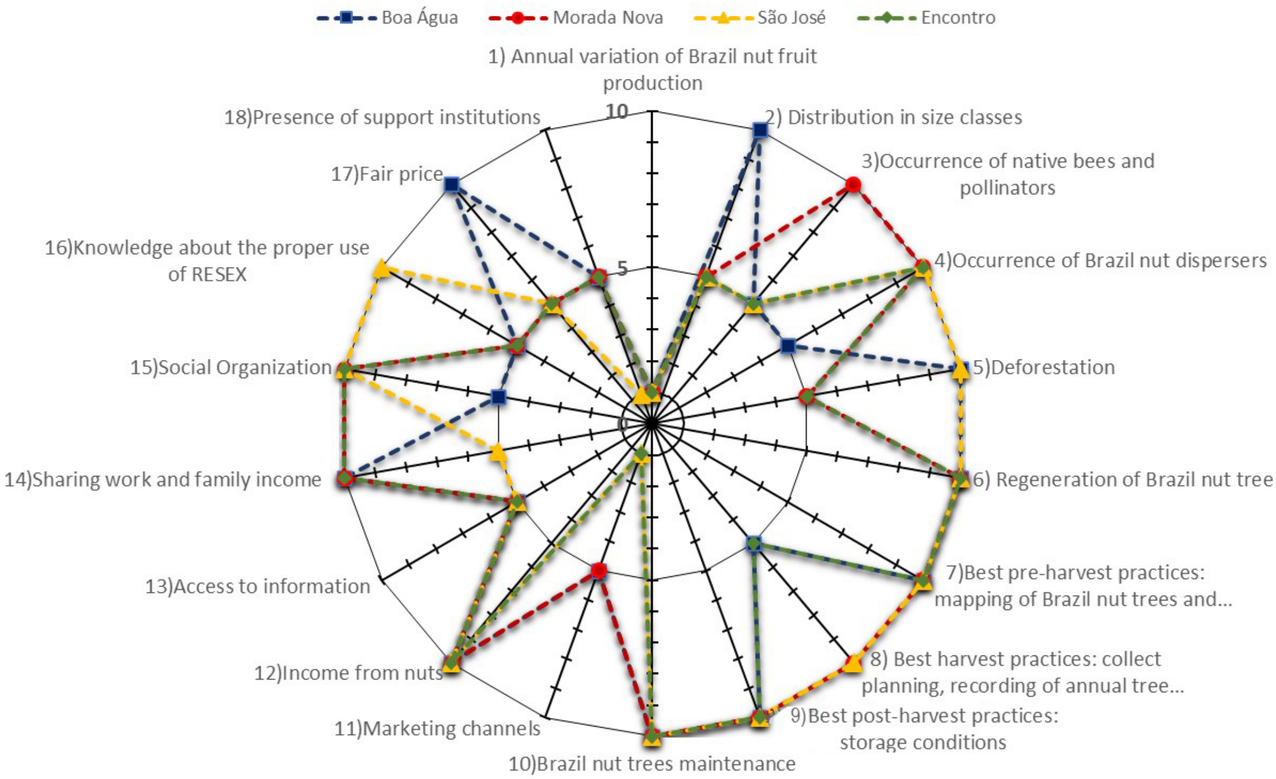

Figure 6 – Integration of the evaluation results of indicators for four native Brazil nut stands in the Community Porvir, RESEX Chico Mendes – Acre State, Brazil.
Source: prepared by the author based on data collected in the research.

Conclusions

The creation of a framework of indicators, built with the collaboration of community, based on the MESMIS method associated with other participatory research tools, allowed the articulation of knowledge (traditional and scientific) and the construction of a set of 18 strategic sustainability indicators (including evaluation parameters) with easy access to harvesters.

The set of indicators built, contemplating the environmental, technical-economic, and social dimensions, as well as different sustainability attributes, showed good applicability for participatory evaluations in the context of the management system studied.

The research sampling is reduced (only one community and only one evaluation cycle), which can be a limiting factor to infer about the viability of this set of indicators to monitor sustainability of the native Brazil nut management in different situations and scales. Nevertheless, the indicators evaluated serve as a basis for building similar processes in other communities, considering the local specificities of each management system and the dialog with harvesters.

General recommendations to improve sustainability of the systems studied are:

- Long-term research to better understand factors that affect production of Brazil nut trees and recommend silvicultural practices to improve production;
- Search for partnerships, projects, and/or learning processes to increase the management capacity of the local association and aggregate product value and differentiation, and seek differentiated markets;
- Community organization to define commercialization strategies that are beneficial to the community and to guarantee the full adoption of best management practices, achieving quality standards for nuts that favor access to differentiated markets.

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Contribution of authors:

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References

Acre. 2012. Secretaria de Estado de Meio Ambiente do Acre. Plano de Desenvolvimento Comunitário (PDC) – Comunidade Porvir. Epitaciolândia, 82 pp.

Angelo, H.; Almeida, A.N.; Calderon, R.A.; Pompermayer, R.S.; Souza, A.N., 2013. Determinantes do preço da castanha-do-Brasil (Bertholletia excelsa) no mercado interno brasileiro. Scientia Forestalis (IPEF), v. 41, (98), 195-203 (Accessed July 27, 2018) at: https://www.ipef.br/publicacoes/scientia/nr98/cap05.pdf.

Astier, M.; García-Barrios, L.; Galván-Miyoshi, Y.; González-Esquivel, C.; Masera, O.R., 2012. Assessing the sustainability of small farmer natural resource management systems. A critical analysis of the MESMIS program (1995-2010). Ecology and Society, v. 17, (3). http://dx.doi.org/10.5751/ES-04910-170325.

Astier, M., Hollands, J., 2007. Sustentabilidad y campesinado. Seis experiencias agroecológicas en Latinoamérica. 2. ed. Mundiprensa-GIRA-ILEIA, Ciudad de México.

Bellen, H.M., 2006. Indicadores de Sustentabilidade: uma análise comparativa. 2. ed. FGV, Rio de Janeiro, 256 pp.

Bertwell, T.D.; Kainer, K.A.; Cropper, W.P. Jr.; Staudhammer, C.L.; Wadt, L.H.O., 2018. Are Brazil nut populations threatened by fruit harvest? Biotropica, v. 50, (1), 50-59. http://dx.doi.org/10.1111/btp.12505.

Brose, M.E., 2016. Cadeias produtivas sustentáveis no desenvolvimento territorial: a castanha na Bolívia e no Acre. Interações, Campo Grande, v. 17, (1), 77-86. https://doi.org/10.20435/1518-70122016108.

Cândido, G.A.; Nóbrega, M.M.; Figueiredo, M.T.E.; Souto Maior, M.M., 2015. Avaliação da sustentabilidade de unidades de produção agroecológicas: um estudo comparativo dos métodos Idea e Mesmis. Ambiente & Sociedade, v. 18, (3), p. 99-120. http://dx.doi.org/10.1590/1809-4422ASOC756V1832015.

Caporal, F.R.; Nogueira, R.S.; Silva, D.S., 2010. Agroecologia: superar o discurso ecotecnocrático na busca de indicadores de sustentabilidade. In: Ferreira, J.M.L.; Alvarenga, A. de P.; Santana, D.P.; Vilela, M.R. (Eds.), Indicadores de sustentabilidade em sistemas de produção agrícola. Epagri, Belo Horizonte, pp. 47-86.

Cartaxo, C.B.C.; Souza, J.M.L; Wadt, L.H.O; Alvares, V.S.; Fonseca, F.L., 2016. O papel de comunidades tradicionais na definição de políticas públicas de promoção da cadeia produtiva de castanha-do-brasil. Diálogo de Saberes: Relatos da Embrapa. In: Dias, T.; Eidt, J.S.; Udry, C. (Eds.). Coleção Povos e Comunidades Tradicionais. Embrapa, Brasília, pp. 301-311. v. 2.

Comin, J.J; Fayad, J.A.; Kurtz, C.; Mafra, A.L.; Curmi, P., 2016. Guia prático de avaliação participativa da qualidade do solo em sistema de plantio direto de hortaliças (SPDH). Open Brasil Gráfica e Editora, Florianópolis. (Comunicado Técnico).

Duchelle, A.; Zambrano, A.M.; Wunder, S.; Boerner, J.; Kainer, K.A., 2014. Smallholder specialization strategies along the forest transition curve in Southwestern Amazonia. World Development, v. 64, (Suppl. 1), S149-S158. http://dx.doi.org/10.1016/j.worlddev.2014.03.001.

Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA. 2017. Boletim do arranjo de projetos tecnologias para o fortalecimento da cadeia de valor da castanha-do-brasil, da Empresa Brasileira de Pesquisa Agropecuária (Embrapa). EMBRAPA, Brasil (Accessed September 28, 2017) at: https://www.embrapa.br/busca-de-noticias/-/noticia/26131296/pesquisa-aponta-queda-de-70-na-producao-de-castanha-da-amazonia.

Farias, M.S., 2013. Percepção dos atores envolvidos no monitoramento do plano de manejo da Reserva Extrativista Chico Mendes, Acre, Brasil. Monography, Universidade Federal do Paraná e Universidade Federal do Acre, Rio Branco.

Fonseca, F.L.; Cartaxo, C.B.C.; Wadt, L.H.O., 2019. Challenges in adopting good management practices for sustainable extraction of Brazil nuts in Acre, Brazil. In: XXV IUFRO World Congress, 2019, Curitiba. Pesquisa Florestal Brasileira. Embrapa, Curitiba, pp. 527-527. v. 39.

Fittipaldy, M.C.P.M., 2017. Reserva Extrativista Chico Mendes: dos empates à pecuarização? Edufac, Rio Branco (Accessed December 8, 2019) at: http://www2.ufac.br/editora/livros/reserva-extrativista-chico-mendes.pdf.

Gallopín, G.C., 1996. Environmental and sustainability indicators and the concept of situational indicators: a system approach. Environmental Modelling & Assessment, v. 1, (3), 101-117. https://doi.org/10.1007/BF01874899.

Gardner, T.; Costi, H.T., 2014. Carta do Editor. Boletim do Museu Paraense Emilio Goeldi. Ciências Naturais, Belém, v. 9, (2).

Gomes, C.V.A.; Perz, S.G.; Vadjunec, J.M., 2012. Convergence and contrasts in the adoption of cattle ranching: Comparisons of smallholder agriculturalists and forest extractivists in the Amazon. Journal of Latin American Geography, v. 11, (1), 99-120. https://doi.org/10.1353/lag.2012.0018.

Gomes, J.C.C., 2010. As técnicas participativas na pesquisa agrícola: fundamentos teóricos e algumas dificuldades práticas. In: Brose, M. (Ed.), Metodologia participativa: uma introdução a 29 instrumentos. 2. ed. Tomo Editorial, Porto Alegre, pp. 307-314.

Hammond, A.; Adriaanse, A.; Rodenburg, E.; Bryant, D.; Woodward, R., 1995. Environmental indicators: a systematic approach to measuring and reporting on environmental policy performance in the context of sustainable development. World Resources Institut, Washington, D.C.

Kainer, K.A.; Wadt, L.H.O.; Staudhammer, C.L., 2018. The evolving role of Bertholletia excelsa in Amazonia: contributing to local livelihoods and forest conservation. Desenvolvimento e Meio Ambiente, v. 48, (1), 477-497. https://doi.org/10.5380/dma.v48i0.58972.

López-Ridaura, S.; Masera, O.; Astier, M., 2002. Evaluating the sustainability of complex socio-environmental systems. the MESMIS framework. Ecological Indicators, v. 2, (1-2), 135-148. https://doi.org/10.1016/S1470-160X(02)00043-2.

Loureiro, J.P.B.; Santos, M.A.S.; Rodrigues, H.E.; Souza, C.C.F.; Rebello, F.K., 2020. Avaliação de sistemas de manejo de recursos naturais com base em indicadores de sustentabilidade: uma revisão sistemática da literatura sobre o uso do método MESMIS. Research, Society and Development, v. 9, (8), e538986067. http://dx.doi.org/10.33448/rsd-v9i8.6067.

Marques, J.F.; Skorupa, L.A.; Ferraz, J.M.G., 2003. (Ed.). Indicadores de sustentabilidade em agroecossistemas. Embrapa Meio Ambiente, Jaguariúna, 281 pp.

Mascarenhas, F.S.; Brown, I.F.; Silva, S.S., 2018. Deforestation and forest fires transforming the reality of the Chico Mendes Extractive Reserve. Desenvolvimento e Meio Ambiente, v. 48, 236-262. https://doi.org/10.5380/dma.v48i0.58826.

Masera, O.; Astier, M.; López-Ridaura, S., 1999. Sustentabilidad y manejo de recursos naturales: el marco de evaluación MESMIS. Mundi-Prensa, México, 109 pp.

Masera, O; Lopez-Riadura S. (org.). Sustentabilidad y Sistemas Campesinos: cinco experiencias de evaluaciónenel México rural. México: Mundi-Prensa, 346 p., 2000.

Melane-Lavado, A.; Álvarez-Herranz, A., 2018. Different ways to access knowledge for sustainability-oriented innovation. The effect of foreign direct investment. Sustainability (Switzerland), v. 10, (11), 4206. https://doi.org/10.3390/su10114206.

Oliveira, I.D.; Brown, I.F.; Silva, S.S., 2017. Geotecnologias e mídia social como ferramentas para alerta de eventos climáticos extremos: exemplo da seca de 2016 na Amazônia Sul-ocidental. In: XVIII Simpósio Brasileiro de Sensoriamento Remoto-SBSR, 2017, Santos. INPE, São Jose dos Campos, pp. 7126-7133.

Peres, C.A.; Baider, C.A.; Zuidema, P.A.; Wadt, L.H.O.; Kainer, K.A.; Gomes-Silva, D.A.P.; Salomão, R.P.; Simões, L.L.; Franciosi, E.R.N.; Valverde, F.C.; Gribel, R.; Shepard Jr., G.H.; Kanashiro, M.; Coventry, P.; Yu, D.W.; Watkinson, A.R.; Freckleton, R.P., 2003. Demographic Threats to the sustainability of Brazil nut exploitation. Science, v. 22, (1091698), 2112-2114. http://dx.doi.org/10.1126/science.1091698.

Picanço, C.A.S.; Costa, R.C., 2019. Análise da cadeia produtiva da castanha-do-Brasil coletada na reserva biológica do Rio Trombetas, Oriximiná, Pará. Brazilian Journal of Development, v. 5, (10), 19460-19483. http://dx.doi.org/10.34117/bjdv5n10-170.

Proença, I.C.L.; Massaroto, J.A., 2018. Estudo da sustentabilidade em agroecossistemas orgânicos na Amazônia mato-grossense, Brasil. ELO – Diálogos em Extensão, v. 7, (2), 15-27. http://dx.doi.org/10.21284/elo.v7i2.1257.

Ribeiro, M.B.N.; Jerozolimski, A.; Robert, P.; Salles, N.V.; Kayapó, B.; Pimentel, T.P.; Magnusson, W.E., 2014. Anthropogenic landscape in Southeastern Amazonia: Contemporary impacts of low-intensity harvesting and dispersal of brazil nuts by the Kayapó indigenous people. Plos One, v. 9, (7), e102187. http://dx.doi.org/10.1371/journal.pone.0102187.

Roboredo, D.; Bergamasco, S.M.P.P.; Ara, A.; Gervázio, W.; Domingues, T.R., 2018. Clusterizacão de sistemas de manejos e a construção de indicadores de sustentabilidade utilizando a metodologia MESMIS. RA'E GA - O Espaço Geográfico em Análise, v. 43, 23-42. http://dx.doi.org/10.5380/raega.v43i0.48787.

Schlindwein, S.L., 2010. Indicadores de sustentabilidade e aprendizagem social. In: Ferreira, J.M.L.; Alvarenga, A.P.; Santana, D.P.; Vilela, M.R. (Eds.), Indicadores de sustentabilidade em sistemas de produção agrícola. EPAMIG, Belo Horizonte, pp. 87-106.

Scoles, R.; Gribel, R., 2011. Population structure of Brazil Nut (Bertholletia excelsa, Lecythidaceae) stands in two areas with different occupation histories in the Brazilian Amazon. Human Ecology, v. 39, 455-464. http://dx.doi.org/10.1007/s10745-011-9412-0.

Scoles, R.; Gribel, R., 2015. Human Influence on the Regeneration of the Brazil Nut Tree (Bertholletia excelsa Bonpl., Lecythidaceae) at Capanã Grande Lake, Manicoré, Amazonas, Brazil. Human Ecology, v. 43, (6), 843-854. http://dx.doi.org/10.1007/s10745-015-9795-4.

Silva, L.M.S.; Resque, A.G.L.; Feitosa, L.L.; Nogueira, A.C.N., 2013. Avaliando a sustentabilidade de agroecossistemas familiares: adaptando o MESMIS para distintos contextos da Amazônia brasileira. In: IV Congresso Latino-americano de Agroecologia – Universidad Nacional Agraria La Molina, Lima, 16 pp.

Silva, T.P.; Pontes, A.N.; Albuquerque, A.R., 2020. Cadeias de produção sustentáveis no extrativismo de castanha do Brasil na Amazônia brasileira. Brazilian Journal of Development, v. 6, (8), 63460-63478. http://dx.doi.org/10.34117/bjdv6n8-687.

Simoni, J.S., 2009. A multidimensionalidade da valorização de produtos locais: implicações para políticas públicas, mercado, território e sustentabilidade na Amazônia. Doctoral Thesis, Centro de Desenvolvimento Sustentável, Universidade de Brasília, Brasília.

Staudhammer, C.L.; Wadt, L.H.O.; Kainer, K.A.; Cunha, T.A., 2021. Comparative models disentangle drivers of fruit production variability of an economically and ecologically important long-lived Amazonian tree. Scientific Reports, v. 11, 2563. https://doi.org/10.1038/s41598-021-81948-4.

Steenbock, W.; Silva, R.O.; Seoane, C.E.; Froufe, L.C.M.; Braga, P.C.; Silva, R.M., 2013. Geração e uso de indicadores de monitoramento de agrofloresta por agricultores associados a Cooperafloresta. In: Steenbock, W.; Costa e Silva, L.; Silva, R.O.; Rodrigues, A.S.; Perez-Cassarino, J.; Fonini, R. (Eds.), Agrofloresta, ecologia e sociedade. Kairós, Curitiba, pp. 305-320.

Vivan, J.L.; Floriani, G.S., 2001. Construção participativa de indicadores de sustentabilidade em sistemas agroflorestais em rede na Mata Atlântica. In: Congresso Brasileiro de Sistemas Agroflorestais, 5., 2001, Curitiba. SAFs: desenvolvimento com proteção ambiental: anais. Embrapa Florestas, Colombo, pp. 134-139.

Wadt, L.H.O.; Kainer, K.A.; Gomes-Silva, D.A.P., 2005. Population structure and nut yield of a *Bertholletia excelsa* stand in Southwestern Amazonia. Forest Ecology and Management, v. 211, (3), 371-384. http://dx.doi.org/10.1016/j.foreco.2005.02.061

Wadt, L.H.O.; Kainer, K.A.; Staudhammer, C.L.; Serrano, R.O.P., 2008. Sustainable forest use in Brazilian extractive reserves: natural regeneration of Brazil nut in exploited populations. Biological Conservation, v. 141, (1), 332-346. http://dx.doi.org/10.1016/j.biocon.2007.10.007.

Wadt, L.H.O.; Passetti, A.M.R.S.; Pereira, V.A.M.; Fonseca, F.L.; Alvares, V.S.; Cartaxo, C.B.C.; Souza, J.M.L., 2016. Experiência de adoção de boas práticas de manejo para o extrativismo sustentável da castanha-do-brasil em duas comunidades extrativistas da Resex Chico Mendes, Acre. Diálogo de Saberes: Relatos da Embrapa. In: Dias, T.; Eidt, J.S.; Udry, C. (Eds.), Coleção Povos e Comunidades Tradicionais. Embrapa, Brasília, pp. 289-300. v. 2.

Walker, W.S.; Gorelik, S.R.; Baccini, A.; Aragon-Osejo, J.L.; Josse, C.; Meyer, C.; Macedo, M.N.; Augusto, C.; Rios, S.; Katan, T.; Souza, A.A.; Cuellar, S.; Llanos, A.; Zager, I.; Mirabal, G.D.; Solvik, K.K.; Farina, M.K.; Moutinho, P.; Schwartzman, S., 2020. The role of forest conversion, degradation, and disturbance in the carbon dynamics of Amazon indigenous territories and protected areas. Proceedings of the National Academy of Sciences of the United States of America, v. 117, (6), 3015-3025. https://doi.org/10.1073/pnas.1913321117.

Zuidema, P.A.; Boot, R.G.A., 2002. Demography of the Brazil nut tree (Bertholletia excelsa) in the Bolivian Amazon: impact of seed extraction on recruitment and population dynamics. Journal of Tropical Ecology, v. 18, (1), 1-31. http://dx.doi.org/10.1017/S0266467402002018.

ABES

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Participatory process for mapping socio-environmental determinants of health by community agents: Contributions to urban management and planning

Processo participativo para o mapeamento de determinantes socioambientais de saúde por agentes comunitárias: contribuições para a gestão e o planejamento urbano

Renata Ferraz de Toledo[1], Ana Paula Koury[1], Carolina Monteiro de Carvalho[2], Francisco Nilson Paiva dos Santos[3]

ABSTRACT

Studies about socio-environmental determinants are recognized as important to better understand the factors that influence health and quality of life, and how they operate to generate inequalities. This article reports the mapping of socio-environmental determinants of health, carried out by community health agents from the community of Paraisópolis, the second-largest slum in the city of São Paulo (state of São Paulo), seeking to analyze potential contributions of this participatory process to urban management and planning. As part of an action research study and following the stages of Paulo Freire's Research Itinerary (Culture Circles), the mapping was carried out by integrating the Talking Map technique with Geographic Information Systems (GIS), in what has been called Participatory GIS or Geographic Information Systems with Social Participation (PGIS). Positive aspects were recognized and addressed by community agents, as well as several situations of socio-environmental vulnerability as a result of the agglomerated nature of the place, directly related to urban management and planning needs. This shows that, through a participatory mapping process, citizens cannot only better identify, but also more effectively communicate their needs and qualify intervention strategies in the territory. Therefore, it is possible to address the residents' priorities more representatively, especially in places where traditionally marginalized social groups live. And also, community health agents, who play a central role in this research process because they live and work in the same place, are fundamental to boost, mobilize, and support the complex aspects involved, both in Primary Health Care, as well as in urban management and planning.

Keywords: primary health care; social determinants of health; Paraisópolis; action research; geographic information systems with social participation.

RESUMO

Estudos sobre determinantes socioambientais são reconhecidos como importantes para melhor compreender fatores que influenciam na saúde e qualidade de vida e como eles podem operar na geração de iniquidades. Este artigo relata o mapeamento de determinantes socioambientais de saúde realizado por agentes comunitárias de Paraisópolis, a segunda maior favela da cidade de São Paulo (SP), buscando analisar possíveis contribuições desse processo participativo para a gestão e o planejamento urbano. Como parte de uma pesquisa-ação e seguindo etapas do itinerário de pesquisa de Paulo Freire (Círculos de Cultura), o mapeamento foi realizado integrando a técnica do mapa-falante com sistemas de informação geográfica (SIG), no que vem sendo chamado de SIG participativo ou SIG com participação social. Foram reconhecidos pelas agentes comunitárias, tornando-se objetos de reflexão, aspectos positivos, bem como diversas situações de vulnerabilidade socioambiental do aglomerado diretamente relacionadas às demandas de gestão e planejamento urbano. Isso evidencia, portanto, que, por meio desse processo de mapeamento participativo, os cidadãos podem não apenas melhor identificar, como também comunicar mais eficazmente suas necessidades e qualificar estratégias de intervenção no território, atendendo de modo mais representativo às prioridades dos moradores, especialmente nas localidades em que os grupos sociais tradicionalmente marginalizados residem. Ainda, no caso de agentes comunitárias de saúde, as participantes centrais desta pesquisa, por morarem no local onde atuam elas são essenciais para impulsionar, mobilizar e apoiar as engrenagens complexas tanto da Atenção Básica em Saúde como da gestão e do planejamento urbano.

Palavras-chave: atenção básica em saúde; determinantes sociais da saúde; Paraisópolis; pesquisa-ação; sistemas de informação geográfica com participação social.

[1]Universidade São Judas Tadeu – São Paulo (SP), Brazil.

[2]Universidade de São Paulo – São Paulo (SP), Brazil.

[3]Hospital Albert Einstein – São Paulo (SP), Brazil.

Correspondence address: Renata Ferraz de Toledo – Pesquisa e Pós-Graduação Stricto Sensu, Universidade São Judas Tadeu – Rua Taquari, 546, 2º Andar, Bloco C – CEP: 03166-000 – São Paulo (SP), Brazil. E-mail: renata.toledo@saojudas.br

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Introduction

The socio-environmental determinants of health, that is, the various individual, social, and macro-structural factors that condition and determine people's health and quality of life (CSDH, 2008; Sobral and Freitas, 2010), were recognized and mapped by community health agents (CHAs) in the territory covered by Paraisópolis II Basic Health Unit (BHU), in the community of Paraisópolis, city of São Paulo (state of São Paulo). The talking map construction technique was used in association with participatory mapping, applied in an action research process (Toledo and Giatti, 2015), and the stages of the Culture Circles, part of Paulo Freire's Research Itinerary (Freire, 2019), were followed. Participatory mapping is a set of approaches and techniques that combines modern cartography tools with participatory methods to record and represent the spatial knowledge of local communities and, therefore, bring about social change (Cochrane and Corbett, 2020; Mapping For Rights, 2020), by identifying priorities and necessary interventions (Freitas et al., 2020). This method is part of a Participatory Geographic Information System (PGIS).

Together with other health professionals, CHAs are part of Family Health Strategy (FHS) teams that carry out individual and collective actions, especially in education and health promotion and disease prevention, at people's homes or in a community context, in a certain area attached to a reference BHU, according to the guidelines for Preventive Health and Primary Health Care of the Brazilian Unified Health System (*Sistema Único de Saúde*, SUS). As they also live in the area where they professionally work, CHAs are immersed in the local context. Therefore, it is expected that they can more easily recognize the socio-environmental determinants that influence the health of the community and interact with the population. They also give voice to their potential claims, since very asymmetric power relations tend to hinder intercommunication between health professionals and users. Several studies even show bonds and affection between CHAs and the community, with positive implications for the territory (Bezerra and Feitosa, 2018; Brasil, 2018; Faria and Paiva, 2020; Silva et al., 2020).

In the specific setting of this research, Paraisópolis community, located in Vila Andrade, Morumbi neighborhood, in the southern zone of the city of São Paulo (SP), several problems directly and indirectly impact the health of the local population: absent or poor basic sanitation, unhealthy housing, presence of disease vector animals, among others that are associated with incomplete urbanization projects, especially due to political issues involving administration changes that intensify degradation of the territory, situations of vulnerability, and social exclusion (Maziviero and Silva, 2018).

Maps of the territory covered by Paraisópolis II BHU were then produced by CHAs representing socio-environmental determinants with positive and negative influence on the health of local residents, by integrating the Talking Map technique with Geographic Information Systems (GIS), in what has been called Participatory GIS or Geographic Information Systems with Social Participation (PGIS) (Carvalho and Giatti, 2018). PGIS represents the spatial knowledge of local people by applying geospatial technologies that facilitate social engagement and participation in decision-making processes and support communication and advocacy of the community's interests. Therefore, they have great power to produce social changes (McCall, 2004).

Some studies have shown contributions of geoprocessing in the health area, especially in Primary Care, as evidenced in the systematic review conducted by Salinas Rebolledo et al. (2018), given the growing demand for interdisciplinary and intersectoral actions focused on the socio-environmental determinants of health. The authors identified benefits from the use of this technology, for example, in estimating the health professionals' commute time in the territory, in spatially quantifying access to health services and programs, and in identifying environmental conditions and situations of inequality, among other aspects that make decision-making more efficient. On the other hand, the authors also mention that the publications analyzed do not highlight the potential contributions of geoprocessing to motivate the work of health professionals or even engage the community.

Thus, geoprocessing offers clear benefits for the health area, especially in Primary Care, as well as for urban planning. Many papers have explored the correlations between health and environmental conditions, resorting to geoprocessing tools. In this field, contributions that show this relationship stand out, mainly in vulnerable territories (Arcoverde et al., 2018; Almeida et al., 2020). In urban planning, the papers explore the new information technologies applied to the participatory mapping of urban vulnerabilities (Kahila-Tani et al., 2019; Abranches, 2020). The possible contributions of this Health Care level (Maman et al., 2009; Goldstein et al., 2013; Fornace et al., 2018; Arouca et al., 2019; Magalhães, 2021; Moraes et al., 2021), especially by the performance of CHAs, in the management and planning of urban spaces have been less explored by the literature.

Therefore, the question is how the mapping process of socio-environmental determinants of health, when carried out in a participatory manner and by Paraisópolis CHAs, can contribute to urban management and planning.

Although this research provides results referring to the specific territory of Paraisópolis, São Paulo, we believe in the replicability potential of the methodology reported herein, as well as in its relevance to improve studies and practices in this interdisciplinary field, in an interface between health, environment, and urbanism.

Therefore, this article aims at analyzing potential contributions of the participatory process of mapping socio-environmental determinants of health to urban management and planning, when carried out by community agents.

Socio-environmental determinants of health

Associations between the way people live and eat, the environment they occupy, etc., and health are not recent; they date back to ancient times and, for centuries, philosophers have made assumptions trying to understand the factors that influenced human health and the process of illness. In the 19th century, John Snow's studies on cholera, which mapped cases of the disease in a London neighborhood, are noteworthy, as well as the social medicine movement, more intense during that time in Germany, France, and England, where socio-environmental aspects were timidly considered in the conception of health. However, later in the same century, with the discovery of microscopic agents that spread diseases, the focus was shifted to controlling these pathogens, inaugurating a period of strong biological determinism (Sobral and Freitas, 2010).

During the 20th century, the socio-environmental factors were present in the reflections of various events in the health area and the documents resulting thereof. Philippi Junior et al. (2014) consider the creation of the World Health Organization (WHO) in 1946 as a significant milestone in the constitution of environmental systems, as well as the first General Health Assembly in 1948, where health is defined as more than the absence of disease, a state of complete physical, mental, and social well-being. Other documents gradually incorporated this view of comprehensive health throughout the century and expanded the understanding of its multi-causality, as identified in the Declaration of Alma-Ata, resulting from the International Conference on Primary Health Care, held in 1978, and in the 8th National Health Conference, held in Brazil in 1986, an important landmark of Brazilian sanitary practices. Additionally, it is possible to mention the Health Promotion Movement, which highlights, among other aspects, the importance of environments that are conducive to health and healthy public policies for people to live healthy lives; or even in the Organic Health Law itself, known as the SUS Law (Brazilian Federal Law 8,080, of September 19th, 1990).

However, it can be asserted that it was only recently, since the creation of the World Commission on Social Determinants of Health (CSDH) by the WHO in 2005, that the focus has shifted to better understanding which factors can influence health and how they operate in generating health inequalities (CSDH, 2008), especially among the most vulnerable, that is, those with greater difficulty or limited capacity to react to certain risks (Carmo and Guizardi, 2018). The health of individuals and social groups is now recognized as resulting from individual, social, and macro-structural determinants, that is, the different situations in which people are born, grow, work, live, and age throughout their lives (CSDH, 2008; Akerman et al., 2011).

This layered organization of the social determinants of health was proposed by the Dahlgren and Whitehead Model, which considers the following as individual determinants: hereditary characteristics, gender, age, and lifestyle; as social determinants: the various living and working conditions, such as access to and quality of housing, food, sanitation, education and health services, among others; and, as macro-structural determinants: the general economic, social, cultural, environmental, and health public policies. This model also highlights the interdependence between these layers and determinants, and that actions aimed at addressing situations of inequalities must be taken simultaneously at the individuals' proximal level, at the intermediate level, and at the distal level, to favor adequate conditions and allow healthy choices (Sobral and Freitas, 2010).

Research studies relating the various socio-environmental factors with human health have been conducted with different approaches and in different contexts. When investigating the aged population, Cassol (2012) recognized three scenarios of how environmental determinants influence the health-disease process: the first one relating cardiovascular and neoplastic diseases both to genetic characteristics and to living and working conditions, highlighting the association with environmental pollutants; the second relating infectious and parasitic diseases to precarious socio-environmental conditions, such as absent or ineffective sanitation; and the third connecting situations of violence and accidents to health-disease processes.

Several studies on determinants of respiratory diseases in general, conducted by Antunes et al. (2014), in different regions of Salvador, BA, and on the incidence of tuberculosis, conducted by Acosta and Bassanesi (2014), in different regions of the city of Porto Alegre, RS, also identified an association between schooling, income, sanitation services, health services, and characteristics and location of the houses and a higher number of cases. The relationship between atmospheric contaminants and health problems is also the focus of research studies carried out by Silva et al. (2017), Abe and Miraglia (2018) and Corá et al. (2020), drawing attention to determinants related to industrialization, urban mobility, and the importance of public policies for transportation and air pollution control.

Sociodemographic variables and environmental and structural conditions are considered in the research study by Honorato et al. (2014), conducted in the state of Espírito Santo, as important determinants to understand and fight dengue. The authors recognized deficient or absent sanitation and precarious housing, especially in contexts of social inequality in large urban agglomerations, as factors that contribute to maintaining the number of disease cases and/or increasing its incidence. Similarly, health risks and problems associated with precarious sanitation services are surveyed and discussed in the studies by Ogata et al. (2016) on the quality of drinking water; by Chayb and Kozusny-Andreani (2015) on the presence of pathogens in different types of waste, with emphasis on the risks of contamination of household waste; and by Lobato and Jardim (2014) on diseases related to inadequate environmental sanitation.

The approach of socio-environmental determinants is also considered in the Health Impact Assessment (HIA), recommended by the WHO and widely disseminated and used in other countries, associated with environmental licensing processes of large enterprises, which require planned and complex actions. This methodology, still not widely used in Brazil, analyzes, in association with the social players involved, both positive and negative aspects of health resulting from interventions in a territory, whether originating from projects, programs, plans,

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or public policies. It does not overlap with other assessments, so it is possible to consider the health variable that is generally not taken into account in these studies by the decision-maker (Silveira and Fenner, 2017).

Cassol (2012) and Camponogara et al. (2013) address the importance of this expanded and systemic perspective to health, considering its multi-causality and the various socio-environmental contexts that impact it, as well as the role and appreciation of the health professionals working in Primary Care, such as the CHAs. In the opinion of these authors, the research studies carried out evidenced knowledge of the territory by these professionals, as they work and live there, which is fundamental to enhance the actions focused on the complexity of the socio-environmental determinants of health.

Experiences developed by the Manguinhos Territorial Laboratory (*Laboratório Territorial de Manguinhos*, LTM) also seek to enhance the actions of FHS teams and the integration of different knowledge by proposing "extended action research communities", consisting of researchers from Fiocruz and other institutions, residents of Rio de Janeiro informal settlements (Manguinhos, Alemão, and Rocinha), and health professionals working in these locations, to brainstorm and seek more efficient collaborative solutions to issues associated with socio-environmental determinants, in contexts of high vulnerability (Porto et al., 2015).

It is also emphasized that important advances are acknowledged by Borde et al. (2014) in mapping research studies about the social determinants of health in Brazil since the creation of the National Commission on Social Determinants of Health, in terms of number and quality of research studies. In turn, as highlighted by the authors, there are still enormous regional and intra-urban differences in the country in terms of urban sprawl and peripheralization, not often considered in research studies using data from information systems with indicators generally based on a mean value that does not reflect actual social inequalities. In addition to that, despite the search for bringing science, politics, and society closer together through innovative research processes on this theme, these are still very scarcely reflected in public policies aimed at reducing situations of vulnerability and, consequently, inequalities. This is due to the challenges associated, for example, with the communication, evaluation, and research processes themselves, which are still very restricted to the academic population, either in their production or dissemination, and interact very little with other relevant social players, such as technical professionals from governmental sectors in the various areas involved.

Territory under analysis and urban planning

Paraisópolis, the territory under analysis in this article, is the second-largest informal settlement in São Paulo, with nearly 80,000 inhabitants, most of them living in areas of high socio-environmental vulnerability, overlapping risks, and health inequalities. The area is divided into seven different sectors, five of them located in the main cluster, and two in satellite clusters. These sectors are characterized by different degrees of access to infrastructure and public services, according to a survey commissioned by the Municipal Housing Secretariat (*Secretaria Municipal de Habitação*, SEHAB) in 2004 and analyzed by several authors (Rezende and Alvim, 2016; Maziviero and Silva, 2018).

The main cluster belongs to the Campo Limpo District Council and, according to the 2004 survey, it had 17,184 households in 1 Km^2 approximately at that time. The Southeast quadrant, composed of the Grotão and Grotinho sectors, was the most vulnerable and concentrated nearly 30% of the households with the worst indicators of access to sewage, electricity, and waste collection compared to the other sectors.

The West Antonico sector concentrates the largest number of households and is cut by the stream that gives the sector its name. To the East of the stream there are the two BHUs located within the main cluster, 500 meters apart from each other in the North-South direction. The Figure 1 shows the location of the BHUs and the main territorial frameworks of the main cluster.

The survey commissioned by the SEHAB in 2004 was part of a strategy for the management of the areas occupied by the population in situations of social vulnerability. These areas were included in urban consolidation and public service strategies after the institution of the Special Social Interest Zones by the São Paulo Strategic Master Plan in 2002. Therefore, since the 2004 survey, several improvements have been made in the complex; however, there is

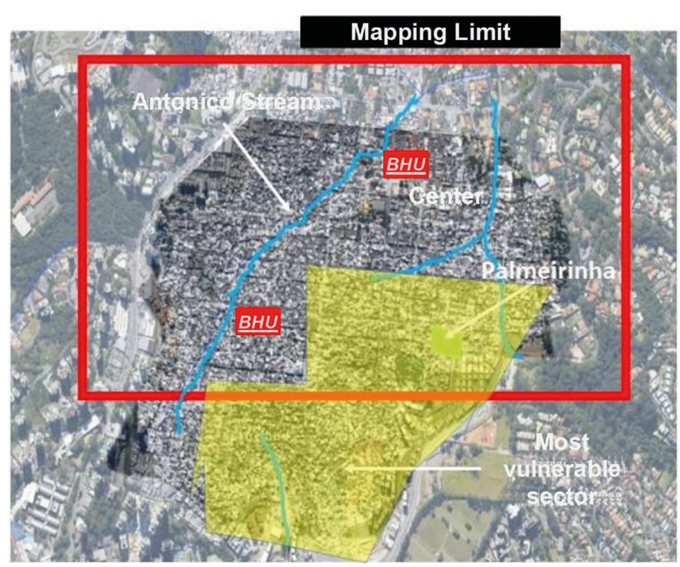

Figure 1 – Map of the main cluster of Paraisópolis. It includes the indications corresponding to the two BHUs located within the cluster, the Antonico stream, the central sector, the vulnerable sectors, and the Palmeirinha field.

still a major lack of infrastructure works and services, as shown in this article.

Maziviero and Silva (2018) provide a history of interventions initiated and carried out in the Paraisópolis complex, during the municipal administrations of Marta Suplicy (2001-2004), José Serra (2005-2008), Gilberto Kassab (2009-2012), and Fernando Haddad (2013-2016). According to data presented by the authors, in the first three administrations analyzed, nearly 90% of the water and sewage networks were implemented, in addition to paving works. Despite that, the drainage and stream canalization works were carried out in a much smaller proportion than necessary. The authors' survey maps 19 works finished between José Serra and Fernando Haddad administrations, as well as two unfinished works. In their vast majority, these works met the two most vulnerable sectors of the complex. In these sectors, the urbanization of Palmeirinha (2005-2008) was carried out, in addition to two schools and a Unified Educational Center (*Centro Educacional Unificado*, CEU) (2005-2008), eight housing undertakings (2009-2012), a BHU (2009-2012), a State Technical School (*Escola Técnica Estadual*, ETEC) (2009-2012), and two social devices (2013-2016). Regarding the canalization and drainage works of the streams that cut through the area, only the Swamp was delivered during Haddad's administration.

Rezende and Alvim (2016) provide an overview of the 19 projects developed and not implemented for the complex since 2001. Many of these include linear parks, urbanization works, and innovative housing solutions which would undoubtedly contribute to solving many of the complex's environmental problems if they had been implemented. This is the case, for example, of the works planned for the Antonico stream in 2012, which were not executed, and which could have a major socio-environmental impact on the Paraisópolis complex, since it is located in an area with the highest number of houses. Execution of this work is in the guidelines indicated in the Regional Plan Folder of the Campo Limpo District Council (Prefeitura de São Paulo, 2016a, 2016b).

Participatory master plans were defined by the City Statute (Federal Law 10, 257 of 2001) and, in the city of São Paulo, it was the Master Plan approved in 2002 that instituted a local planning system based on the creation of District Councils (formerly regional administrations) and mandatory regional plans. Although operative, these local instances of city planning fail to achieve the desired representativeness. The regional plans still represent the weakest link of the general city planning system. Nevertheless, regional plans strengthen local governance, as they more directly deal with the city's specific problems. In addition, it is acknowledged that the mobilizing potential of mapping socio-environmental determinants is still little explored by interdisciplinary urban studies, which could strengthen the institutional mechanisms of urban planning and social control at the local level.

Understanding participatory planning and its applications

In the current COVID-19 pandemic context, which more strongly affected the world throughout most of 2020, huge social inequalities, especially in developing countries and their peripheral metropolitan areas, have highlighted the importance and urgency of tools that expand social inclusion in the decision-making process for more sustainable and efficient urban planning. PGIS are tools that combine technical expertise in GIS with community knowledge produced along with citizens, and can be used both by experts and community members in their planning and decision-making processes (McCall, 2004; Fagerholm et al., 2021).

Based on the need to bring science and society closer together, creating a bridge between planners and citizens, PGIS emerged in the 1990s, integrating people's perceptions and knowledge with spatial techniques (Ferreira et al., 2017). It is based on a method called *SoftGIS*, which is a multidisciplinary approach incremented in Finland by researchers in the PGIS field, whose main purpose is to support planning and decision-making, including a better understanding of local knowledge and how citizens perceive their environment, from their involvement in this participatory mapping process and its integration with urban planning activities and phases. The term *SoftGIS* refers to the subjective and also qualitative nature of the data collected together with the citizens, as opposed to the *HardGIS* designation, which consists of, for example, the collection and use of data from official agencies or traditional maps, commonly used in GIS (Kahila-Tani et al., 2019). The main objective is to integrate this co-produced knowledge and improve local living conditions (Kahila-Tani et al., 2016).

PGIS can even provide social innovation and change, for example, by favoring social sustainability and justice practices along with vulnerable communities. By means of its participatory process, PGIS promotes better collective decisions, through social learning and the consequent empowerment of those who participate in its development, by the collaborative construction of knowledge in the various stages of this process (Kahila-Tani et al., 2019). Thus, with the incorporation of narratives, perceptions, and values of the social players participating in georeferencing, a technological component with high social innovation potential is obtained (Cidell, 2008).

The PGIS method can be applied and developed in several ways, according to the target audience to be worked on, such as traditional mapping with the use of GPS and topographic maps, talking maps — an instrument applied in the research reported herein — scale maps, three-dimensional maps and models; interpretation of satellite images and aerial photos, and tools that use the Internet, such as the *OpenStreetMap* (OSM) free platform. As already mentioned, community data can be treated both quantitatively and qualitatively given the wide variety of instruments mentioned that can be used. Since every point marked on a map has a history, with the support of geoprocessing techniques and spatial analysis, more accurate diagnoses are performed, as well as spatial analysis, such as calculating distances and formulating strategies for local improvements (Rantanen and Kahila, 2009). In addition, *SoftGIS* data can be confronted with *HardGIS* data for a comparison between citizens' perception and the current structure of the place under study, enriching the analyses produced (Kahila-Tani et al., 2016). Thus, participatory mapping and the construction of PGIS with the data collected are a fundamental environmental and urban planning tool, aimed at different approaches, such as tourism and ecotourism, risk and disaster management, environmental/public health, mobility, evaluation of ecosystem services, green and blue urban areas, sanitation, studies on marginalized social groups, among others.

In addition to that, due to its participatory, reflective, and dialogic nature, and because it contributes to the process of democratizing science, PGIS shares the principles of both action research (Toledo and Giatti, 2015) and Freire's Research Itinerary, the Circles of Culture (Freire, 2019), methodological approaches guiding the research herein analyzed. In health, the main contributions are territory appropriation by CHAs and other health professionals, and the establishment of bonds between the professionals and the population, through territory mapping, in addition to maximizing the potential of the analyses produced and improvements in the performance and communication between the stakeholders (Goldstein et al., 2013). Currently, some participatory mapping initiatives support communities vulnerable to the COVID-19 pandemic, such as the participatory mapping promoted by UNHabitat, which maps out good practices for informal settlements in several countries to cope with the pandemic (UNHabitat, 2020).

Map production in the territory of Paraisópolis, in the context of action research

As part of an action research process (Toledo and Giatti, 2015), between February and May 2019, four meetings were held in the form of Culture Circles (Freire, 2019) at Paraisópolis II BHU, with the participation of 29 CHAs from the six local health teams. These meetings were mediated by the coordinating nurse of one of these teams, who is also one of the authors of this article, and who has been working in this territory since 2012. Therefore, the coordinating nurse has a pre-established relationship of trust and bond with the CHAs participating in this action research, as expected from methodological approaches of this nature, thus enabling the path of Freire's Research Itinerary in four meetings, following the stages of thematic investigation, problematization or coding and decoding, and critical unveiling (Freire, 2019; Santos and Toledo, 2020).

The objectives of the first meeting, held in February 2019, were to present the research, answer questions, and acknowledge the expectations of the participating CHAs. In the following meeting, in March 2019, the generating themes were surveyed, based on the identification and mapping of socio-environmental determinants of health, according to the perception of the CHAs participating in the research (thematic investigation stage). Health education processes around the issues surveyed and potential relationships between the determinants and health were also concurrently developed in this meeting and the third meeting, held in April 2019, integrating technical knowledge and local traditional knowledge (coding and decoding stage). In the last meeting, in May 2019, it was sought to recognize ways to qualify the CHAs' health education and promotion practices, based on this mapping and collaborative learning process (critical unveiling stage) (Santos and Toledo, 2020).

Considering that the focus of this article is the analysis of a participatory mapping of socio-environmental determinants, further details of the action research process and Paulo Freire's Research Itinerary (the Culture Circles) stages, as well as of the instruments and socio-educational strategies used in this research, can be found in Santos and Toledo (2020).

The participatory mapping of the socio-environmental determinants of health, the focus of this article, was then initiated in the second meeting, which took place on March 12th, 2019, lasting four hours, for which the Talking Map construction technique was used. It is a diagnostic and/or planning instrument, which must be collectively prepared with the purpose of graphically representing (using drawing and/or collages) a certain situation or reality. When completed, it must be presented (the maps are given a "voice") to promote a debate. By favoring reflection, dialog, and search of consensus among the participants, a space for social and educational processes is also created (Toledo and Giatti, 2015; Toledo et al., 2020).

On previously printed maps of the six FHS coverage areas of Paraisópolis II BHU, the CHAs, divided into six groups, were then encouraged to represent, through drawings, local socio-environmental determinants that, according to their perception, could positively or negatively influence the health of Paraisópolis residents and, at the end of the drawings, a representative of each group presented their "map". Among the negative aspects represented and/or mentioned, it is possible to name the following: inadequate disposal of waste on the streets and streams; open sewage; pet abandonment; vector animals (rats, cockroaches, etc.); humid, poorly ventilated wooden houses ("shacks") that are very close together,; drug use and trafficking; accumulators (of objects, animals, garbage); sexual abuse; and people's lack of care and respect towards the physical space and the community (people are not aware of collective well-being, cars on the sidewalks, and loud music). Among the positive aspects, the following stand out: the varied commercial establishments (bakery, markets, pizzerias, butcher shop, stores, and bars); the BHU, the Specialist Outpatient Clinics (*Ambulatório Médico de Especial-*

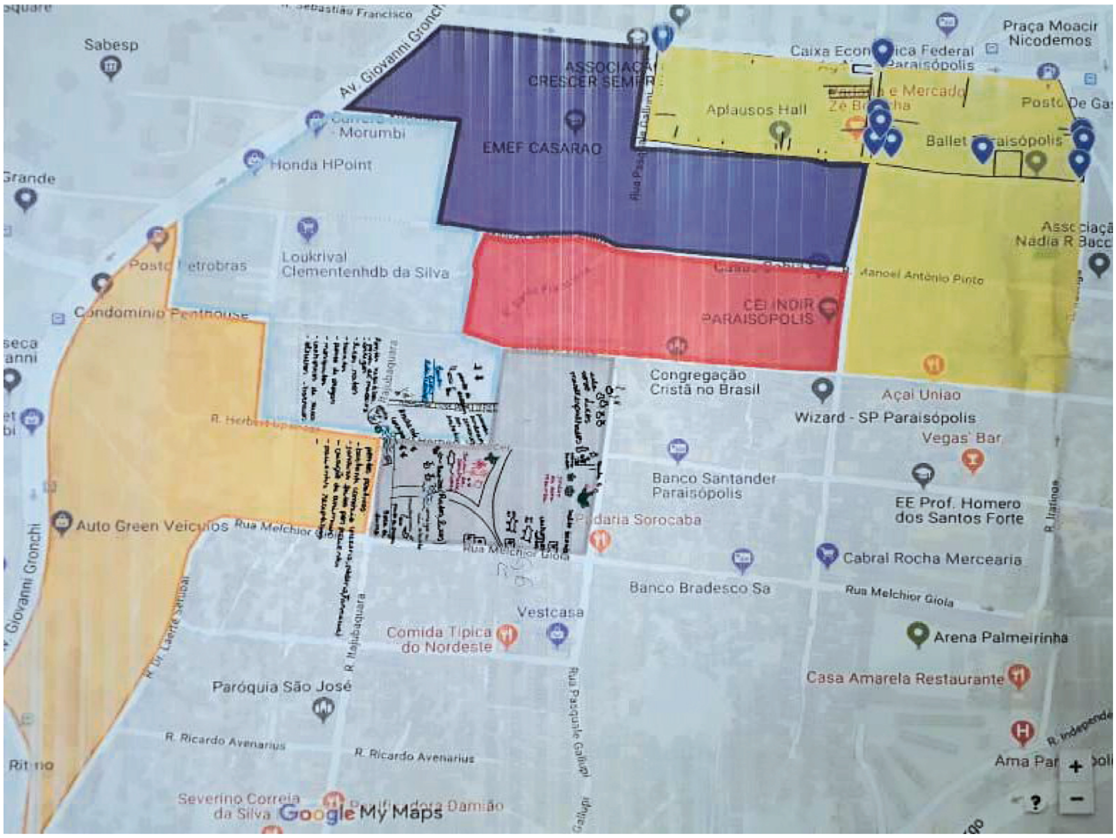

Figure 2 – One of the talking-maps produced by the CHAs about socio-environmental determinants of health in the FHS territory of the Paraisópolis II BHU, 2019.

idades, AME), dentists, CHAs, Outpatient Medical Care (*Assistência Médica Ambulatorial*, AMA), and the Psychosocial Care Center (*Centro de Atenção Psicossocial*, CAPS); the social projects and non-governmental organizations (NGOs) such as Bom Prato, Casa da Mulher, etc.; the spaces for leisure and sports, such as courts, ballet school; trees on the streets and yards in the houses; the schools and "*mães crecheiras*" ("childcare mothers"), who are willing to take care of children at their homes; good acceptance by patients; and the churches (Santos and Toledo, 2020).

The following are images of one of the maps worked on by one of the CHA groups, in which the micro-areas attached to Paraisópolis II can be seen, distinguished by colors (Figure 2); and of approximate clippings of some aspects represented by the CHAs in each micro-area (Figure 3).

The socio-environmental determinants of health, represented and mentioned in the CHAs' presentations, were categorized, by similarity and as suggested by the CHAs, into generating themes (thematic investigation stage of Freire's Research Itinerary — Culture Circles) during the process of building these talking-maps. They were as follows: poor sanitation, animals, housing and other facilities, social issues/violence, and behavioral factors (categories of generating themes — negative socio-environmental determinants); commerce; health services, NGOs/social projects, sports and leisure, green areas, education, behavioral factors, animals, and churches (categories of generating themes — positive socio-environmental determinants). These generating themes were then addressed in more detail in the following meetings, trying to codify them, that is, to contextualize them in the reality experienced by the CHAs and decode them by the notion of socio-environmental determinants of health, trying to understand how they operated to generate inequalities and situations of vulnerability in Paraisópolis community, through a shared process of education in health (Santos and Toledo, 2020).

The socio-environmental determinants recognized by the CHAs in this research are in agreement with those that have been reported in the literature, both from a conceptual point of view (CSDH, 2008; Sobral and Freitas, 2010; Akerman et al., 2011) and in association studies (Cassol, 2012; Acosta and Bassanesi, 2014; Antunes et al., 2014; Honorato et al., 2014; Lobato and Jardim, 2014; Chayb and Kozusny-Andreani, 2015; Ogata et al., 2016; Silva et al., 2017; Abe and Miraglia, 2018; Corá et al., 2020).

Figure 3 – Clippings from the Talking-maps produced by the CHAs about socio-environmental determinants of health in the FHS territory of Paraisópolis II BHU, 2019.
Source: Santos and Toledo (2020).

Also, according to Porto et al. (2015), the various socio-environmental problems found in vulnerable communities, such as the lack of basic sanitation, respiratory problems, and drug use and abuse, among others, make up a serious and complex scenario, with the FHS and the CHA performance being a very important reference of care for the population. This is because this complexity is evident in tangible social determinants, clearly recognized by economic, environmental, social, and epidemiological data. But it is also present in intangible determinants, in the way local residents and professionals from these territories perceive and assess their living conditions.

To expand this perception and analyze its potential for territory management and planning, during the process, the talking maps were georeferenced. This means the negative and positive socio-environmental determinants recognized and mapped by the CHAs were referenced in known geographical coordinates, with the use of the *QuantumGIS* free software, configuring a database or PGIS.

Each point mapped out by the CHAs was manually digitalized with the software, generating a final map of points overlaid on the *OpenStreetMap* street layer. This street layer is intended for local orientation, and was also used as the basis to generate the talking maps. For analysis purposes, other information plans can be added, such as other health data considered relevant. However, the research reported herein focused on the participatory mapping of the socio-environmental determinants of health.

Therefore, the following maps (Figures 4 and 5) represent the perception and knowledge of the CHAs working in Paraisópolis II BHU, produced in a team effort during this action research. The first version of these maps was presented to the CHAs at one of the Culture Circles meetings (on May 14th, 2019) so that they could give their opinions on the colors, symbols, and shapes that were used. For ethical reasons, it was decided not to geo-reference socio-environmental determinants associated with violence issues (such as drug consumption and trafficking points).

Also, in this meeting, and from the analysis of the georeferenced maps through a free conversation circle, the CHAs were invited to reflect on whether these maps could assist in the work of the health teams. It was asked, for example, if the community had access to this material, whether this could contribute to qualifying the process of education and health promotion and how, as well as other actions of the health teams. This seems to be the case, as ob-

Figure 4 – Map of socio-environmental determinants with a negative influence on health in the territory covered by Paraisópolis BHU, SP, according to the perception of CHAs, 2019.

Figure 5 – Map of socio-environmental determinants with a positive influence on health in the territory covered by Paraisópolis BHU, SP, according to the perception of CHAs, 2019.

served from these statements: "*it's a good idea because, normally, the patients can only see their own problems, but having a broader view can help them to reflect*"; "*it's important to show problems on a map because sometimes the patients think they are the only ones facing a particular problem. But seeing that other people go through the same situation, maybe the patients will understand that it's not something easy to solve as they believe*". Some CHAs also suggested using the maps in the work teams to facilitate approaching the theme of socio-environmental determinants (Santos and Toledo, 2020).

The trigger for greater territory appropriation by Primary Care health professionals, especially CHAs, as a result of more opportunities for dialog and participation, and their contributions to understanding and coping with local demands, is also evidenced in the literature (Camponogara et al., 2013; Goldstein et al., 2013; Bezerra and Feitosa, 2018; Salinas Rebolledo et al., 2018; Faria and Paiva, 2020; Silva et al., 2020).

Finally, the participatory production of these maps allowed the CHAs involved not only to recognize the combination of some socio-environmental determinants present in the location, but also to better understand that such a combination can increase situations of vulnerability. This is because living in areas at risk that have not been effectively urbanized, with absent or poor sanitation, precarious houses and consequently unhealthy conditions, poverty, violence, social exclusion, among others, are factors that overlap in the territory and which, according to Smith and Ezatti (2005), can occur in the homes, in the community, or they can be associated with public policies and global phenomena.

Conclusions

The analyses carried out from the results of this research showed that, through the PGIS and participatory mapping, citizens can more effectively recognize and communicate their needs and, thus, intervention strategies in the territory and local maintenance actions can more representatively address the residents' priorities for the improvement of their towns. Participatory mapping shows itself as a powerful instrument to stimulate participatory urban management and planning, integrating different social players, especially in towns with traditionally marginalized social groups.

In the case of CHAs, who play a central role in the research under analysis, they are essential to drive, mobilize, and support the complex aspects involved, both in Primary Health Care and urban management and planning because they live and work in the same place. They are health-promoting professionals who are sensitive to the needs of the territory, interacting in real-time with the difficulties, and even network with other health professionals, that is, providing a collaborative learning process to the entire team. The research evidenced that living in a community favors a better understanding of the most urgent needs and situations that can harm the population more seriously. When mapping socio-environmental determinants of health, among the most relevant aspects, were absent or poor basic sanitation, unhealthiness in housing, commercial sites, and green areas, among others, which are also determinants directly related to the urban management and planning needs.

The results of this research and its dissemination also meet the objectives of the World and National Commissions on Social Determinants of Health by contributing to generating and expanding information and knowledge networks, producing scientific evidence on the subject matter, increasing mobilization around the theme, and stimulating the qualification of environmental, social, health, and urban planning public policies that promote equality.

Although participatory mapping develops territorial approaches that allow for relevant intersectoral dialogs at the local level, the several knowledge and cultural competencies of these players, such as the CHAs, have to be more fully recognized. Also, clearer strategies must be formulated for including these professionals in the local city planning and management system to achieve sustainable development and reduced local inequality in vulnerable areas.

It is therefore considered that this mapping and its analysis, originated and developed as a demand perceived during this action research process, has the potential to positively impact aspects related to health, environmental, social, educational, cultural, and urban planning, in the territory covered by the FHS, of Paraisópolis II BHU in Paraisópolis community, city of São Paulo (state of São Paulo).

The innovative character and replicability potential of socio-environmental determinant mapping by the PGIS in other locations is also highlighted. Talking map techniques can be integrated, configuring a Geographic Information System. From its collaborative production and dissemination in different communication channels, such as the community and technical-scientific ones, this product is expected to contribute to qualifying health promotion, education, and environmental education actions, as well as expanding social mobilization and improving planning and governance processes, advancing towards sustainability.

In terms of future perspectives, it is also considered that the products generated in processes of this nature have enormous potential for solid developments in local governance, such as in neighborhood planning, which can later be integrated into District Council local planning for the area where they are produced, becoming a part of the city's general planning system, contributing to solid improvements in different towns in the future.

Contribution of authors:

Toledo, R.F.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing — original draft, Supervision, Writing — review & editing; Koury, A.P.: Conceptualization, Validation, Formal analysis, Writing — original draft, Writing — review & editing; Carvalho, C.M.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing — original draft, Writing — review & editing; Santos, F.N.P.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing — original draft, Writing — review & editing.

References

Abe, K.; Miraglia, S., 2018. Avaliação de impacto à saúde do programa de controle de poluição do ar por veículos automotores no município de São Paulo, Brasil. Revista Brasileira de Ciências Ambientais, (47), 61-73. https://doi.org/10.5327/Z2176-947820180310.

Abranches, M., 2020. Planejamento urbano participativo: o mapeamento dos problemas da cidade pelos seus diversos atores. Cajuína, Cotia, 124 pp.

Acosta, L.M.W.; Bassanesi, S.L., 2014. O paradoxo de Porto Alegre: determinantes sociais e incidência de tuberculose. Revista Brasileira de Epidemiologia, v. 17, (Supl. 2), 88-101. https://doi.org/10.1590/1809-4503201400060008.

Akerman, M.; Maymone, C.C.; Gonçalves, C.B.; Chiaro, A.; Buss, P.M., 2011. As novas agendas de saúde a partir de seus determinantes sociais. In: Galvão, L.A.C.; Finkelman, J.; Henao, S. (Eds.), Determinantes ambientais e sociais da saúde. Opas; Editora Fiocruz, Rio de Janeiro, pp. 1-15.

Almeida, L.S.; Cota, A.L.S.; Rodrigues, D.F., 2020. Saneamento, Arboviroses e Determinantes Ambientais: impactos na saúde urbana. Ciência & Saúde Coletiva, v. 25, (10), 3857-3868. https://doi.org/10.1590/1413-812320202510.30712018.

Antunes, F.P.; Costa, M.C.N.; Paim, J.S.; Cruz, A.; Silva, L.M.V.; Barreto, M., 2014. Determinantes sociais dos diferenciais intraurbanos das internações por doenças respiratórias em Salvador (BA), Brasil. Revista Brasileira de Epidemiologia, v. 17, (Supl. 2), 29-38. https://dx.doi.org/10.1590/1809-4503201400060003.

Arcoverde, M.A.M.; Berra, T.Z.; Alves, L.S.; Santos, D.T.; Belchior, A.S.; Ramos, A.C.V.; Arroyo, L.H.; Assis, I.S.; Alves, J.D.; Queiroz, A.A.R.; Yamamura, M.; Palha, P.F.; Chiaravalloti Neto, F.; Silva-Sobrinho, R.A.; Nihei, O.K.; Arcêncio, R.A., 2018. How do social-economic differences in urban areas affect tuberculosis mortality in a city in the tri-border region of Brazil, Paraguay and Argentina. BMC Public Health, v. 18, (1), 1-14. https://doi.org/10.1186/s12889-018-5623-2.

Arouca, M.G.; Neves, I.B.C.; Brito, R.L., 2019. +Lugar: Um aplicativo gamificado destinado à saúde coletiva. Anais do Seminário Tecnologias Aplicadas a Educação e Saúde (Accessed Oct. 12, 2019) at: https://revistas.uneb.br/index.php/staes/article/view/8224.

Bezerra, Y.R.N.; Feitosa, M.Z.S., 2018. A afetividade do agente comunitário de saúde no território: um estudo com os mapas afetivos. Ciência & Saúde Coletiva, v. 23, (3), 813-822. http://dx.doi.org/10.1590/1413-81232018233.00292016.

Borde, E.; Akerman, M.; Pellegrini Filho, A., 2014. Mapeamento das capacidades de pesquisa em saúde e seus determinantes sociais no Brasil. Cadernos de Saúde Pública, v. 30, (10), 2081-2091. https://doi.org/10.1590/0102-311X00162513.

Brasil. 1990. Lei Federal Brasileira nº 8.080, de 19 de setembro de 1990. Lei Orgânica da Saúde. (Accessed Sep. 21, 2019) at: http://www.planalto.gov.br/ccivil_03/leis/l8080.htm.

Brasil. 2001. Lei Federal Brasileira nº 10.257, de 10 de julho de 2001. Estatuto da Cidade. (Accessed Dec. 2, 2019) at: http://www.planalto.gov.br/ccivil_03/leis/leis_2001/l10257.htm

Brasil. 2018. Lei Federal Brasileira nº 13.595, de 5/1/2018. Altera a Lei nº 11.350, de 5/10/2006, para dispor sobre a reformulação das atribuições, a jornada e as condições de trabalho, o grau de formação profissional, os cursos de formação técnica e continuada e a indenização de transporte dos profissionais Agentes Comunitários de Saúde e Agentes de Combate às Endemias (Accessed Sep. 21, 2019) at: http://www.planalto.gov.br/ccivil_03/_Ato2015-2018/2018/Lei/L13595.htm#art1.

Camponogara, S.; Erthal, G.; Viero, M.C., 2013. A problemática ambiental na visão de agentes comunitários de Saúde. Ciência, Cuidado e Saúde, v. 12, (2), 233-240. https://doi.org/10.4025/cienccuidsaude.v12i2.18584.

Carmo, M.E.; Guizardi, F.L., 2018. O conceito de vulnerabilidade e seus sentidos para as políticas públicas de saúde e assistência social. Cadernos de Saúde Pública, v. 34, (3), e00101417. https://doi.org/10.1590/0102-311x00101417.

Carvalho, C.M.; Giatti L.L., 2018. Participatory GIS for urban sustainability and resilience: a perspective of social learning and ecology of knowledge. In: Azeiteiro, U.; Akerman, M.; Leal Filho, W.; Setti, A.; Brandli, L. (Eds.). Lifelong learning and education in healthy and sustainable cities. World Sustainability Series. Springer, Cham, pp. 21-34. https://doi.org/10.1007/978-3-319-69474-0_2.

Cassol, P.B., 2012. A gerontologia interface o meio ambiente como estratégia no cuidado e promoção da saúde. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental, v. 6, (6), 1043-1048. http://dx.doi.org/10.5902/223611704959.

Chayb, E.; Kozusny-Andreani, D., 2015. Estudo comparativo da contaminação por micro-organismos patogênicos em resíduos domiciliares e de saúde em Uberlândia (MG). Revista Brasileira de Ciências Ambientais, (37), 72-87. https://doi.org/10.5327/Z2176-9478201512414.

Cidell, J., 2008. Challenging the contours: critical cartography, local knowledge, and the public. Environment and Planning A: Economy and Space, v. 40, (5), 1202-1218. https://doi.org/10.1068/a38447.

Cochrane, L.; Corbett, J., 2020. Participatory mapping. In: Servaes, J. (Ed.). Handbook of communication for development and social change. Springer, Singapore, pp. 705-713. https://doi.org/10.1007/978-981-15-2014-3_6.

Commission on Social Determinants of Health – CSDH, 2008. Closing the gap in a generation: health equity through action on the social determinants of health. Final Report of the Commission on Social Determinants of Health. World Health Organization, Geneva (Accessed Sep. 21, 2019) at: http://apps.who.int/iris/bitstream/10665/43943/1/9789241563703_eng.pdf.

Corá, B.; Leirião, L.; Miraglia, S., 2020. Impacto da poluição do ar na saúde pública em municípios de alta industrialização do estado de São Paulo. Revista Brasileira de Ciências Ambientais, v. 55, (4), 498-509. https://doi.org/10.5327/Z2176-947820200671.

Fagerholm, N.; Raymond, C.M.; Olafsson, A.S.; Brown, G.; Rinne, T.; Hasanzadeh, K.; Broberg, A.; Kyttä, M., 2021. A methodological framework for analysis of participatory mapping data in research, planning, and management. International Journal of Geographical Information Science, v. 35, (9), 1848-1875. https://doi.org/10.1080/13658816.2020.1869747.

Faria, C.C.M.V.; Paiva, C.H.A., 2020. O trabalho do agente comunitário de saúde e as diferenças sociais no território. Trabalho, Educação e Saúde, v. 18, (supl. 1), e0025183. https://doi.org/10.1590/1981-7746-sol00251

Ferreira, D.; Albino, L.; Freitas, M.J.C.C., 2017. Mapeamento participativo para a gestão de risco de desastres: região dos Baús, Ilhota-SC. Revista Brasileira de Cartografia, v. 69, (4), 713-730.

Fornace, K.M.; Surendra, H.; Abidin, T.R.; Reyes, R.; Macalinao, M.L.M.; Stresman, G.; Luchavez, J.; Ahmad, R.A.; Supargiyono, S.; Espino, F.; Drakeley, C.J.; Cook, J., 2018. Use of mobile technology-based participatory mapping approaches to geolocate health facility attendees for disease surveillance in low resource settings. International Journal of Health Geographics, v. 17. https://doi.org/10.1186/s12942-018-0141-0.

Freire, P., 2019. Pedagogia do oprimido. Paz e Terra, Rio de Janeiro, 256 pp.

Freitas, Â.; Rodrigues, T.C.; Santana, P., 2020. Assessing urban health inequities through a multidimensional and participatory framework: evidence from the EURO-HEALTHY Project. Journal of Urban Health, v. 97, 857-875. https://doi.org/10.1007/s11524-020-00471-5.

Goldstein, R.A.; Barcellos, C.; Magalhães, M. de A.F.M.; Gracie, R.; Viacava, F., 2013. A experiência de mapeamento participativo para a construção de uma alternativa cartográfica para a ESF. Ciência & Saúde Coletiva, v. 18, (1), 45-56. https://doi.org/10.1590/S1413-81232013000100006.

Honorato, T.; Lapa, P.P.A.; Sales, C.M.M.; Santos, B.R.; Tristão-Sá, R.; Bertolde, A.I.; Maciel, E.L.N., 2014. Análise espacial do risco de dengue no Espírito Santo, Brasil, 2010: uso de modelagem completamente Bayesiana. Revista Brasileira de Epidemiologia, v. 17, (supl. 2), 150-159. https://doi.org/10.1590/1809-4503201400060013.

Kahila-Tani, M.; Broberg, A.; Kyttä, M.; Tyger, T., 2016. Let the citizens map — public participation GIS as a planning support system in the Helsinki master plan process. Planning Practice & Research, v. 31, (2), 195-214. https://doi.org/10.1080/02697459.2015.1104203.

Kahila-Tani, M.; Kytta, M.; Geertman, S., 2019. Does mapping improve public participation? Exploring the pros and cons of using public participation GIS in urban planning practices, Landscape and Urban Planning, v. 186, 45-55. https://doi.org/10.1016/j.landurbplan.2019.02.019.

Lobato, G.; Jardim, M., 2014. Caracterização de indicadores de desenvolvimento sustentável na relação saúde e ambiente por meio das doenças relacionadas ao saneamento ambiental inadequado (DRSAI). Revista Brasileira de Ciências Ambientais, (33), 23-31 (Accessed Dec 13, 2019) at: http://www.rbciamb.com.br/index.php/Publicacoes_RBCIAMB/article/view/230

Magalhães, T.C. 2021. Construção participativa do mapeamento do território da ESF Novo Tempo em Santa Helena de Minas: projeto de intervenção. Trabalho de Conclusão de Curso. Escola de Saúde Pública do Estado de Minas Gerais (Accessed Dec 13, 2019) at: http://repositorio.esp.mg.gov.br:8080/xmlui/handle/123456789/375

Maman, S.; Lane, T.; Ntogwisangu, J.; Modiba, P.; Vanrooyen, H.; Timbe, A.; Visrutaratna, S.; Fritz, K., 2009. Using participatory mapping to inform a community-randomized trial of HIV counseling and testing. Field Methods, v. 21, (4), 368-387. http://doi.org/10.1177/1525822X09341718.

Mapping For Rights, 2020. Portal de dados abertos. Mapping For Rights, The Rainforest Foundation, UK (Accessed January 19, 2020) at: https://www.mappingforrights.org/participatory-mapping.

Maziviero, M.C.; Silva, A.S., 2018. O caso do COMPLEXO Paraisópolis em gestões: diferenças conceituais em programas de intervenção em favelas em São Paulo. Urbe Revista Brasileira de Gestão Urbana, v. 10, (3), 500-520. https://doi.org/10.1590/2175-3369.010.003.ao03.

McCall, M.K., 2004. Can participatory-GIS strengthen local-level spatial planning? Suggestions for better practice. GISDECO, Skudai, Johor, Malaysia.

Moraes, I.C.; Marengo, S.N.; Schacht, G.L.; Passos, D.S., 2021. Mapeamento participativo aplicado à Estratégia de Saúde da Família: a experiência em Santo Amaro, BA. Revista Brasileira de Cartografia, v. 73, (2), 646-665. https://doi.org/10.14393/rbcv73n2-56943.

Ogata, I.; Oliveira, R.; Meira, C.; Nascimento, R.; Henriques, J., 2016. Avaliação de risco à saúde associada à qualidade da água para consumo humano em Campina Grande, paraíba. Revista Brasileira de Ciências Ambientais, (40), 1-15. https://doi.org/10.5327/Z2176-947820160026.

Philippi Junior, A.; Andreoli, C.V.; Bruna, G.C.; Fernandes, V., 2014. Histórico e evolução do sistema de gestão ambiental no Brasil. In: Philippi Junior, A.; Roméro, M.A.; Bruna, G.C. (Eds.). Curso de gestão ambiental. 2ª ed. Manole, Barueri, pp. 19-50. (Coleção Ambiental, v. 13).

Porto, M.F.S.; Cunha, M.B.; Pivetta, F.; Zancan, L.; Freitas, J.D., 2015. Saúde e ambiente na favela: reflexões para uma promoção emancipatória da saúde. Serviço Social & Sociedade, (123), 523-543. https://doi.org/10.1590/0101-6628.035.

Prefeitura de São Paulo, 2016a. Cadernos de propostas dos planos regionais das subprefeituras: perímetro de ação – Campo Limpo). Prefeitura de São Paulo, São Paulo (Accessed Dec 13, 2019) at: https://gestaourbana.prefeitura.sp.gov.br/wp-content/uploads/2018/02/PA-CL.pdf.

Prefeitura de São Paulo, 2016b. Cadernos de propostas dos planos regionais das subprefeituras: quadro analítico – Campo Limpo. Prefeitura de São Paulo, São Paulo (Accessed Dec 2, 2019) at: https://gestaourbana.prefeitura.sp.gov.br/wp-content/uploads/2018/02/QA-CL.pdf.

Programa das Nações Unidas para os Assentamentos – UNHabitat, 2020. Mapa de respostas Covid para favelas e assentamentos informais. Organização das Nações Unidas (Accessed January 19, 2020) at: https://unhab-cov19.ushahidi.io/views/map.

Silva, L.; Abe, K.; Miraglia, S., 2017. Avaliação de impacto à saúde da poluição do ar no município de Diadema, Brasil. Revista Brasileira de Ciências Ambientais, (46), 117-129. https://doi.org/10.5327/Z2176-947820170258.

Rantanen, H.; Kahila, M., 2009. The SoftGIS approach to local knowledge. Journal of Environmental Management, v. 90, (6), 1981-1990. https://doi.org/10.1016/j.jenvman.2007.08.025.

Rezende, W.S.; Alvim, A.T.B., 2016. Projeto urbano e espaço público em favelas. Revista Nacional de Gerenciamento de Cidades, v. 4, (28), 76-96. https://doi.org/10.17271/23188472.

Salinas Rebolledo, E.A.; Chiavaralloti Neto, F.; Giatti, L.L., 2018. Experiencias, beneficios y desafíos del uso de geoprocesamiento para el desarrollo de la atención primaria de salud. Revista Panamericana de Salud Publica, v. 42, e153. https://doi.org/10.26633/RPSP.2018.153.

Santos, F.N.P.; Toledo, R.F., 2020. Círculos de cultura sobre determinantes socioambientais: pesquisa-ação com agentes comunitárias de saúde de Paraisópolis, SP. Revista Gaúcha de Enfermagem, v. 41, e20190353. https://doi.org/10.1590/1983-1447.2020.20190353.

Silva, T.L.; Soares, A.N.; Lacerda, G.A.; Mesquita, J.F.O.; Silveira, D.C., 2020. Política Nacional de Atenção Básica 2017: implicações no trabalho do Agente Comunitário de Saúde. Saúde e Debate, v. 44, (124), 58-69. http://dx.doi.org/10.1590/0103-1104202012404.

Silveira, M.; Fenner, A.L.D., 2017. Avaliação de Impactos à Saúde (AIS): análises e desafios para a Vigilância em Saúde do Brasil. Ciência & Saúde Coletiva, v. 22, (10), 3205-3214. https://doi.org/10.1590/1413-812320172210.18272017.

Smith, K.R.; Ezatti, M., 2005. How environmental health risks change with development: the epidemiologic environmental risk transitions revisited. Annual Review of Environment and Resources, v. 30, 291-333. https://doi.org/10.1146/annurev.energy.30.050504.144424.

Sobral, A.; Freitas, C.M., 2010. Modelo de organização de indicadores para a operacionalização dos determinantes socioambientais da saúde. Saúde e Sociedade, v. 19, (1), 35-47. http://dx.doi.org/10.1590/S0104-12902010000100004.

Toledo, R.F.; Giatti, L.L., 2015. Challenges to participation in action research. Health Promotion International, v. 30, (1), 162-173. https://doi.org/10.1093/heapro/dau079.

Toledo, R.F.; Matuk, T.; Coradello, M.A.; Moraes, M., 2020. Aprendizagem social e diálogo: experiência de criação de pólos de educação ambiental em dois parques municipais da cidade de São Paulo. In: Monteiro, R.A.A.; Sorrentino, M.; Jacobi, P.R. (Eds.). Diálogo e transição educadora para sociedades sustentáveis. IEE-USP, Editora na Raiz, São Paulo, pp. 197-210 (Accessed May 7, 2020) at: https://editoranaraiz.wordpress.com/2020/09/22/livro-dialogo-e-transicao-e-educadora-para-sociedades-sustentaveis/

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Methods to analyze spatio-temporal rainfall variability: application to the Pajeú river basin, Pernambuco

Método de análise da variabilidade espaço-temporal da precipitação: aplicação na bacia hidrográfica do rio Pajeú-Pernambuco

Janaina Oliveira Maria de Assis[1], *Athos Farias Menezes*[1], *Werônica Meira de Souza*[2], *Maria do Carmo Martins Sobral*[1]

ABSTRACT

This paper addresses a methodology for analyzing spatio-temporal rainfall variability as a tool to support action planning that could mitigate negative impacts and reduce conflicts over water use in the Pajeú river basin, located in the semi-arid region of the state of Pernambuco. We used daily rainfall data from 11 rainfall stations, between 1964 and 2016, provided by the Pernambuco Water and Climate Agency (*Agência Pernambucana de Águas e Clima* — APAC) and the National Water Agency (*Agência Nacional de Águas* — ANA). This analysis employed the RClimDex software to calculate rainfall-related climate extremes indices, aiming at monitoring and detecting climate changes and alterations in the regional rainfall pattern. The results indicated a change in the rainfall pattern in the Pajeú river basin, and all climate indices obtained converge toward the increase in water scarcity in the area, contributing to the recurrent droughts that impact the region.

Keywords: RClimDex; climate change; semi-arid.

RESUMO

Este artigo aborda uma metodologia de análise da variabilidade espaço-temporal da precipitação como ferramenta para subsidiar o planejamento de ações que venham a mitigar os impactos negativos e reduzir os conflitos pelo uso da água na bacia hidrográfica do rio Pajeú, localizada na porção semiárida do estado de Pernambuco. Foram utilizados dados diários de precipitação de 11 postos pluviométricos, no período de 1964 a 2016, fornecidos pela Agência Pernambucana de Águas e Clima (APAC) e pela Agência Nacional de Águas (ANA). Para esta análise, utilizou-se o *software* RClimDex para calcular os índices de extremos climáticos provenientes de precipitação pluviométrica, visando monitorar e detectar as mudanças do clima e a alteração do padrão pluviométrico da região. Os resultados indicaram modificação no padrão pluviométrico na bacia do Pajeú, e todos os índices climáticos calculados convergem para o aumento da escassez hídrica na região, contribuindo para as recorrentes secas que abalam a região.

Palavras-chave: RClimDex; mudanças climáticas; semiárido.

[1]Universidade Federal de Pernambuco – Recife (PE), Brazil.

[2]Universidade Federal do Agreste – Garanhuns (PE), Brazil.

Correspondence address: Maria do Carmo Martins Sobral – Centro de Tecnologia e Geociências – Avenida da Arquitetura, s/n. – Cidade Universitária – CEP: 50740-550 – Recife (PE), Brazil. E-mail: maria.msobral@ufpe.br

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Introduction

Climate change has increased water stress in several river basins in Brazil and in the world, leading to greater pressure for water resources management, especially in low rainfall areas, such as the Brazilian Northeast semi-arid region. According to studies by the Brazilian Panel on Climate Change (PBMC, 2014), this region is one of the most vulnerable to the impacts of climate change in Latin America (Marengo et al., 2018; Silva et al., 2020). Bork et al. (2017) state that most studies on climate change assessing certain Brazilian locations show an increasing trend in extreme events throughout this century compared to the climate of the last century. Such a finding allows predicting severe drought or heavy rainfall problems in the future.

For Grassi et al. (2013) and Zhang et al. (2014), extreme climate events are directly related to climate change, inducing hydrological and thermal anomalies, which affect the livelihood of the population and modify existing relationships.

In addition to climate factors, the semi-arid region of the Northeast negatively stands out for its high rates of socioeconomic vulnerability and low human development index due to the great poverty in the area, increasing the migration potential (Nobre et al., 2019; Galvão et al., 2020).

Moreover, agriculture is a very common economic practice in the region, especially dryland farming (Lemos and Santiago, 2020), which, given the low investments in agricultural techniques, completely relies on the availability of natural resources, thus suffering with potentially negative impacts on water resources and compromising the economy and quality of life of the local population (Huang et al., 2016).

Regarding future scenarios, projections by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) indicate an increase in the frequency of extreme events in semi-arid regions of the planet, causing longer droughts as a consequence of the reduced rainfall, as well as the rise in temperatures in the upcoming decades. As a result, evapotranspiration will increase, while water availability will decrease (Sobral et al., 2018; Cardoso et al., 2019; Santos et al., 2019). IPCC's Fifth Assessment Report also showed that extreme climate events are associated with increased frequency, severity, and duration of precipitation (Seley et al., 2014; Yilmaz et al., 2014).

According to the Report of the Brazilian Panel on Climate Change (PBMC, 2013), the Northeastern semi-arid region will likely have its rainfall reduced by up to 20% by 2040. This report also indicates that Brazil should become at least 3°C warmer by the end of the century, and rainfall might increase, on average, by 30% in the South and Southeast regions and decrease by up to 40% in the North and Northeast regions (Souza et al., 2018).

These PBMC percentages are climate prognoses estimated in mean values based on IPCC optimistic and pessimistic scenarios, which point to an increase of 1–3°C and 2–4°C, respectively (Montenegro et al., 2010; Cavalcante Junior et al., 2016).

This paper aims to present a method to analyze spatio-temporal rainfall variability in the Pajeú river basin as a tool to support action planning that could mitigate negative impacts and reduce conflicts over water use.

Method

Study area

The selected study area was the Pajeú river basin, located in the Sertão of Pernambuco State, a semi-arid region of the Brazilian Northeast. It is located between the coordinates 07°16'20" and 08°56'01" S and 36°59'00" and 38°57'45" W, specifically in the Pernambuco Sertão and São Francisco mesoregions.

The Pajeú river basin covers 27 municipalities, 16 of them completely within the basin area. It involves all Pajeú microregions and part of the Sertão of Moxotó, Salgueiro, and Itaparica. It has an area of 16,685.63 km^2, that is, 16.9% of the total area of Pernambuco, making it the largest river basin of the state in territorial extension (Figure 1).

From a climate perspective, the basin area is characterized by very irregular rainfall, with January to April as the main rainy season. Sertão rains originate from cold fronts, upper tropospheric cyclonic vortices (UTCV), and the intertropical convergence zone (ITCZ). The last one is the main rainfall production system in the Pernambuco semi-arid region (Pernambuco, 2006).

In the Pernambuco Sertão, rainfall starts in December (extreme west) and is associated with cold front instabilities and UTCV. As of February or March, depending on the year, ITCZ begins to act throughout the Sertão, which is already in its main rainy season.

Total annual precipitation usually fluctuates between 400 and 1,200 mm. The dry season can last from 7 to 10 months, and semi-aridity is very pronounced in the lower region, near the São Francisco River, where total annual values often range from 400 to 500 mm. Rainfall increases in the north, reaching averages between 700 and 800 mm.

We selected the Pajeú river basin as a case study for this statistical method of precipitation analysis due to its economic and social relevance in the semi-arid region of Pernambuco, besides it being the largest basin of the state in territorial extension. Thus, we emphasize the importance of implementing this methodology, using river basins as a planning unit to design short- and medium-term actions.

Data acquisition and analysis

This work assessed 52 years of daily rainfall data — 1964 to 2016. Data were collected from the Pernambuco Water and Climate Agency (*Agência Pernambucana de Águas e Clima* — APAC), through its online database (APAC, 2021), and the National Water Agency (*Agência Nacional de Águas* — ANA), from its hydrologic information system (HIDROWEB) (ANA, 2021).

Among the rainfall stations located in the Pajeú river basin, 11 were selected for their good data quality and homogeneity, with few issues, and for representing a satisfactory spatial distribution of the whole basin (Figure 2).

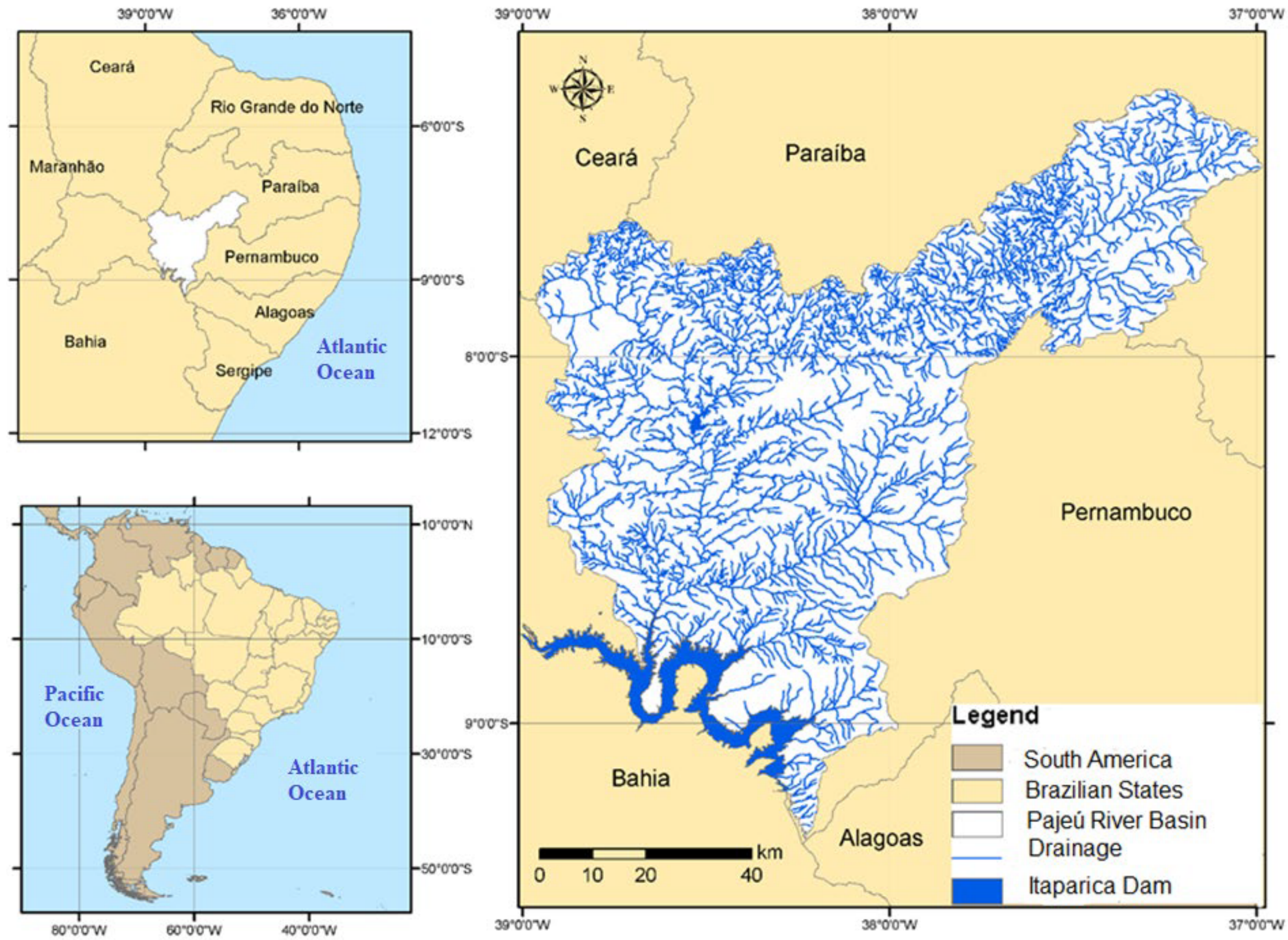

Figure 1 – Spatial location of the Pajeú river basin.

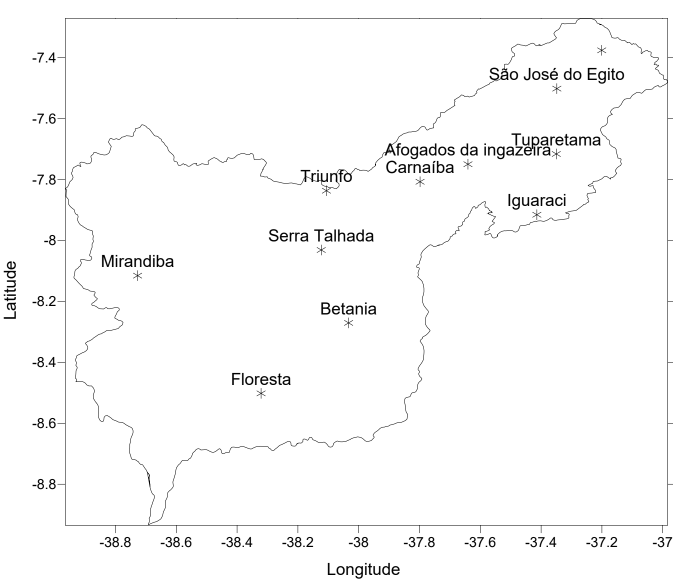

Figure 2 – Spatial distribution of rainfall stations in the Pajeú river basin.

Evaluation of climate extremes indices

We used the RClimDex software, version 3.2.1, to identify trends in climate extremes indices. Recommended by the World Meteorological Organization (WMO), the software calculates climate extremes indices to monitor and detect climate changes. It was developed by Byron Gleason, a researcher at the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA). This software is available for free on the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) website (http://cccma.seos.uvic.ca/ETCCDMI).

RClimDex 3.2.1 calculates all 27 basic indices (11 related to precipitation and 16 to temperature) recommended by the ETCCDMI and provides statistical information for each index, including: linear trend calculated by the least-squares method, statistical significance of the trend (p-value), coefficient of determination (R^2), and standard error of estimate, in addition to annual time-series graphs. The software was used to obtain all rainfall-related climate indices, whose values are listed in Table 1.

Table 1 – Climate indices related to daily rainfall with definitions and units.

Index	Index name	Definition	Unit	Equation
PRCPTOT	Total annual precipitation in wet days	Total annual precipitation in wet days (RR*≥1 mm)	mm	$PRCPTOT_j = \sum_{i=1}^{I} RR_{ij}$
CDD	Consecutive dry days	Maximum number of consecutive days with RR*<1 mm	days	$RR_{ij} \geq 1mm$
CWD	Consecutive wet days	Maximum number of consecutive days RR≥1 mm	days	$RR_{ij} \geq 1mm$
R10 mm	Number of days with precipitation above 10 mm	Number of days per year with precipitation ≥10 mm	days	$RR_{ij} \geq 10mm$
R20 mm	Number of days with precipitation above 20 mm	Number of days per year with precipitation ≥20 mm	days	$RR_{ij} \geq 20mm$
R50 mm	Number of days with precipitation above 50 mm	Number of days per year with precipitation ≥50 mm	days	$RR_{ij} \geq nnmm$
SDII	Simple daily intensity index	Total annual precipitation divided by the number of wet days (defined as PRCPTOT≥1 mm)	mm/day	$SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$
Rx1day	Maximum 1-day precipitation amount	Monthly maximum precipitation in 1 day	mm	$Rx1day_j = \max(RR_{ij})$
Rx5day	Maximum consecutive 5-day precipitation amount	Monthly maximum precipitation in 5 consecutive days	mm	$Rx5day_j = \max(RR_{kj})$
R95p	Very wet days	Total annual precipitation with RR>95 percentile	mm	$R95\,p_j = \sum_{w=1}^{W} RR_{wj}$
R99p	Extremely wet days	Total annual precipitation with RR>95 percentile	mm	$R99\,p_j = \sum_{w=1}^{W} RR_{wj}$

*RR: daily rainfall rate.
Source: RClimDex (2004).

The climate indices described above generate annual time series graphs composed of trends and calculated by the least-squares linear regression method, with statistical significance, showing the adjustments of these linear trends for the graphs.

Data quality control is a prerequisite for calculating indices using the RClimDex 3.2.1 software and consists of the following procedures:

- replace all missing values (which must already be coded as -99.9) for internal formats recognized by R (i.e., declares them as not available);
- replace all unacceptable data matrix values by -99.9, including precipitation values less than zero (notably absurd).

The p-value calculated by Student's *t*-test represents the level of statistical significance. If the p-value of any index is equal to or less than 0.1, the index trend is statistically significant at 90%; if it is equal to or less than 0.05, the statistical significance is at 95%, and p-values less than 0.01 show a trend with statistical significance at 99%.

This study adopted Student's *t*-test because it is one of the most widely used distributions in statistics, with applications ranging from statistical modeling to hypothesis testing. Other methods could also be used, such as Mann-Kendall, linear regression, and Pettitt parametric tests; however, the RClimDex software employs Student's *t*-test in its operational package.

The present investigation used this test to evaluate whether the trend values obtained were significant or not. Student's *t*-test is one of the most widely used distributions for small samples and in meteorological studies (Kousky and Kayano, 1994; Kayano and Kousky, 1996; Castro, 2002; Silva and Sousa, 2013). It can be calculated by Equation 1:

$$tc = t/\sqrt{(n-2) + t^2} \quad (1)$$

In which:
tc = percentile value;
c = degree of freedom — we used=95 or 95%;
t = percentile value.

Maps were generated with the calculated climate index data using the Golden Software Surfer, which allows complete visualization of the spatial behavior of the studied variable. We adopted the kriging method, which is based on data interpolation, obtained using tabular data and geographic location. In kriging, intermediate data values are preserved, and the result is a continuous surface of smoother data, minimizing the contrasts between polygons. Kriging uses mathematical functions to add larger weights in positions closest to the sampling points and lower weights in the farthest positions, thus creating new interpolated points based on these linear data combinations (Viola et al., 2010).

After the spatial trend analysis of climate extremes indices, we performed a time analysis of each index to have an overview of the interannual climate variability throughout the Pajeú river basin. To this end, we calculated the weighted average of the basin with the Thiessen method.

Results and Discussion

The analysis of spatio-temporal rainfall variability in the Pajeú river basin showed a significant change in precipitation pattern and behavior throughout the study site. Over the 52 years analyzed, we could identify both the decrease in total annual precipitation and the increase in consecutive days without rainfall, a situation that converges toward a state of water scarcity in the region. In addition to reduced precipitation and increased dry days, we found a decreasing trend in daily rainfall intensity and number of days with moderate and strong rainfall.

Table 2 describes the trend values of climate extremes indices calculated based on rainfall data from the Pajeú river basin, covering the period between January 1964 and December 2016.

Values highlighted in gray are statistically significant; those in gray and italics have p<0.1; those in gray and bold have p<0.05.

Values without a gray background in the table presented p>1 and no statistical significance, as their reliability was below 90%. As a result, they were not considered in the analyses, since it is not safe to state that they are actual trends.

Table 2 shows that, among all indices calculated, those with the highest number of statistically significant results were the total annual precipitation index (PRCPTOT) and the number of days with rain above 10 and 20 mm (R10 mm and R20 mm, respectively).

Total annual precipitation analysis

First, the PRCPTOT analysis revealed a marked decrease in precipitation, detected in all municipalities that presented statistical significance.

According to this result, the study area showed a rainfall reduction ranging from 107.6 mm to 380.5 mm in the 52 years analyzed. The municipality of Floresta had the lowest rainfall reduction, with a rate of -2.07 mm/year, while Carnaíba presented the highest rainfall decrease, with a rate of -7.61 mm/year, as shown in Figure 3.

Figure 3 also demonstrates that the lowest rainfall reduction occurred in the southern part of the basin, which is closer to the São Francisco River and has the highest semi-aridity index according to the climate classification of the basin. The rainfall reduction in the study area over 52 years corroborates the history of water scarcity that has been affecting the semi-arid region of the Brazilian Northeast, which currently faces the most severe drought in recent decades.

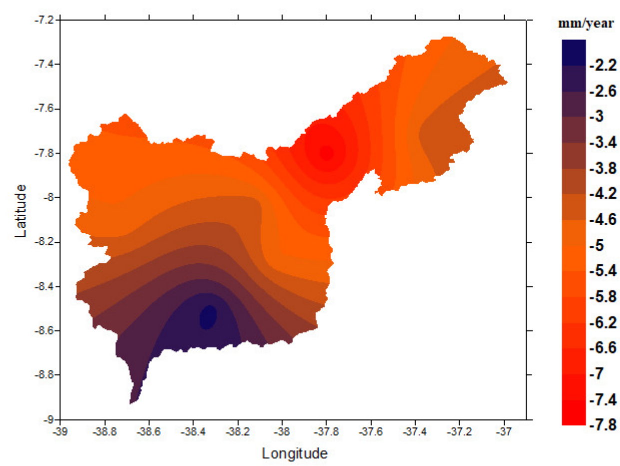

Figure 3 – Spatial distribution of total annual precipitation in the Pajeú river basin from 1964 to 2016.

Table 2 – Trends in rainfall-related climate extremes indices for 11 municipalities along the Pajeú river basin.

	PRCPTOT (mm)	CDD (days)	CWD (days)	R10mm (days)	R20mm (days)	R50mm (days)	SDII (mm/day)	Rx1day (mm)	Rx5day (mm)	R95p (mm)	R99p (mm)
Afogados da Ingazeira	0.906	*0.345*	*-0.03*	0.072	0.029	0.012	**0.085**	0.225	0.458	1.392	0.504
Betânia	**-4.945**	0.546	-0.015	**-0.145**	*-0.06*	-0.016	-0.029	*-0.439*	**-1.081**	*-1.346*	-0.701
Carnaíba	*-7.617*	-0.987	0.009	**-0.328**	*-0.175*	0.006	**-0.15**	0.167	*-0.895*	0.085	0.782
Floresta	*-2.073*	0.002	*-0.027*	*-0.103*	-0.039	*-0.016*	**-0.183**	-0.08	-0.446	*-1.231*	0.51
Iguaraci	**-5.021**	*0.572*	-0.004	*-0.12*	*-0.076*	-0.006	0.035	-0.261	-0.272	-1.231	-1.204
Itapetim	-3.661	0.191	-0.001	**-0.175**	*-0.077*	0.004	-0.039	-0.246	-0.301	0.008	-0.573
Mirandiba	*-4.885*	-0.074	**-0.056**	**-0.177**	*-0.09*	**-0.046**	**-0.181**	*-0.388*	-0.473	-1.523	-0.231
São José do Egito	*-2.37*	-0.299	-0.002	-0.109	*-0.07*	-0.002	0.019	0.112	-0.328	-0.055	-0.175
Serra Talhada	*-4.398*	0.525	-0.009	*-0.126*	-0.031	-0.018	0.022	0.021	-0.298	-1.291	-0.201
Triunfo	-5.321	*0.703*	*-0.057*	-0.164	-0.096	0.003	0.037	*-0.302*	-0.472	-0.295	-0.479
Tuparetama	*-4.348*	0.42	**-0.055**	**-0.337**	**-0.151**	0.008	**-0.211**	0.377	-0.114	0.959	**-1.158**

Considering that the historical average rainfall of the Brazilian Northeast semi-arid region, particularly of the Pajeú river basin, ranges from 400 to 800 mm a year, we found a loss of approximately a whole year of precipitation during these 52 years (1964–2016), a situation that tends to worsen if this scenario becomes a reality. This rainfall variation in the region can be attributed to large-scale circulation, while rainfall intensity might influence climate variability.

Similar results were found by Assis (2016) in an analysis of the São Francisco river basin, in the Submédio stretch, which covers part of the Pernambuco semi-arid region and part of mid-northern Bahia, where even higher decreasing trends in rainfall have been detected, reaching approximately 14 mm/year in the Araripina microregion.

The study evidenced the need to deepen the analysis of climate extremes indices, given the economic, political, and social importance of the Pajeú river basin to the state, as it is the largest basin of Pernambuco. The Pajeú River is the largest tributary of the São Francisco River, and its basin extends across important municipalities whose economy relies on agriculture, both irrigated and dryland farming — the latter completely dependent on climatic factors.

Moncunill (2006) conducted a study in Ceará and also found negative trends in annual precipitation between 1974 and 2003. We underline that few studies in Northeastern Brazil use this methodology, which is more concentrated and widespread in the South, Southeast, and Midwest regions of Brazil, as well as other South American countries.

The Brazilian semi-arid region is not the only one experiencing an increase in water scarcity. Vargas-Amelin and Pindado (2014) investigated the Mediterranean region of Spain, also characterized by a semi-arid climate, and found a decrease in rainfall when analyzing a 70-year period (1940 to 2010).

Figure 4 shows the linear trend calculated for total annual precipitation, also from 1964 to 2016. This analysis revealed that, in most years, the total annual precipitation was below the trend line, that is, over these 52 years, rainfall gradually remained below the historical average rainfall for the region.

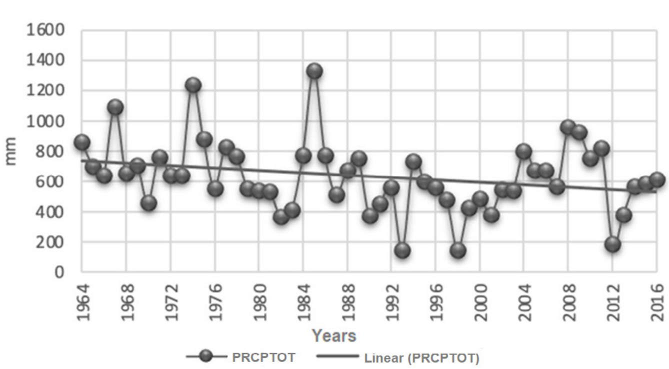

Figure 4 – Linear trend of total annual precipitation in the Pajeú river basin from 1964 to 2016.

Total annual precipitation reached its highest values in 1967, 1974, and 1985. These results are a consequence of strong and moderate La Niña events, which contributed to the higher total rainfall in these years. On the other hand, years with total annual precipitation below the historical average were more prevalent, with a gradually decreasing trend in these rainfall values. As shown in the graph in Figure 4, 1993, 1998, and 2012 stand out for having the lowest total annual precipitation values, not reaching 200 mm/year. 1993 and 1998 are associated with strong El Niño events, inhibiting rainfall in Northeastern Brazil. Despite the lack of El Niño events, 2012 was an extremely dry year due to acting systems and sea surface temperature anomaly (SSTA).

Another important factor in the time trend analysis of the total annual precipitation index is that rainy years, with annual rainfall above average, occurred mainly until the late 1980s, with a predominance of dry years thereafter. This rainfall pattern change in the Pajeú river basin demonstrates a possible climate variation. This detailed analysis is made separately for each year in the following sub-section, which addresses the rainfall anomaly index.

Analysis of consecutive dry and wet days

According to Table 2, the analysis of the indices number of consecutive dry days (CDD) and maximum number of days with precipitation above 1 mm (consecutive wet days — CWD) shows an increasing trend in dry days and consequent decrease in rainy days among the municipalities that presented statistical significance. These indices are inversely proportional and complementary.

CDD variation fluctuated between 0.34 days/year and 0.70 days/year in Afogados da Ingazeira and Triunfo, respectively. Namely, Triunfo, which stands out from other municipalities for its local microclimate and higher annual rainfall rates, also has the highest trend in consecutive days without rain.

Triunfo did not show statistical significance in the total annual precipitation index, so we can state that, in addition to the higher number of dry days, the city might also be experiencing a gradual decrease in precipitation. CWD variation ranged from -0.02 (Floresta) to -0.05 (Triunfo).

Although not high, the CDD and CWD trend variation is significant since the Pajeú river basin already shows a reduction in its annual rainfall. Figure 5 depicts the CDD and CWD spatial distribution.

The time analysis of these indices reveals that some years reach 120 CDDs. Once more, 1993, 1998, and 2012 stand out since these years had the longest dry period in addition to the highest annual rainfall reduction. In a similar study, but that calculated the rainfall anomaly index, Assis et al. (2015) also identified 1993, 1998, and 2012 as the driest years of the whole series of data studied (1964–2014) for river basins in the Pernambuco semi-arid region.

The graph showing the number of CWDs indicates a decreasing time trend, that is, increasingly fewer successive rainy days. Again, 1993, 1998, and 2012 stand out, this time for having less

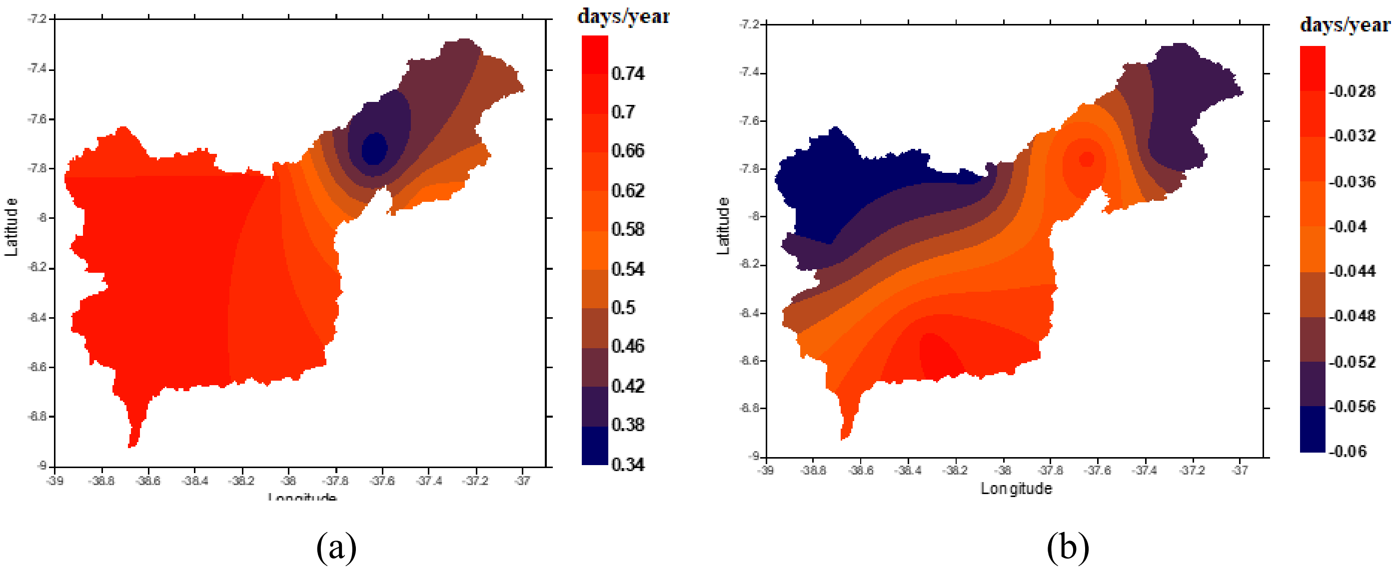

Figure 5 – (A) Spatial distribution of the number of consecutive dry days and (B) consecutive wet days (rain >1 mm) in the Pajeú river basin in days/year (1964–2016).

than five CWDs per year. The CDD increase and CWS decrease mean not only less rain in the study area, as evidenced by the PRCPTOT index, but the progressive concentration of rains in a shorter interval.

Nóbrega (2010) analyzed 35 rainfall stations in the Sertão of Pernambuco and found similar results, indicating a higher number of dry days in the rainy season. Nóbrega et al. (2015) investigated the entire state of Pernambuco from 1978 to 2010 using the same methodology for the assessment of climate extremes indices, concluding that rains are becoming increasingly concentrated in a few days over the year in the Sertão and Agreste of Pernambuco. Sertão also had the highest numbers and extremely dry spells. Figure 6 illustrates the CDD and CWD time trends.

Analysis of days with strong and moderate precipitation

The analysis of R10 mm, R20 mm, and R50 mm points to negative trends in all indices, that is, a reduction in days with rain above 10 mm, 20 mm, and 50 mm per year.

These indices are directly proportional to total annual precipitation and CDD since, when annual rainfall decreases and the number of dry days increases, rainfall becomes less intense; thus, days with moderate (10 mm and 20 mm) and strong (50 mm) rains are increasingly sporadic.

Comparing the results of Table 2, the R10 mm index ranges from -0.10 days/year to -0.33 days/year in Floresta and Tuparetama, respectively. The R20 mm index varies from -0.06 days/year (Betânia) to -0.175 (Carnaíba). In turn, the R50 mm index ranges from -0.002 days/year to -0.046 days/year in Floresta and Mirandiba, respectively. Figure 7 shows the spatial distribution of R10 mm, R20 mm, and R50 mm.

The time trend of the R10 mm index reveals a decreasing line, with 1974 and 1985 standing out with the highest peaks. Therefore, these years had more days with precipitation equal to or above 10 mm. The region had approximately 40 days of moderate rainfall in 1974 and around 50 days in 1985.

1974 and 1985, which presented the greatest number of days with moderate rainfall, also had the highest total rainfall in the calculation of the PRCPTOT index. On the other hand, 1993 and 1998 showed the lowest number of days with moderate rainfall, not exceeding the five-day range. We highlight that these years also presented the lowest total annual precipitation in the PRCPTOT index. This finding shows the proportion between the index calculations, which are complementary.

As in the R10 mm index, the linear trend of the R20 mm index was negative, indicating a lower number of days with precipitation above 20 mm. The highest peaks occurred in 1967, 1974, and 1985, with approximately 15 days of moderate rainfall.

According to the PRCPTOT index, these same years showed higher total annual precipitation. After calculation of the weighted average for the time analysis, the R50 mm index showed no noticeable trend and thus was not considered for this analysis. Figure 8 presents the linear time trend graphs of the R10 mm and R20 mm indices.

Daily rainfall intensity analysis

The simple daily intensity index (SDII), which represents the daily rainfall intensity and results from the proportion between total annual

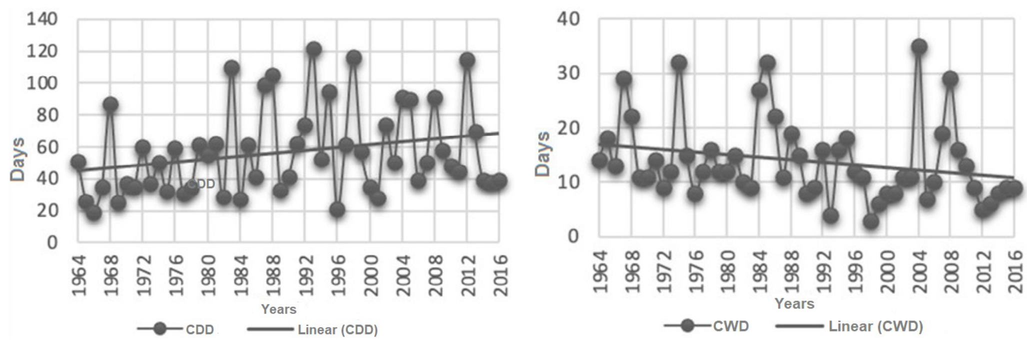

Figure 6 – (A) Linear trend of the number of consecutive dry days and (B) number of consecutive wet days (rain >1 mm) in the Pajeú river basin in days/year (1964–2016).

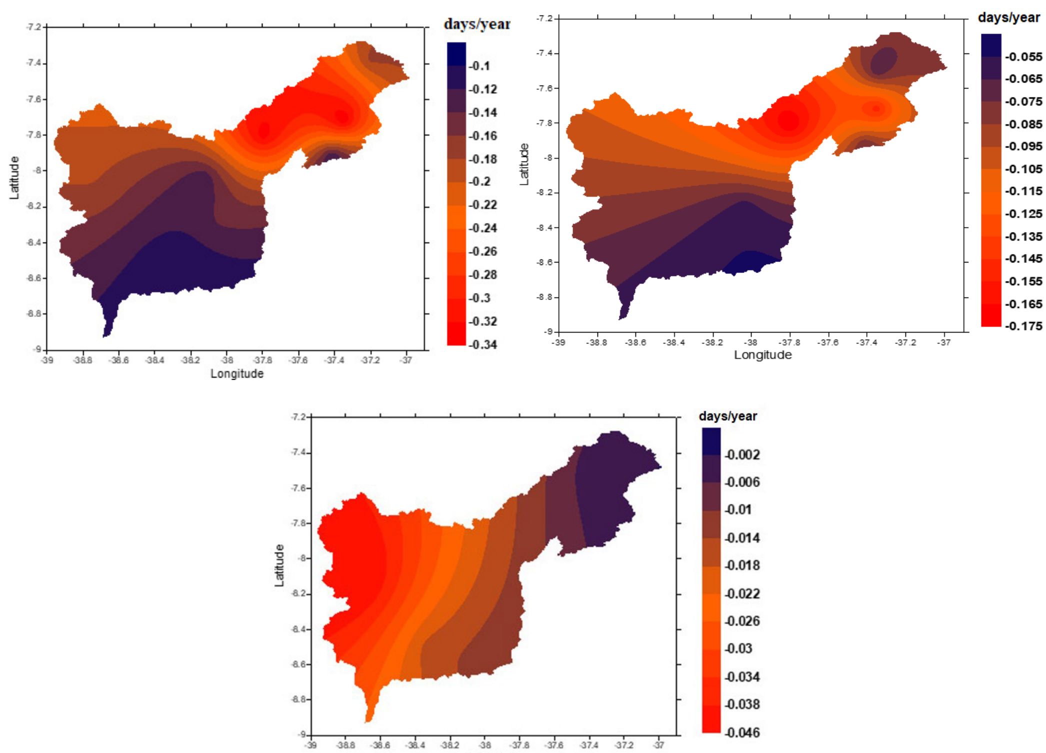

Figure 7 – Spatial distribution map of the climate indices (A) R10 mm, (B) R20 mm, and (C) R50 mm in the Pajeú river basin in days/year (1964–2016).

precipitation and the number of rainy days, presented both positive and negative trends. However, municipalities with statistical significance showed a prevalence of negative trends, with a decrease in daily rainfall intensity; only one city had a positive trend for this index — Afogados da Ingazeira, with a value of 0.085 mm/day. Regarding negative indices, Tuparetama stood out, with -0.211 mm/day, as seen in Table 2.

Municipalities with a decrease in daily rainfall intensity also had a reduction in total annual precipitation. The only municipality with an upward trend in daily rainfall intensity also experienced an increase in total annual precipitation, albeit without statistical significance.

Similar results were found by Silva et al. (2012) in a study of the state of Bahia from 1970 to 2006, which assessed climate change detection indices. They identified a downward trend in daily rainfall intensity and total annual precipitation in the Baixo São Francisco region. According to the authors, this rainfall variation can be attributed to large-scale circulation, while rainfall intensity might influence climate variability.

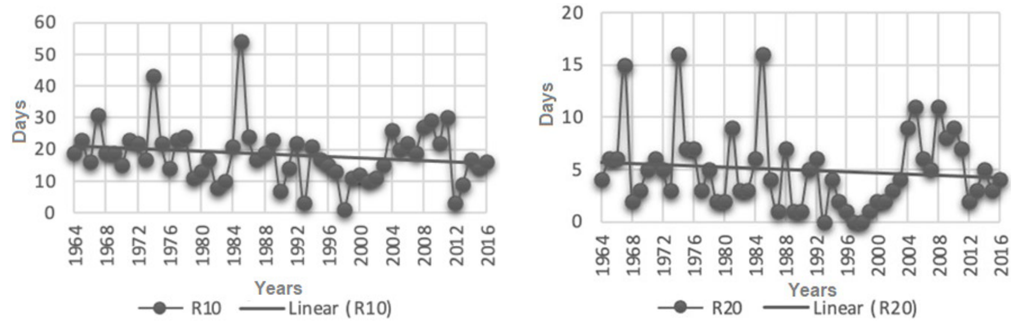

Figure 8 – (A) Linear trend of the number of days/year with precipitation ≥10 mm — R10 mm and (B) ≥20 mm — R20 mm in the Pajeú river basin (1964–2016).

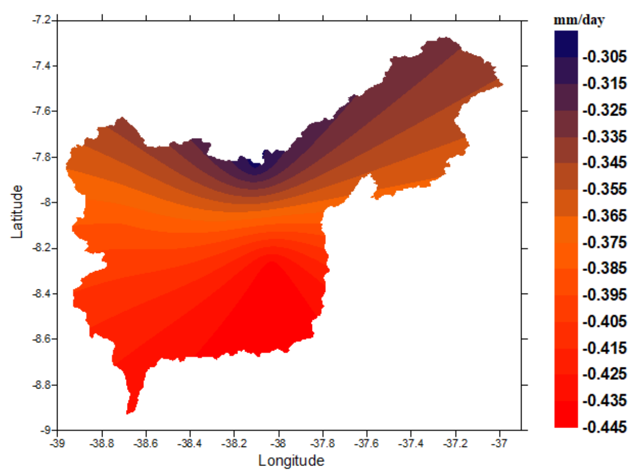

Figure 9 – Spatial distribution map of the simple daily intensity index in the Pajeú river basin in mm/day (1964–2016).

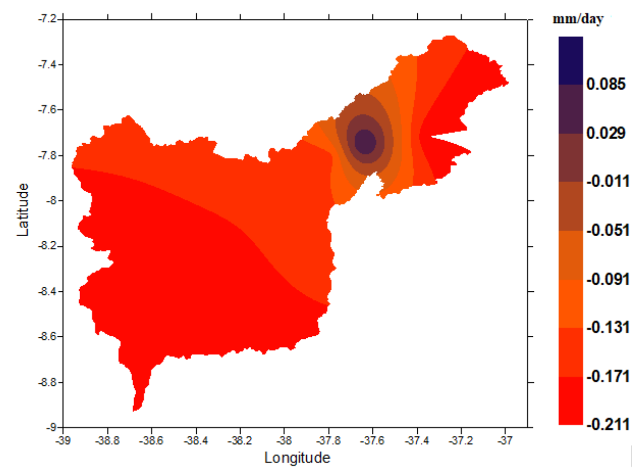

Figure 10 – Spatial distribution map of the Rx1day index in the Pajeú river basin in mm/day (1964–2016).

Figure 9 depicts the SDII spatial distribution, which clearly evidences a decrease in daily rainfall intensity throughout the basin, except for Afogados da Ingazeira, in the northernmost part of the basin, which presents an increase in the daily rainfall intensity index.

The time analysis of the daily rainfall intensity index showed no trend, as, after the calculation of the weighted average, heavy rains are distributed to other rainfall stations; thus, the average value does not represent the reality of each municipality.

Monthly maximum precipitation analysis

The Rx1day and Rx5day indices, which correspond to the maximum 1-day and consecutive 5-day precipitation amount, presented a statistically significant trend in few municipalities, three for the Rx1day index and two for the Rx5day index. Nonetheless, both showed negative trends, converging toward a decrease in Rx1day and Rx5day. This result is complementary to the total annual precipitation index since as total annual precipitation decreases, so does the precipitation amount in one and five consecutive days. The Rx1day index ranges from -0.302 in Triunfo to -0.439 mm/day in Betânia.

Figure 10 demonstrates the Rx1day spatial distribution, indicating a gradual daily rainfall intensity, decreasing as it approaches the southern part of the basin, which is closer to the São Francisco River and classified as the most semi-arid area of the Pajeú river basin. Since the Rx5day index presented statistical significance in only two municipalities, we could not interpolate the values in the map.

Concerning time trends, the Rx1day and Rx5day indices present the monthly maximum 1-day and consecutive 5-day precipitation amounts. The results displayed in the graph correspond to the month (in one year) with the highest precipitation value in mm for the period (one day/five days).

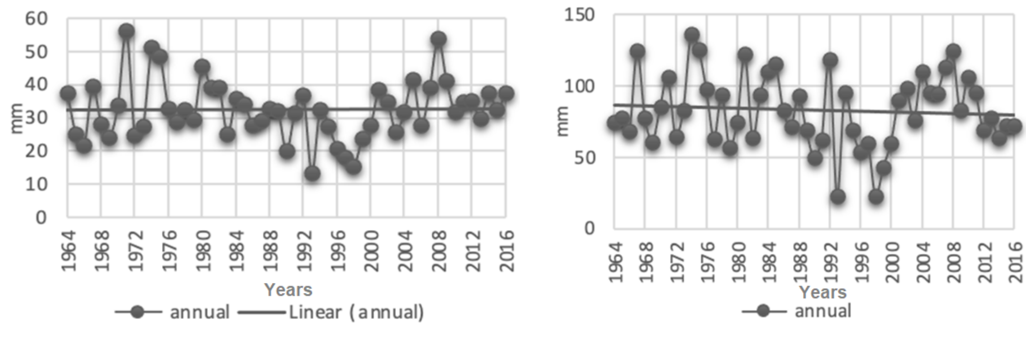

Figure 11 – Linear trend of monthly maximum 1-day precipitation — Rx1day and monthly maximum consecutive 5-day precipitation — Rx5day in the Pajeú river basin in mm/year (1964–2016).

As shown in Figure 11, the Rx1day index did not exceed 60 mm in any of the 52 years analyzed. 1993 and 1998 stood out once again because they presented the lowest accumulated rainfall in one day. The analysis of the Rx5day index revealed that the maximum value of concentrated precipitation in 5 consecutive days almost reached 150 mm in many years, especially in the first half of the data series analyzed. The highest rainfall peaks were in 1974, which, as indicated in the PRCPTOT calculations, was one of the years with the greatest annual precipitation.

The climate extremes indices R95p and R99p, which correspond to wet and extremely wet days, presented statistical significance in only two and one municipalities, respectively. Therefore, they were not considered in this analysis, since the study area presented, in previous indices, a trend in rainfall scarcity and gradual precipitation reduction, making the analysis of wet days ineffective for the present investigation.

Conclusions

The climate index results indicate a precipitation pattern change in the Pajeú river basin, given the homogeneity of the trends presented.

The decrease in total annual precipitation, in addition to the rise in consecutive dry days, corroborates other indices, showing signs of increased water scarcity in the region. These answers contribute to studies of recurrent droughts that progressively affect the semi-arid region of the Brazilian Northeast.

This projection of increased water scarcity points to a trend in greater demand for water use and conflicts in the basin, as the basin water is widely used for irrigation.

In this context, implementing public policies that promote strategies for reducing these conflicts and ensure regional sustainability is crucial. This analysis and the methodology applied can be extended and used in other river basins with similar characteristics.

Contribution of authors:

Assis, J.M.O.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing — original draft. Menezes, A.F.: Cartography, Validation, Formal analysis, Writing — original draft. Souza, W.M.: Methodology, Formal analysis, Supervision. Sobral, M.C.: Methodology, Validation, Formal analysis, Investigation, Supervision, Visualization.

References

Agência Nacional de Águas (ANA). 2021. HidroWeb: sistemas de informações hidrológicas. ANA (Accessed August 2021) at: http://hidroweb.ana.gov.br/HidroWeb.

Agência Pernambucana de Águas e Clima (APAC). Sistema de meteorologia e monitoramento. APAC (Accessed August 2021) at: http://old.apac.pe.gov.br/meteorologia/monitoramento-pluvio.php.

Assis, J.M.O., 2016. Variabilidade do clima e cenários futuros de mudanças climáticas no trecho submédio da bacia hidrográfica do rio São Francisco. Tese de Doutorado, Programa de Pós-Graduação Engenharia Civil, Universidade Federal de Pernambuco, Recife.

Assis, J.M.O.; Souza, W.M.; Sobral, M.C., 2015. Análise Climática da Precipitação no Submédio da Bacia do Rio São Francisco com Base no Índice de Anomalia de Chuva. Revista Brasileira de Ciências Ambientais (Online), (36), 115-117. https://doi.org/10.5327/Z2176-947820151012.

Bork, C.K.; Castro, A.S.; Leandro, D.; Corrêa, L.B.; Siqueira, T.M., 2017. Índices de precipitação extrema para os períodos atual (1961-1990) e futuro (2011-2100) na bacia do rio Taquari-Antas, RS. Revista Brasileira de Ciências Ambientais (Online), (46), 29-45. https://doi.org/10.5327/Z2176-947820170233.

Cardoso, A.S.; Alves, E.A.; Marques, E.A.T.; Castro, C.M.V.A.; Casé, M.; Sobral, M.C.M., 2019. Avaliação da toxicidade de piscicultura do semiárido de Pernambuco (Brasil). Brazilian Journal of Development, v. 5, (11), 24934-24961. https://doi.org/10.34117/bjdv5n11-171.

Castro, C.A.C., 2002. Interações trópicos-extratrópicos na escala de tempo intrasazonal durante o verão austral e seus efeitos na América do Sul. Dissertação de Mestrado, Instituto Nacional de Pesquisas Espaciais, São Paulo.

Cavalcante Junior, E.G.; Medeiros, J.F.; Espínola Sobrinho, J.; Figueirêdo, V.B.; Costa, P.N.; Santos, W.O., 2016. Development and Water Requirements of Cowpea Under Climate Change Conditions in the Brazilian Semi-Arid Region. Revista Brasileira de Engenharia Agrícola e Ambiental, v. 20, (9), 783-788. http://dx.doi.org/10.1590/1807-1929/agriambi.v20n9p783-788.

Galvão, M.L.M.; Santos, M.A.; Silva, F.N.; Silva, V.P., 2020. Connections Between Wind Energy, Poverty and Social Sustainability in Brazil's Semiarid. Sustainability, v. 12, (3), 864. http://dx.doi.org/10.3390/su12030864.

Grassi, B.; Redaelli, G.; Visconti, G., 2013. Arctic Sea Ice Reduction and Extreme Climate Events over the Mediterranean Region. Journal of Climate, v. 26, 10101-10110. https://doi.org/10.1175/JCLI-D-12-00697.1.

Huang, J.; Ji, M.; Xie, Y.; Wang, S.; He, Y.; Ran, J., 2016. Global semi-arid climate change over last 60 years. Climate Dynamics, (46), 1131-1150. https://doi.org/10.1007/s00382-015-2636-8.

Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 pp.

Kayano, M.T.; Kousky, V.E., 1996. Tropical circulation variability with emphasis on interannual and intraseasonal time scales. Revista Brasileira de Meteorologia, v. 11, (1-2), 6-17.

Kousky, V.; Kayano, M.T., 1994. Principal modes of outgoing longwave radiation and 250-mb circulation for the South American sector. Journal of Climate, v. 7, (7), 1131-1143. https://doi.org/10.1175/1520-0442(1994)007%3C1131:PMOOLR%3E2.0.CO;2.

Lemos, J.J.S.; Santiago, F.D., 2020. Instabilidade temporal na produção agrícola familiar de sequeiro no semiárido do nordeste brasileiro. Desenvolvimento em Questão, v. 18, (50), 186-200. https://doi.org/10.21527/2237-6453.2020.50.186-200.

Marengo, J.A.; Alves, L.M.; Alvala, R.C.S.; Cunha, A.P.; Brito, S.; Moraes, O.L.L., 2018. Climate Characteristics of the 2010-2016 Drought in The Semiarid Northeast Brazil Region. Anais da Academia Brasileira de Ciências, v. 90, (2 Supl. 1), 1678-2690. https://doi.org/10.1590/0001-3765201720170206.

Moncunill, D.F., 2006. The rainfalltrend over Ceará and its implications. In: 8ª Conferência Internacional de Meteorologia e Oceanografia do Hemisfério Sul, Foz do Iguaçu. Anais... pp. 315-323.

Montenegro, S.G.; Montenegro, A.; Ragab, R., 2010. Improving agricultural water management in the semiarid region of Brazil: experimental and modelling study. Irrigation Science, v. 28, 301-316. https://doi.org/10.1007/s00271-009-0191-y.

Nobre, P.; Pereira, E.B.; Lacerda, F.F.; Bursztyn, M.; Haddad, E.A.; Ley, D., 2019. Solar smart grid as a path to economic inclusion and adaptations to climate change in the Brazilian semiarid Northeast. International Journal of Climate Change Strategies and Management, v. 11, (4), 499-517. https://doi.org/10.1108/ijccsm-09-2018-0067.

Nóbrega, R.S.; Farias, R.F.L.; Santos, C.A.C., 2015. Variabilidade temporal e espacial da precipitação pluviométrica em Pernambuco através de índices de extremos climáticos. Revista Brasileira de Meteorologia, v. 30, (2), 171-180. https://doi.org/10.1590/0102-778620130624.

Nóbrega, S.N., 2010. Modelagem climática no Nordeste do Brasil: cenários e incertezas. In: Galvíncio, J.D.; Silva, D.F.; Nóbrega, S.N. (Eds.), Mudanças climáticas e recursos hídricos: aplicações no estado de Pernambuco. Ed. Universitária da UFPE, Recife, pp. 1-25.

Painel Brasileiro de Mudanças Climáticas – PBMC. 2013. Sumário Executivo do GT2. In: Ambrizzi, T.; Araujo, M. (Eds.), Primeiro Relatório de Avaliação Nacional do Painel Brasileiro de Mudanças Climáticas. Rio de Janeiro, PBMC.

Painel Brasileiro de Mudanças Climáticas – PBMC. 2014. Base científica das mudanças climáticas. In: Ambrizzi, T.; Araujo, M. (Eds.), Primeiro Relatório da Avaliação Nacional sobre Mudanças Climáticas. COPPE, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 464 pp, pp. 25-63.

Pernambuco. 2006. Atlas de bacias hidrográficas de Pernambuco. Secretaria de Ciência, Tecnologia e Meio Ambiente, Recife.

RClimDex, 2004. Manual del usuario (Accessed June 2021) at: http://etccdi.pacificclimate.org/software.shtml.

Santos, C.A.S.; Rocha, F.A.; Ramos, T.B.; Alves, L.M.; Mateus, M.; Oliveira, R.P.; Neves, R., 2019. Using a hidrologic model to asses the performance of regional climate models in a semi-arid watershed in Brazil. Water, v. 11, (1), 170. https://doi.org/10.3390/w11010170.

Selvey, L.A.; Rutherford, S.; Dodds, J.; Dwyer, S.; Robinson, S.M., 2014. The impact of climate-related extreme events on public health workforce and infrastructure - how can we be better prepared? Australian and New Zealand Journal of Public Health, v. 38, (3), 208-210. https://doi.org/10.1111/1753-6405.12219.

Silva, D.F.S.; Sousa, A.B., 2013. Detecção de tendências climáticas no estado de Alagoas. Revista Brasileira de Geografia Física, v. 6, (3), 442-455. https://doi.org/10.26848/rbgf.v6.3.p442-455.

Silva, G.B.; Souza, W.M.; Azevedo, P.V., 2012. Cenários de mudanças climáticas no estado da Bahia através de estudos numéricos e estatísticos. Revista Brasileira de Geografia Física, v. 5, (5), 1019-1034. https://doi.org/10.26848/rbgf.v5i5.232891

Silva, G.K.; Silveira, C.; Silva, M.; Marcos Júnior, A.; Souza Filho, F.; Guimarães, S., 2020. Análise de projeções das mudanças climáticas sobre precipitação e temperatura nas regiões hidrográficas brasileiras para o século XXI. Revista Brasileira de Ciências Ambientais (Online), 1-17. http://dx.doi.org/10.5327/Z2176-947820200624.

Sobral, M.C.; Assis, J.M.O.; Oliveira, C.R.; Silva, G.M.N.; Morais, M.; Carvalho, R.M.C., 2018. Impacto das mudanças climáticas nos recursos hídricos no submédio da bacia hidrográfica do Rio São Francisco - Brasil. Revista Eletrônica do PRODEMA, v. 12, (3), 95-106. https://doi.org/10.22411/rede2018.1203.10.

Souza, A.G.S.S.; Ribeiro Neto, A.; Rossato, L.; Alvalá, R.C.S.; Souza, L.L., 2018. Use of SMOS L3 Soil Moisture Data: Validation and Drought Assessment for Pernambuco State, Northeast Brazil. Remote Sensing, v. 10, (8), 1314. https://doi.org/10.3390/rs10081314.

Vargas-Amelin, E.; Pindado, P., 2014. The challenge of climate change in Spain: Water resources, agriculture and land. Journal of Hydrology, v. 518, (parte B), 243-249. https://doi.org/10.1016/j.jhydrol.2013.11.035.

Viola, M.R.; Mello, C.R.; Pinto, D.B.F.; Mello, J.M.; Ávila, L.F., 2010. Métodos de interpolação espacial para o mapeamento da precipitação pluvial. Revista Brasileira de Engenharia Agrícola e Ambiental, v. 14, (9), 970-978. https://doi.org/10.1590/S1415-43662010000900009.

Yilmaz, A.G.; Hossain, I.; Perera, B.J.C., 2014. Effect of climate change and variability on extreme rainfall intensity-frequency-duration relationships: a case study of Melbourne. Hydrology and Earth System Sciences, v. 18, (10), 4065-4076. https://doi.org/10.5194/hess-18-4065-2014.

Zhang, Y.; Wang, J.C.; Jing, J.H.; Sun, J.C., 2014. Response of groundwater to climate change under extreme climate conditions in North China Plain. Journal of Earth Science, v. 25, 612-618. https://doi.org/10.1007/s12583-014-0443-5.

ABES

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Adsorption of methylene blue dye by different methods of obtaining shrimp residue chitin

Adsorção de corante azul de metileno por diferentes métodos de obtenção de quitina de resíduo de camarão

Iliane Muller Otto[1], *Luiza Beatriz Gamboa Araújo Morselli*[1], *Dienifer Aline Braun Bunde*[1], *Simone Pieniz*[1], *Maurízio Silveira Quadro*[1], *Robson Andreazza*[1]

ABSTRACT

The textile industry, very important for the world economy, generates an effluent containing dyes, and which, when discarded in water bodies without proper treatment, can cause impacts to human health and the environment. One of these widely used dyes is methylene blue, whose characteristics are high solubility in water and its toxic potential, and which effects range from eye irritations, nausea, vomiting and even mental confusion. Among the potential adsorbents of this dye is chitin, which is a biopolymer extracted from the shrimp exoskeleton. Aiming at the development of a low-cost adsorbent material with potential use in the textile effluent treatment industry, the ability to remove methylene blue dye by shrimp residue chitin, obtained by eleven different methodologies, was verified. The three most efficient treatments reached approximately 75% of dye removal, proving the high adsorption power of shrimp residue. In addition to providing technological development of materials, the research brings socio-economic benefits to the fishermen's colony with the use of shrimp residue for the adsorption of other waste from the textile industry, contributing to the sustainability of both activities and reducing the environmental impact.

Keywords: biopolymer; dye removal; fishing waste; textile waste.

RESUMO

A indústria têxtil, muito importante para a economia mundial, gera um efluente que contém corantes e, quando descartado em corpos hídricos sem o tratamento adequado, pode causar impactos na saúde humana e no meio ambiente. Um desses corantes amplamente utilizado é o azul de metileno, cujas características são a alta solubilidade em água e seu potencial tó xico, causando desde irritações nos olhos, náuseas e vômitos até confusão mental. Entre os potenciais adsorventes desse corante está a quitina, que é um biopolímero extraído do exoesqueleto do camarão. Objetivando o desenvolvimento de um material adsorvente de baixo custo com potencial uso na indústria de tratamento de efluentes têxteis, verificou-se a capacidade de remoção de corante azul de metileno por quitina de resíduo de camarão, obtida por onze diferentes metodologias. Os três tratamentos mais eficientes alcançaram aproximadamente 75% de remoção do corante, comprovando o alto poder de adsorção do resíduo de camarão. Além de proporcionar desenvolvimento tecnológico de materiais, a pesquisa traz benefícios socioeconômicos para a colônia de pescadores com a utilização de resíduo de camarão para a adsorção de outro resíduo proveniente da indústria têxtil, contribuindo para a sustentabilidade de ambas as atividades e reduzindo o impacto ambiental.

Palavras-chave: biopolímero; remoção de corante; resíduo pesqueiro; resíduo têxtil.

[1]Universidade Federal de Pelotas – Pelotas (RS), Brazil.

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Introduction

The pollution of water bodies is a worrying environmental impact, considering that it brings more comprehensive damage to the environment, due to difficulties in controlling and monitoring, and provides indirect impacts to the soil, atmosphere, economy, public health and ecosystems in general (Barbosa, 2014). The sources of water pollution come from inadequate land occupation, deforestation and untreated dumping of sanitary and industrial effluents in water bodies (Sánchez, 2013). Among the effluents released in the springs is the effluent of the textile industry.

Brazil, the second largest textile chain in the West and the fourth largest knitwear producer in the world, produced approximately 2.04 million tons of pieces only in 2019 (ABIT, 2021). In the production process of the textile industry, dyes are generally used, which are recalcitrant, highly toxic molecules, even in low quantities (Ferreira et al., 2007). During the washing of textile parts, approximately one third of reactive dyes are left in wastewater, which, when released into water bodies, without proper treatment, can impact human health and the environment (Oliveira et al., 2018).

One of these dyes widely used in the textile, cellulose and cosmetic industries is methylene blue (MB), whose characteristics are the high solubility in water and its toxic potential, causing eye irritations, nausea, vomiting and even mental confusion (Wang et al., 2011; Bedin et al., 2018). Therefore, it is of paramount importance to remove this dye from industrial effluents (Sabar et al., 2020).

For the removal of MB from effluents, physical-chemical processes of effluent treatment are used, such as coagulation, or removal with activated charcoal, whose cost is high (Oliveira et al., 2018). The treatment of textile effluents requires efficient practices, through the use of alternative adsorbent materials, seeking efficiency and cost-effectiveness (Queiroz et al., 2019).

According to Bailey et al. (1999, p. 2469), the adsorbent must have "little processing, be of an abundant nature, or a by-product or material of waste from another industry." Potential adsorbents are numerous organic residues, such as sugarcane residues (Jorge et al., 2015), ryegrass straw (Silva et al., 2018), fly ash (Cunico et al., 2015), green coconut (Oliveira et al., 2018), pine and bamboo sawdust (Müller et al., 2019). Many research on adsorption of dyes from crustacean residues (Dotto et al., 2011; 2015; Labidi et al., 2019; Mabel et al., 2019) refer to the use of chitin.

Chitin is a biopolymer extracted from the shrimp exoskeleton and, after the deacetylation process, turns into chitosan, which is also widely studied as an adsorbent of dyes (Bajaj et al., 2015). Chitin, the second most available natural biopolymer after cellulose (Ahmed et al., 2020), received due attention only after the beginning of the 21st century, when studies revealed the biological importance of its characteristics and by-products (Wan et al., 2021). Chitin and Chitosan are structurally related, renewable and low-cost biopolymers, which are gaining importance as sustainable alternatives for various applications (Kostag and Seoud, 2021; Kumaran et al., 2021; Ribeiro et al., 2018).

There are also studies aimed at using chitin or chitosan to remove elements such as copper (Frantz et al., 2017; Adeeyo et al., 2019), aluminum (Lobo-Recio et al., 2013), gold (Zhao et al., 2019; Chang, 2021) and arsenic (Shan et al., 2020). Studies that make changes in the chemical and physical characteristics of chitin or chitosan indicate optimized results with variations in pH, use of clay, combination of chitin with chitosan, preparation of chitosan films, for example (Wang et al., 2011; Auta and Hameed, 2014; Honório et al., 2014; Frantz et al., 2017).

The process of obtaining chitin and chitosan require energy consumption and reagents, which imply actions to be performed with criteria. Due to these characteristics, the extraction of these products has complexity and added value (Assis and Brito, 2008). On the other hand, chitin and chitosan come from large amounts of waste from the fishing industry. Considering that fish processing can generate 40 to 70% of waste (Dragnes et al., 2009), its use for the development of products with added value can be an alternative for the sustainability of artisanal fishing, generating the interest of fishermen and fish farmers in the residue. Thus, the aim of this study was to verify the ability of blue methylene dye removal by shrimp residue chitin, obtained by different methodologies, for use in the textile effluent treatment industry.

Methodology

Eleven adsorption treatments were performed, based on the adsorption methodologies used by several authors (Longhinotti et al., 1996; Assis and Brito, 2008; Auta and Hameed, 2014; Wang et al., 2011). The adsorbate used was methylene blue in solution with an initial concentration of 20 mg L^{-1} and molar mass of 319.85 g mol^{-1}. As adsorbent, samples of 1g of chitin were used. Shrimp residues were collected in the Fishermen's Colony, located in the city of Pelotas, RS, in the south of Brazil, and then frozen. The samples underwent defrosting, washing with water under room temperature and manual separation. The following reagents were used: hydrochloric acid (HCl), for the elimination of minerals present, sodium hydroxide (NaOH), to reduce the protein nitrogen content, and sodium hypochlorite (NaClO), for the removal of pigments and minimization of the odor of shrimp residues in processing.

The steps for obtaining chitin are pre-treatment (PT), demineralization (DM), deproteinization (DP), deodorization (DD) and drying (DR). Chitin was obtained using 11 different methodologies, as shown in Chart 1.

In order to evaluate the quality of the chitin obtained, the scanning electron microscopy (SEM) analysis was performed in the SEM JSM - 6610LV equipment, of the T6 treatment, where the sample was metallized with gold and 15 kV voltage acceleration and magnification ranges of 30, 5,000 and 10,000 times.

The 11 treatments were submitted to adsorption capacity analysis at: 0, 5, 10, 20, 40, 60, 120, 180 and 240 minutes of incubation at 160 RPM and neutral pH. The aliquots, as soon as removed, were centrifuged for removal of the adsorbent from the solution in order to

Chart 1 – Stages of the 11 treatments of chitin.

<table>
<tr><th>STEPS</th><th>SHARE</th><th>T1</th><th>T2</th><th>T3</th><th>T4</th><th>T5</th><th>T6</th><th>T7</th><th>T8</th><th>T9</th><th>T10</th><th>T11</th></tr>
<tr><td rowspan="3">PT</td><td>Autoclave</td><td>127 a 130°C/3h</td><td>NA</td><td colspan="6">127 a 130°C / 3h</td><td colspan="3">NA</td></tr>
<tr><td>Drying</td><td>50°C/24h</td><td>NA</td><td colspan="6">50°C/24h</td><td colspan="3">NA</td></tr>
<tr><td>Crunch</td><td>Blender</td><td>NA</td><td colspan="9">Blender</td></tr>
<tr><td rowspan="7">DM</td><td>Conc. HCl</td><td colspan="11">2.5%</td></tr>
<tr><td>Equipment</td><td>Bath Mary</td><td>NA</td><td colspan="9">Jar Test</td></tr>
<tr><td>Temperature</td><td>50°C</td><td colspan="10">Room temperature</td></tr>
<tr><td>Agitation/time</td><td colspan="2">Manual (10 em 10 min/2h)</td><td colspan="4">120 RPM/1h</td><td colspan="2">160 RPM/3h</td><td>160 RPM/1h</td><td>160 RPM/2h</td><td>160 RPM/3h</td></tr>
<tr><td>Washing</td><td colspan="11">Until neutrality</td></tr>
<tr><td>Drying</td><td>50°C/24h</td><td colspan="5">NA</td><td colspan="5">50°C/24h</td></tr>
<tr><td>Crunch</td><td colspan="6">NA</td><td>Bld.</td><td colspan="4">NA</td></tr>
<tr><td rowspan="7">DP</td><td>Conc. NaOH</td><td colspan="2">5%</td><td colspan="4">15%</td><td colspan="2">5%</td><td colspan="3">15%</td></tr>
<tr><td>Equipment</td><td>Bath Mary</td><td colspan="10">Jar Test</td></tr>
<tr><td>Temperature</td><td>50°C</td><td colspan="10">Room temperature</td></tr>
<tr><td>Agitation/time</td><td>Manual (10 em 10 min/2h)</td><td colspan="5">120 RPM/1h</td><td colspan="2">160 RPM/3h</td><td>160 RPM/1h</td><td>160 RPM/2h</td><td>160 RPM/3h</td></tr>
<tr><td>Washing</td><td colspan="11">Until neutrality</td></tr>
<tr><td>Drying</td><td>50°C/24h</td><td>NA</td><td colspan="3">50°C/24h</td><td>NA</td><td colspan="5">50°C/24h</td></tr>
<tr><td>Crunch</td><td colspan="6">NA</td><td>Bld.</td><td colspan="4">NA</td></tr>
<tr><td rowspan="5">DD</td><td>Conc. NaClO</td><td>0.36%</td><td>NA</td><td>0.4%</td><td>1.2%</td><td>2.0%</td><td>0.5%</td><td colspan="5">1%</td></tr>
<tr><td>Equipment</td><td>NA</td><td>NA</td><td colspan="9">Jar Test</td></tr>
<tr><td>Temperature</td><td>Room temperature</td><td>NA</td><td colspan="9">Room temperature</td></tr>
<tr><td>Agitation/time</td><td>Manual (10 em 10 min/3h)</td><td>NA</td><td colspan="4">120 RPM/1h</td><td colspan="2">160 RPM/3h</td><td>160 RPM/1h</td><td>160 RPM/2h</td><td>160 RPM/3h</td></tr>
<tr><td>Washing</td><td>Until neutrality</td><td>NA</td><td colspan="9">Until neutrality</td></tr>
<tr><td rowspan="2">DR</td><td>Drying</td><td colspan="11">50°C/24h</td></tr>
<tr><td>Crunch</td><td>NA</td><td>Bld.</td><td colspan="9">NA</td></tr>
</table>

PT: pre-treatment; DM: demineralization; DP: deproteinization; DD: deodorization; DR: drying; RPM: revolutions per minute; Conc.: Concentration of; NA: Not applicable; Bld.: blender.

avoid interference during reading in the spectrophotometer. The reading was performed at a wavelength of 660 nm.

The adsorption results were analyzed by regression and Equation 1 to determine adsorption capacity (q) in mg g^{-1}, using the initial concentrations (Ic), the final concentration (Fc), both in mg L^{-1}, the adsorbent mass (m) in g and the volume of the solution in L. Regression analysis and graphs were made through the Sigmaplot 10.0 and Excel programs. The percentage of removal (%R) was determined using Equation 2.

$$q(mg/g) = \frac{(Ic - Fc)}{m} \times V \quad (1)$$

$$\%R = \frac{(Ic - Fc) \times 10C}{Ci} \quad (2)$$

With the results of adsorption capacity obtained, statistical analysis was performed by ANOVA variance, through the f-test, having as variables the 11 treatments of chitin and incubation time of 0 and 240 min. Thus, one can compare the distribution of sample groups independently and summarize a linear regression model by decomposition of the sum of squares for each source of variation using the Fisher-Snedecor F-test. Multiple comparison analysis was performed by the Tukey test with 5% probability of error. The procedures from Vieira (2006) were followed.

Results

Regression of adsorption treatments

The regression results of the adsorption treatments are presented in Figures 1 to 4, and all curves were significant. Although the T1 methodology is more conservative regarding its execution and the T2 is simpler, both demonstrated evident variations to be obtained, according to Figure 1.

It is observed that in the regression analysis of T1 and T2 there is a projection of reduction in concentration between 150 and 240 minutes, but there are no measurements in this interval to confirm this

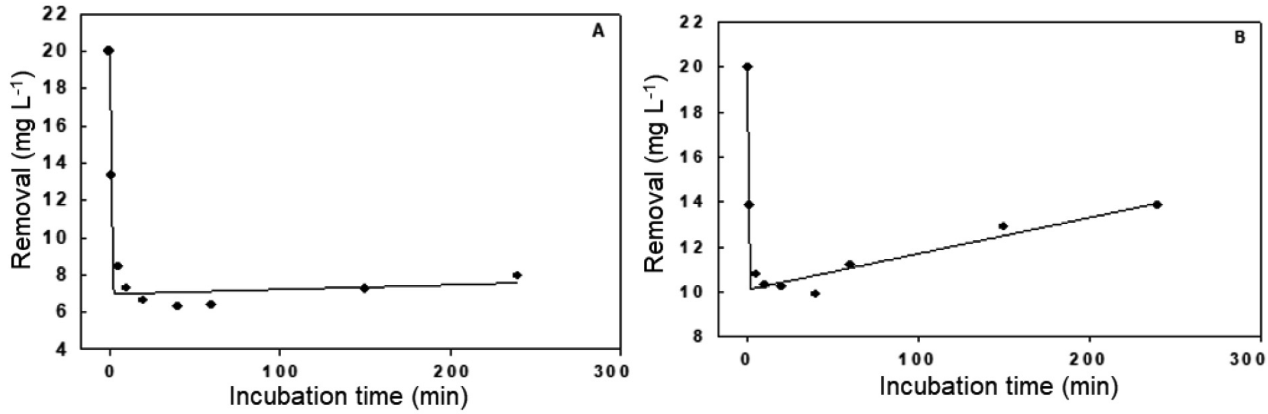

Figure 1 – Regression analysis for adsorption treatments with chitins obtained by the T1 (A) and T2 (B) methodologies.

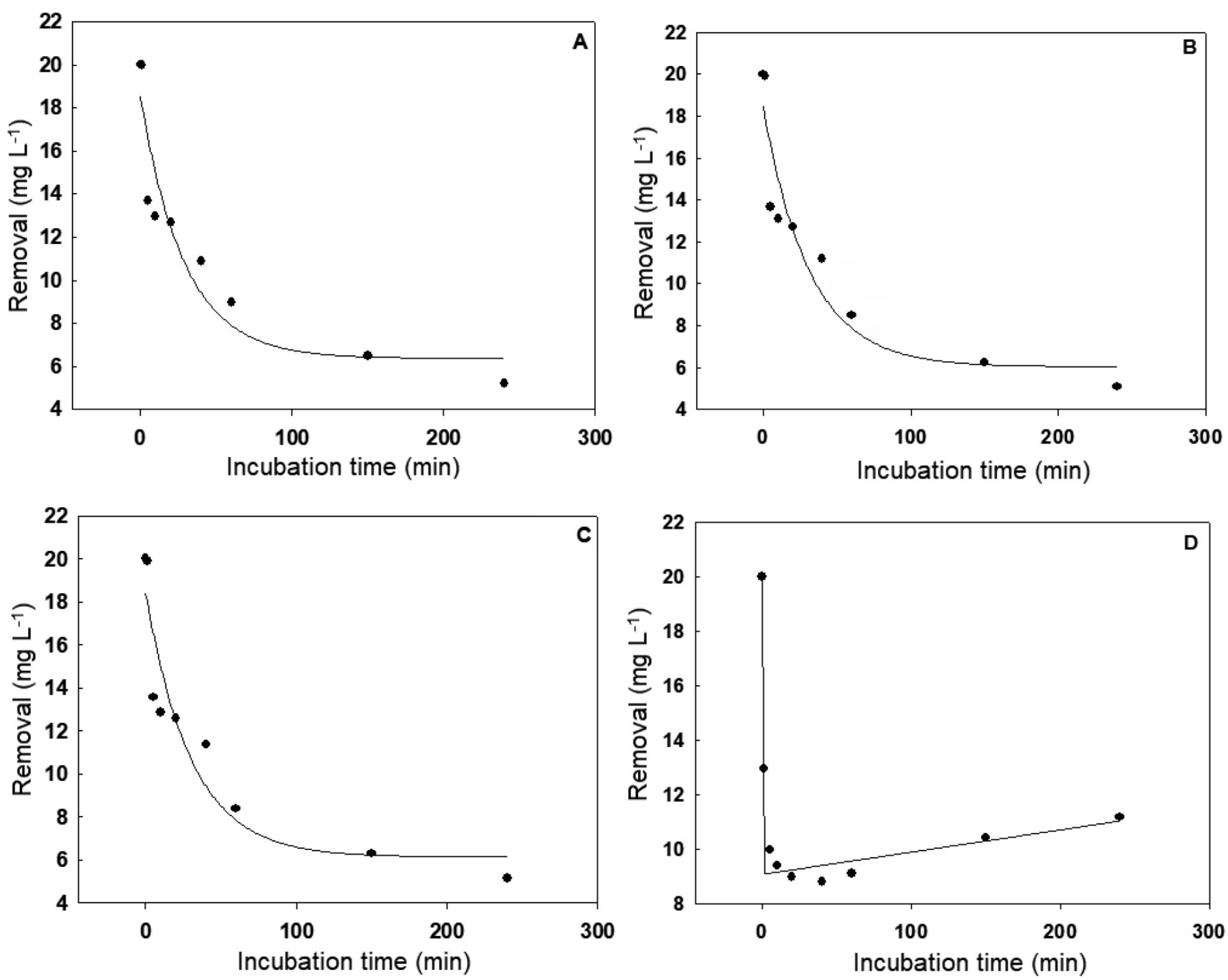

Figure 2 – Regression analysis for adsorption treatments with chitins obtained by methodologies T3 (A), T4 (B), T5 (C) and T6 (D).

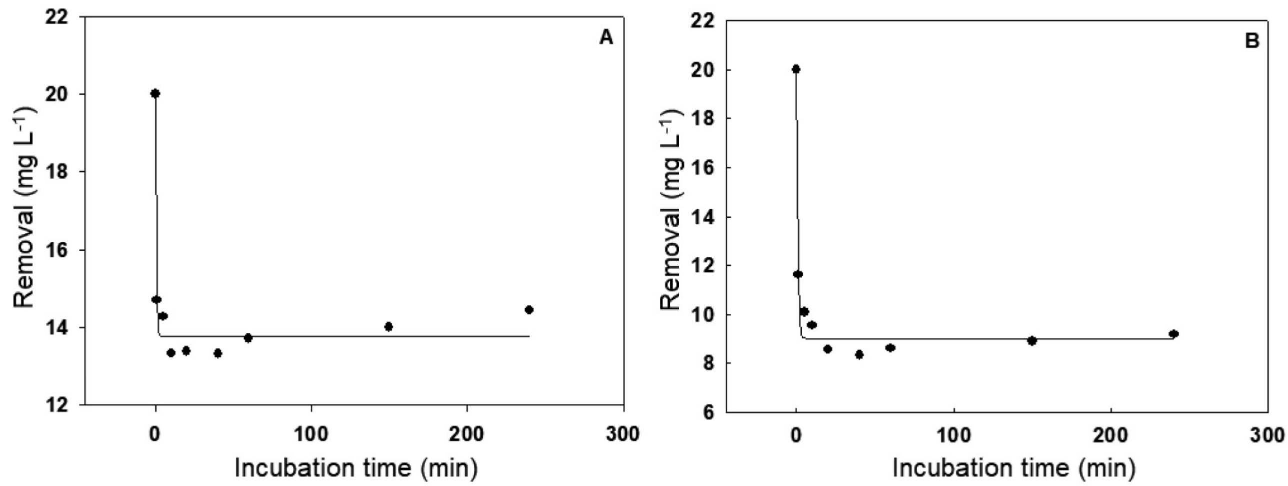

Figure 3 – Regression analysis for adsorption treatments with chitins obtained by methodologies (A) T7 and (B) T8.

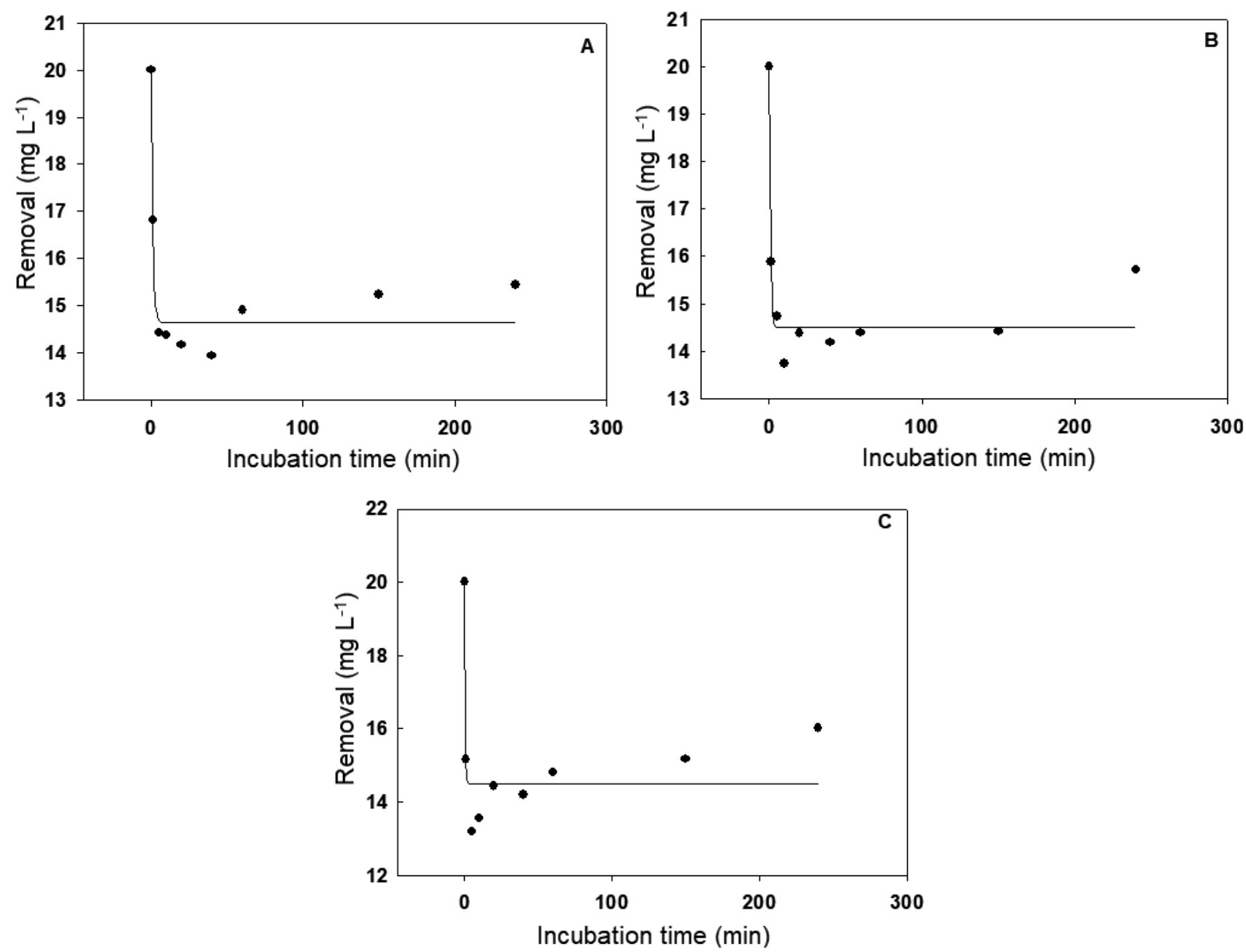

Figure 4 – Regression analysis for adsorption treatments with chitins obtained by the methodologies (A) T9, (B) T10 and (C) T11.

trend. Both in T1 and T2, regression confirmed that at 40 minutes of incubation there was maximum adsorption, that is, when chitin adsorbates the highest amount of MB. This action was confirmed by the following measurements that indicate the decrease in the amount of MB adsorbed. This moment is called the beginning of the desorption.

Figure 2 presents the regression results for T3, T4, T5 and T6, which are characterized by small alterations among them. However, T6 has more significant differences from the deproteinization stage.

The trend curve presents a slight desorption for T3, T4 and T5 between 60 and 100 minutes, however, these 3 treatments had as a marked characteristic the absence of desorption over the 240 minutes of incubation. T6 showed more pronounced curves between the actual adsorption results and the trend line, but showed the beginning of the desorption at 40 min both in the projection and in the analysis in the spectrophotometer.

Figure 3 shows the regression results for T7 and T8, which have as difference the milling in the DM and DP stages. The T7 presents greater accentuation in the curve between 150 and 240 min as compared to the T8. And, in both treatments, the trend line shows the beginning of desorption at 40 min.

The adsorption results of T9, T10 and T11 are presented in Figure 4 and were characterized by the alteration of an action in the stages of DM, DP and DD. It was observed that the curve between the times of 150 and 240 minutes is more accentuated in T9. And, like all previous treatments, except T3, T4 and T5, the trend line shows the beginning of the desorption that occurred at 40 minutes. However, for these three treatments (T9, T10 and T11), the line presents a more tenuous slope.

Scanning electron microscope

A SEM analysis was performed, presented in Figure 5 of chitin T6, with one of the lowest production cost methodologies, in the magnification range of 30 times (A), 5,000 times (B) and 10,000 times (C).

From the SEM analysis, it was observed that chitin presented particles with sizes ranging from 250 µm to 750 µm, approximately, and the average was around 400 µm. In general, the observed particles presented flattened and floccular shape, and there were also particles of

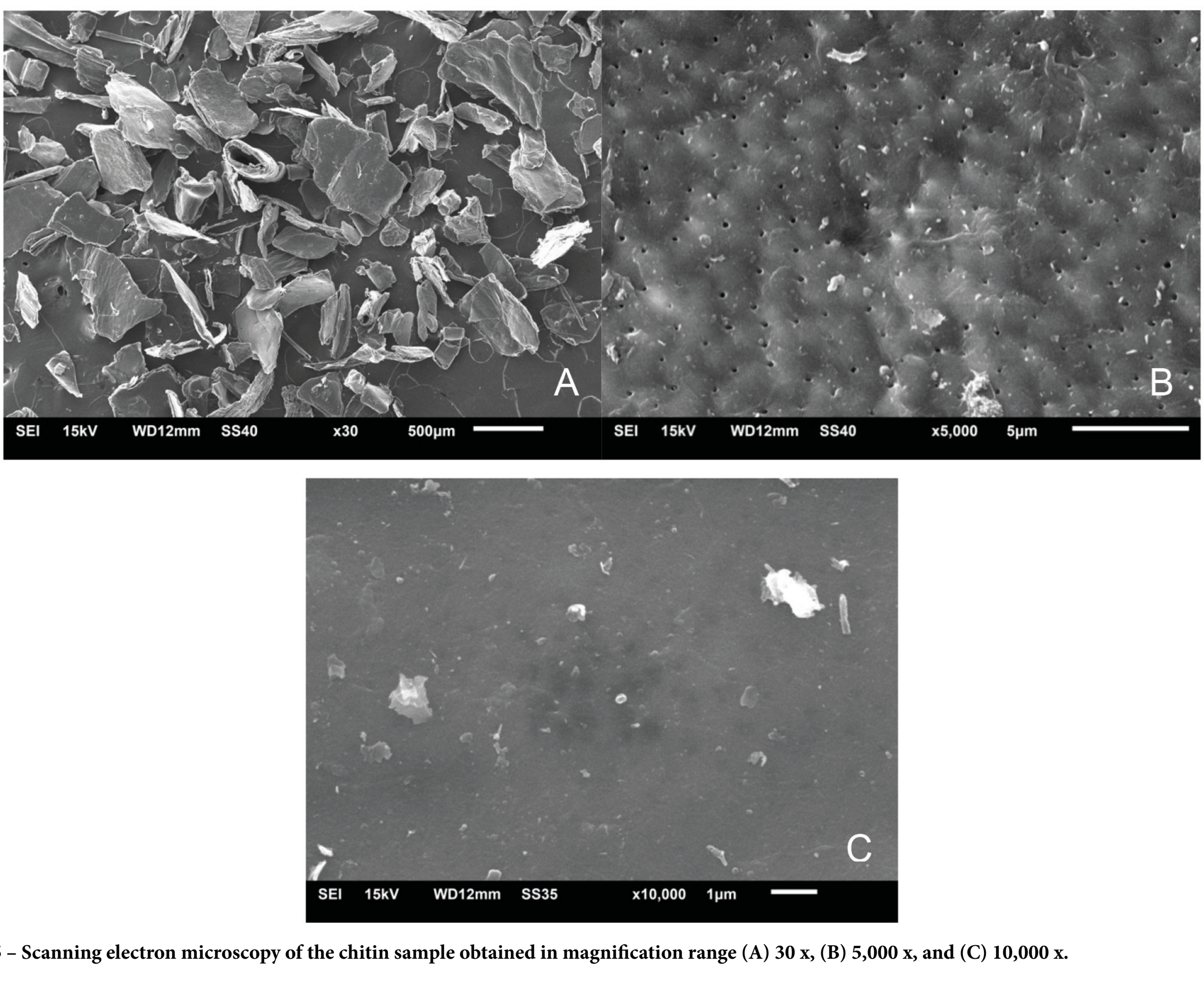

Figure 5 – Scanning electron microscopy of the chitin sample obtained in magnification range (A) 30 x, (B) 5,000 x, and (C) 10,000 x.

more rounded and polygonal shape, in a smaller amount. There was also a large presence of regular and linear faces in the particles, with a low degree of superficial imperfections. And, specifically with the approximation of 5000 times (B), it can be noted that the surface is mostly smooth, but presents a high concentration of pores with very small dimensions, less than 1 nm. This demonstrates that there is still a need for greater treatments to promote chitosan, and that the structures are closer to the chitin format.

Methylene blue adsorption

For the analysis of the results of MB adsorption with different chitins, the percentage of removal was verified at 40 min and at the end of each treatment, i.e., at 240 min of incubation. Finally, the adsorption capacity (q) was verified at 0 and 240 min. The results showed that T3, T4 and T5 obtained the best removal percentages, with 74%, 75% and 74% efficiency in the removal of the dye at the end of incubation, respectively (Figure 6). In addition, treatments T1, T6 and T8 achieved adsorption percentages higher than 50%.

After 240 minutes of incubation, there was a reduction of 58% of the dye with treatment T1 (Figure 6). Treatment T2 demonstrated a removal capacity of 31%. The treatments T3, T4 and T5 did not present desorption until the end of the incubation period. Thus, at the end, the adsorption capacity was verified, which was 2.95 mg g^{-1} for T3, 2.98 mg g^{-1} for T4 and 2.96 mg g^{-1} for T5 (Table 1). Thus, it was observed that there was no significant difference between T3, T4 and T5 regarding the removal percentage.

The maximum adsorption capacity of T7 was 1.33 mg g^{-1}, representing a removal percentage of 34%, and reaching 28% in the total incubation time (Table 1 and Figure 6). For T8, the adsorption capacity in 40 minutes of incubation was 2.33 mg g^{-1}, presenting a removal percentage of 58% at this time and a percentage of 54% at 240 min. The treatments T9, T10 and T11 present, in 40 minutes, the maximum adsorption capacity of 1.21 mg g^{-1}, 1.25 mg g^{-1} and 1.35 mg g^{-1}, respectively. Thus, T9 and T11 presented the same removal percentages of 29%, and T10 had 30% at the beginning of the desorption, but, at 240 minutes, the results were 23% for T9, 21% for T10 and 20% for T11.

Looking exclusively at the statistical analysis presented in Table 1, it is observed that the adsorption capacity data, in 0 and 240 minutes, vary between the different treatments, since the distinct letters in each treatment indicate a differentiation between them, through the analysis by the Tukey test with a probability of error of 5%.

At 0 minutes, the adsorption capacity showed fewer definitions between the variations of the treatments performed, because they present more than one variation, except for T3, T4, T5, T8 and T9. At 240 min, the variations were more defined. Analyzing the results according to the criterion adopted for the regression analysis, similarity, or difference between the methodologies to obtain chitin, it is observed that T1 and T2 differed significantly from each other, as well as T3, T4 and T5 in relation to T6. The statistical similarity occurred between T9, T10 and T11, between T3, T4 and T5, and also when comparing T7 with T2. The coefficient of variation (CV) related to the 11 results represented the variation of the results in relation to the mean, being higher at 0 minutes (22.85%), and lower at 240 minutes (2.92%).

It is observed, therefore, that the results of the regression analysis (Table 1) are close to those of adsorption capacity (q) and adsorption

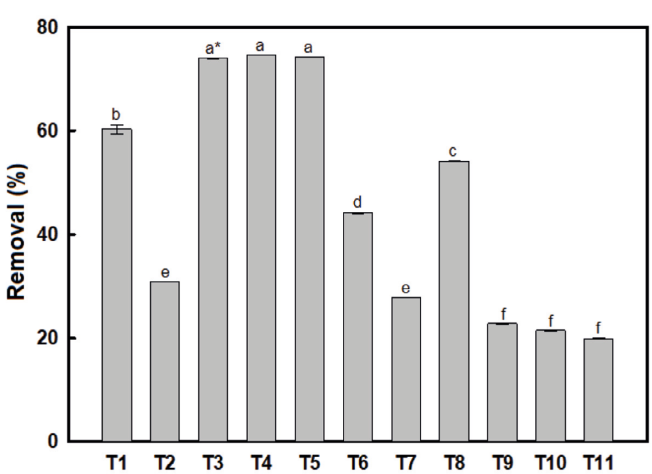

Figure 6 – Percentage of removal of the MB dye from the adsorption tests with chitins obtained from the treatments after 240 minutes of incubation at 160 RPM*.

*Distinct letters represent statistically different treatments by Tukey test with the probability of error of 5%.

Table 1 – Adsorption capacity (mg g^{-1}) of each treatment at 0 minutes and at the end of incubation, at 240 minutes, with the respective statistical analysis*.

Treatment	q in 0 minutes	q in 240 minutes
T1	1.3336 ABC	2.41233 B
T2	1.2330 ABCD	1.23530 E
T3	0.0111 E	2.95840 A
T4	0.0250 E	2.98593 A
T5	0.161 E	2.96763 A
T6	1.4121 AB	1.76647 D
T7	1.0599 BCD	1.11167 E
T8	1.6780 A	2.16447 C
T9	0.6934 D	0.91163 F
T10	0.8238 CD	0.85810 F
T11	0.9698 BCD	0.79700 F
CV	22.85	2.92

*The averages followed by the same letter differ from each other by the Tukey test with a probability of error of 5%; CV: coefficient of variation; CV %: 2.92 at 240 minutes.

percentage (%R), because, for these analyses (q and %R), the best treatments were T3, T4, T5, followed by T1, T8 and T6, and the worst were T9, T10 and T11. The differences between the adsorption capacity in each treatment and the expressiveness of the CV are justified by the methodological variations of chitin. Among the best results of dye adsorption, the methodologies differed only in the concentration of NaClO, which was 0.4%, 1.2% and 2.0% for T3, T4 and T5, respectively. The most efficient methodology was T4, using 1.2% NaClO and adsorption of 75% of dye.

Discussion

The treatments that presented the best results for adsorption were, respectively, those that used chitins of T4, T3 and T5, with results close to 75% and with results higher than 55% in T1, T6 and T8 (Figure 6). These results prove the statement of Ahmed et al. (2020) that chitin, as well as chitosan, has a good adsorption capacity.

The values found in this research were higher than those obtained by: Labidi et al. (2019), with an MB removal between 50% and 60%, through the use of chitosan and chitin; by Dotto et al. (2011) with a 50% removal of textile dyes with chitosan; and Cunico et al. (2015) with a 50% removal from modified fly ash.

However, some studies have achieved higher efficiencies in MB removal, such as: Dotto et al. (2015), with a 85% removal of the dye with shrimp residue; Ahmad and Ansari (2021), who achieved results above 88% in neutral pH, with the use of hybrid clay with modified nanocompost of chitosan; Ma et al. (2016), which reached up to 90% of MB removal by using foam composed of graphene oxide/chitin; Mabel et al. (2019), with an efficiency of 90% of adsorption with crustacean chitin; Lima et al. (2006), with a 97% MB removal with the use of activated carbon; Jorge et al. (2015), which also removed 97% of the initial concentration of MB, but with the use of sugarcane bagasse; Silva et al. (2018), with a removal efficiency of 99% of MB with the use of activated charcoal of ryegrass straw.

Jawad et al. (2020) obtained 90% MB removal efficiency, differing in the methodology applied to the research in time and rotation parameters, from 180 minutes at 110 RPM. The authors verified the highest adsorption capacity of the dye with 31.3 mg g^{-1} in pH 9 solution. Future studies seeking the best efficiency of the adsorbent obtained could be performed, therefore, analyzing pH values distinct from the neutron used, different rotations per minute and different temperatures.

The treatment of textile effluents usually goes through a combination of physical, chemical and/or biological processes. Depending on the process applied, its efficiency and the pollutants present in the effluent, there may be the formation of unwanted by-products, such as halides, metals, acids, aldehydes and sludge generation (Holkar et al., 2016; Khan et al., 2019).

The use of biopolymers produced from shrimp exoskeleton could be evaluated for adsorption of other pollutants, such as heavy metals. Yazidi et al. (2020) and Ma et al. (2016) verified that in addition to MB dye, chitin and chitosan can simultaneously adsorb heavy metals such as molybdenum, lead, cobalt and nickel, elements commonly present in industrial effluents, which demonstrates other potentials for residue application.

For Kostag and Seoud (2021), there should be a search for application of green chemistry, with the use of environmentally benign chemicals, which allow the recycling of solvents. The present study contributes to a relationship of industrial symbiosis, in which there is the return of residues from the fish process as raw material for the process of treatment of another residue, in this case the waste from the textile industry.

Conclusion

Pure chitin obtained from shrimp residues has a high power of adsorption of methylene blue dye, and the research points to an important potential for the use of waste on a commercial scale, in a relationship of industrial symbiosis. In this context, the fishing waste ceases to be an environmental problem and becomes a solution for the treatment of textile effluents, with prospects of economic, social and environmental benefits, enabling employment generation, valorization of the fishing activity and waste management optimization.

This research opens space for studies on the expansion of the adsorption capacity through physical and chemical changes in the adsorbent and combinations of adsorbents. With the methodological differences observed in chitin treatments and their adsorption capacities, an opportunity is observed to improve the processes of obtaining the material.

In addition to providing technological development of materials, the research brings perspectives of socioeconomic benefits to the fishing community, with the use of shrimp residue for the adsorption of other waste from the textile industry, contributing to the sustainability of both activities and reducing the environmental impact.

Contribution of authors:

Otto, I.M.: Data curation, Validation, Visualization, Writing; Morselli, L.B.G.A.: Data curation; BraunBunde, D.A.: Formal analysis; Pieniz, S.: Acquisition of financing; Quadro, M.S.: Methodology; Andreazza, R.: Supervision, Writing – review and editing.

References

Adeeyo, R.O.; Edokpayi, J.N.; Bello, O.S.; Adeeyo, A.O.; Odiyo, J.O., 2019. Influence of selective conditions on various composite sorbents for enhanced removal of copper (II) ions from aqueous environments. International Journal of Environmental Research and Public Health, v. 16, (23), 4596-4614. https://doi.org/10.3390/ijerph16234596.

Ahmad, R.; Ansari, K., 2021. Comparative study for adsorption of congo red and methylene blue dye on chitosan modified hybrid nanocomposite. Process Biochemistry, v. 108, 90-102. http://dx.doi.org/10.1016/j.procbio.2021.05.013.

Ahmed, M.J.; Hameed, B.H.; Hummadi, E.H., 2020. Review on recent progress in chitosan/chitin-carbonaceous material composites for the adsorption of water pollutants. Carbohydrate Polymers, v. 247, 116690-116700. http://dx.doi.org/10.1016/j.carbpol.2020.116690.

Assis, O.B.G.; Brito, D., 2008. Processo básico de extração de quitinas e produção de quitosana a partir de resíduos da carcinicultura. Revista Brasileira de Agrociência. v.14, (1), 91-100. https://doi.org/10.18539/cast.v14i1.1892.

Associação Brasileira da Indústria Têxtil e de Confecção (ABIT). Perfil do Setor. ABIT, 2021 (Accessed March 20, 2021) at: https://www.abit.org.br/cont/perfil-do-setor.

Auta, M.; Hameed, B.H., 2014. Chitosan-clay composite as highly effective and low-cost adsorbent for batch and fixed-bed adsorption of methylene blue. Chemical Engineering Journal, v. 237, 352-361. https://doi.org/10.1016/j.cej.2013.09.066.

Bailey, S.E.; Olin, T.J.; Bricka, R.M.; Adrian, D.D., 1999. A review of potentially low-cost sorbents for heavy metals. Water Research. v. 33, (11), 2469-2479. https://doi.org/10.1016/S0043-1354(98)00475-8.

Bajaj, M.; Freiberg, A.; Winter, J.; Xu, Y.; Gallert, C., 2015. Pilot-scale chitin extraction from shrimp sheik waste by desproteination and decalcification with bacterial enrichment cultures. Applied Microbiology and Biotechnology, v. 99, 9835-9846. https://doi.org/10.1007/s00253-015-6841-5.

Barbosa, R.P., 2014. Avaliação de risco e impacto ambiental. Erica, São Paulo.

Bedin, K.C.; Souza, I.P.A.F.; Cazetta, A.L.; Spessato, L.; Ronix, A.; Almeida, V.C., 2018. CO_2-spherical activated carbon as a new adsorbent for methylene blue removal: kinetic, equilibrium and thermodynamic studies. Journal of Molecular Liquids, v. 269, 132-139. http://dx.doi.org/10.1016/j.molliq.2018.08.020.

Chang, S.H., 2021. Gold(III) recovery from aqueous solutions by raw and modified chitosan: a review. Carbohydrate Polymers, v. 256, 117423. http://dx.doi.org/10.1016/j.carbpol.2020.117423.

Cunico, P.; Kumar, A.; Fungaro, D.A., 2015. Adsorption of dyes from simulated textile wastewater onto modified nanozeolite from coal fly ash. Journal of Nanoscience and Nanoengineering, v. 1, (3), 148-161 (Accessed December 19, 2020) at: http://repositorio.ipen.br/bitstream/handle/123456789/25780/21710.pdf?sequence=1.

Dotto, G.L.; Santos, J.M.N.; Rodrigues, I.L.; Rosa, R.; Pavan, F.A.; Lima, E.C., 2015. Adsorption of Methylene Blue by ultrasonic surface modified chitin. Journal of Colloid and Interface Science, v. 446, 133-140. http://dx.doi.org/10.1016/j.jcis.2015.01.046.

Dotto, G.L.; Vieira, M.L.G.; Gonçalves, J.O.; Pinto, L.A.A., 2011. Remoção dos corantes azul brilhantes, amarelo crepúsculo e amarelo tartrazina de soluções aquosas utilizando carvão ativado, terra ativada, terra diatomácea, quitina e quitosana: estudo de equilíbrio e termodinâmica. Química Nova, v. 34, (7), 1193-1199. https://doi.org/10.1590/S0100-40422011000700017.

Dragnes, B.T.; Stormo, S.K.; Larsen, R.; Ernstsen, H.H.; Elvevoll, E.O., 2009. Utilisation of fish industry residuals: screening the taurine concentration and angiotensin converting enzyme inhibition potential in cod and Salmon. Journal of Food Composition and Analysis, v. 22, (7-8), 714-717. https://doi.org/10.1016/j.jfca.2009.01.020.

Ferreira, O.P.; Alves, O.L.; Macedo, J.S.; Gimenez, I.F.; Barreto, L.S., 2007. Ecomateriais: desenvolvimento e aplicação de materiais porosos funcionais para proteção ambiental. Química Nova, v. 30, (2), 464-467. https://doi.org/10.1590/S0100-40422007000200039.

Frantz, T.S.; Silveira Jr., N.; Quadro, M.S.; Andreazza, R.; Barcelos, A.A.; Cadaval Jr., T.R.S.; Pinto, L.A.A., 2017. Cu (II) Adsorption from copper mine water by chitosan films and the matrix effects. Environmental Science and Pollution Research International, v. 24, (6), 5908-5917. https://doi.org/10.1007/s11356-016-8344-z.

Holkar, C.R.; Jadhav, A.J.; Pinjari, D.V.; Mahamuni, N.M.; Pandit, A.B., 2016. A critical review on textile wastewater treatments: possible approaches. Journal of Environmental Management, v. 182, 351-366. https://doi.org/10.1016/j.jenvman.2016.07.090.

Honório, L.M.C.; Lucena, G.L.; Silva, A.G.; Santos, V., 2014. Avaliação da adsorção dos corantes azul de metileno (AM) e vermelho congo (VC) pela quitosana reticulada com glutaraldeído. Revista de Química Industrial, 3º trimestre, 35-40 (Accessed January 17, 2021) at: http://www.abq.org.br/rqi/2014/744/RQI-744-pagina35.pdf.

Jawad, A.H.; Abdulhameed, A.S.; Reghioua, A.; Yaseen, Z.M., 2020. Zwitterion composite chitosan-epichlorohydrin/zeolite for adsorption of methylene blue and reactive red 120 dyes. International Journal of Biological Macromolecules, v. 163, 756-765. http://dx.doi.org/10.1016/j.ijbiomac.2020.07.014.

Jorge, I.R.; Tavares, F.P.; Santos, K., 2015. Remoção do corante azul de metileno no tratamento de efluentes por adsorção em bagaço de cana de açúcar. Blucher Chemical Engineering Proceedings, v. 2, (1), 491-500. https://doi.org/10.5151/ENEMP2015-LE-730.

Khan, S.; Anas, M.; Malik, A., 2019. Mutagenicity and genotoxicity evaluation of textile industry wastewater using bacterial and plant bioassays. Toxicology Reports, v. 6, 193-201. https://doi.org/10.1016/j.toxrep.2019.02.002.

Kostag, M.; Seoud, O.A. El., 2021. Sustainable biomaterials based on cellulose, chitin and chitosan composites: a review. Carbohydrate Polymer Technologies and Applications, v. 2, 100079. http://dx.doi.org/10.1016/j.carpta.2021.100079.

Kumaran, S.; Anahas, A.M.P.; Prasannabalaji, N.; Karthiga, M.; Bharathi, S.; Rajasekar, T.; Joseph, J.; Prasad, S.G.; Pandian, S.; Pugazhvendan, S.R.; Aruni, W., 2021. Chitin derivatives of NAG and chitosan nanoparticles from marine disposal yards and their use for economically feasible fish feed development. Chemosphere, v. 281, 130746. https://doi.org/10.1016/j.chemosphere.2021.130746.

Labidi, A.; Salaberria, A.; Fernandes, S.; Labidi, J.; Abderrabba, M., 2019. Functional chitosan derivative and chitin as decolorization materials for methylene blue and methyl orange from aqueous solution. Materials, v. 12, (3), 361. http://dx.doi.org/10.3390/ma12030361.

Lima, I.S.; Ribeiro, E.S.; Airoldi, C., 2006. O emprego de quitosana quimicamente modificada com anidrido succínico na adsorção de azul de metileno. Química Nova, v. 29, (3), 501-506. https://doi.org/10.1590/S0100-40422006000300018.

Lobo-Recio, M.Á.; Lapolli, F.R.; Belli, T.J.; Folzke, C.T.; Tarpani, R.R.Z., 2013. Study of the removal of residual aluminum through the biopolymers carboxymethylcellulose, chitin, and chitosan. Desalination and Water Treatment, v. 51, (7-9), 1735-1743. http://dx.doi.org/10.1080/19443994.2012.715133.

Longhinotti, E.; Furlan, L.; Laranjeira, M.C.M.; Fávere, V.T., 1996. Adsorção de azul de metileno e croconato amarelo sobre o biopolímero quitina. Química Nova, v. 19, (3), 221-223 (Accessed December 22, 2020) at: http://quimicanova.sbq.org.br/detalhe_artigo.asp?id=4056

Ma, Z.; Liu, D.; Zhu, Y.; Li, Z.; Li, Z.; Tian, H.; Liu, H., 2016. Graphene oxide/chitin nanofibril composite foams as column adsorbents for aqueous pollutants. Carbohydrate Polymers, v. 144, 230-237. http://dx.doi.org/10.1016/j.carbpol.2016.02.057.

Mabel, M.M.; Sundararaman, T.R.; Parthasarathy, N.; Rajkumar, J., 2019. Chitin Beads from Peneaus sp. Shells asa Biosorbent for Methylene Blue Dye Removal. Polish Journal of Environmental Studies, v. 28, (4), 2253-2259. http://dx.doi.org/10.15244/pjoes/90359

Müller, L.C.; Alves, A.A.A.; Mondardo, R.I.; Sens, M.L., 2019. Adsorção do azul de metileno em serragem de *Pinus elliottii* (pinus) e *Drepanostachyum falcatum* (bambu). Engenharia Sanitária e Ambiental, v. 24, (4), 687-695. http://dx.doi.org/10.1590/s1413-41522019160344.

Oliveira, F.M.; Coelho, L.M.; Melo, E.I., 2018. Avaliação de processo adsortivo utilizando mesocarpo de coco verde para remoção do corante azul de metileno. Matéria, v. 23, (4), 1-14. http://dx.doi.org/10.1590/s1517-707620180004.0557.

Queiroz, M.T.A.; Queiroz, C.A.; Alvim, L.B.; Sabará, M.G.; Leão, M.M.D.; Amorim, C.C., 2019. Reestruturação na forma do tratamento de efluentes têxteis: uma proposta embasada em fundamentos teóricos. Gestão & Produção, v. 26, (1), 1-14. http://dx.doi.org/10.1590/0104-530x1149-19.

Ribeiro, A.G.; Viana, M.; Hattori, G.; Constantino, V.R.; Perotti, G., 2018. Extraction and characterization of biopolymers from exoskeleton residues of the amazon crab *Dilocarcinus pagei*. Brazilian Journal of Environmental Sciences, v. 50, 97-111. https://doi.org/10.5327/Z2176-947820180398.

Sabar, S.; Aziz, H.A.; Yusof, N.H.; Subramaniam, S.; Foo, K.Y.; Wilson, L.D.; Lee, H.K., 2020. Preparation of sulfonated chitosan for enhanced adsorption of methylene blue from aqueous solution. Reactive and Functional Polymers, v. 151, 104584. http://dx.doi.org/10.1016/j.reactfunctpolym.2020.104584.

Sánchez, L.E., 2013. Avaliação de impacto ambiental: conceitos e métodos. 2. ed. Oficina de Textos, São Paulo.

Shan, H.; Peng, S.; Zhao, C.; Zhan, H.; Zeng, C., 2020. Highly efficient removal of As(III) from aqueous solutions using goethite/graphene oxide/chitosan nanocomposite. International Journal of Biological Macromolecules, v. 164, 13-26. http://dx.doi.org/10.1016/j.ijbiomac.2020.07.108.

Silva, E.O.; Andrade, T.D.; Araújo, E.B.; Zottis, R.; Almeida, A.R.F., 2018. Produção de carvão ativado a partir da palha de azevém para adsorção de corante têxtil. Congrega Urcamp, v. 15, (15), 194-208 (Accessed February 15, 2021) at: http://revista.urcamp.tche.br/index.php/rcjpgp/article/view/2814/1923.

Vieira, S. Análise de variância (ANOVA). Atlas, São Paulo, 2006, 204 pp.

Wan, M.; Qin, W.; Lei, C.; Li, Q.-H.; Meng, M.; Fang, M.; Song, W.; Chen, J.; Tay, F.; Niu, L., 2021. Biomaterials from the sea: future building blocks for biomedical applications. Bioactive Materials, v. 6, (12), 4255-4285. http://dx.doi.org/10.1016/j.bioactmat.2021.04.028.

Wang, L.; Zhang, J.; Wang, A., 2011. Fast removal of methylene blue from aqueous solution by adsorption onto chitosan-g-poly (acrylic acid)/attapulgite composite. Desalination, v. 266, (1-3), 33-39.

Yazidi, A.; Sellaoui, L.; Badawi, M.; Dotto, G. L.; Bonilla-Petriciolet, A.; Lamine, A.B.; Erto, A., 2020. Ternary adsorption of cobalt, nickel and methylene blue on a modified chitin: phenomenological modeling and physical interpretation of the adsorption mechanism. International Journal of Biological Macromolecules, v. 158, 595-604. http://dx.doi.org/10.1016/j.ijbiomac.2020.05.022.

Zhao, M.; Zhao, J.; Huang, Z.; Wang, S.; Zhang, L., 2019. One pot preparation of magnetic chitosan-cystamine composites for selective recovery of Au(III) from the aqueous solution. International Journal of Biological Macromolecules, v. 137, 721-731. http://dx.doi.org/10.1016/j.ijbiomac.2019.07.022.

ABES

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Effects of funding on the collaboration and citation in environmental papers and the relationship with nation’s science and technology budgets

Efeitos do fomento sobre a colaboração e citação de artigos da área ambiental e as relações com orçamentos nacionais de ciência e tecnologia

João Carlos Nabout[1], *Ruan Carlos Pires Faquim*[1], *Rodrigo Assis Carvalho*[1], *Karine Borges Machado*[1]

ABSTRACT

Input, output, impact, and processes are central indicators of the science, technology, and innovation production. The input is usually associated to investments made in science and technology, and it varies among different countries and scientific fields. Thus, the input can influence other impact indicators. Here, we evaluated the effect of the input data (i.e., number of funding) on process (i.e., collaboration) and output (i.e., number of citation) indicators of ecological research. Moreover, we detailed the effect of the number of funding on the collaboration and number of citations by each country (based on the nationality of authors). We found that most of published papers had some degrees of financial support, and that the production of papers with funding increased over the years. Funding had a positive effect on the collaboration and citation of papers; however, we observed that: in countries with higher investments in Science and Technology, the number of funding impacts positively and directly on the number of authors (collaboration) and in countries with low levels of investments in Science and Technology, the number of funding impacts positively and directly on the number of citations. Our models presented a low predictive power, but similar to other informetric studies. Our results indicated that impact indicators evaluated have an integrated structure, and the effects at one level can affect other levels. Nonetheless, the impact of the number of funding on informetric data can vary among countries; therefore, these results are important to the development of national policies and future informetric studies.

Keywords: number of authors; collaboration; citation; environmental science; structural equation modeling.

RESUMO

Dados de entrada (*input*), saída (*output*), impacto e processos são indicadores centrais da produção em Ciência, Tecnologia e Inovação. O *input* está associado aos investimentos realizados em ciência e tecnologia, podendo variar entre diferentes países e áreas científicas. Assim, o *input* pode influenciar outros indicadores de impacto. Aqui, avaliamos seu o efeito (número de financiamentos) sobre o processo de colaboração e o número de citações (*output*) da pesquisa ecológica. Além disso, detalhamos o efeito do número de financiamentos sobre a colaboração e o número de citações por país (baseado na nacionalidade dos autores). Verificamos que a maioria dos artigos publicados tinha algum grau de suporte financeiro, e que a produção de artigos com financiamento aumentou ao longo dos anos. O número de financiamentos teve efeito positivo na colaboração e nas citações, porém observamos que: nos países com maior investimento em ciência e tecnologia, o número de financiamentos impacta positivamente e diretamente a colaboração (número de autores); e nos países com menor investimento em ciência e tecnologia, o número de financiamentos impacta positivamente e diretamente as citações. Nossos resultados demonstram que os indicadores de impacto avaliados têm estrutura integrada e os efeitos em um nível podem afetar outros níveis. Entretanto, o impacto do número de fomentos nos indicadores informétricos pode variar entre os países, portanto esse resultado é importante para o desenvolvimento de políticas nacionais e para futuros estudos informétricos.

Palavras-chave: número de autores; colaboração; citação; ciências ambientais; modelagem de equações estruturais.

[1]Universidade Estadual de Goiás – Anápolis (GO), Brazil.

Correspondence address: João Carlos Nabout – BR 153 – Km 99, 3105 – Fazenda Barreira do Melo – CEP: 75132-903 – Anápolis (GO), Brazil. E-mail: joao.nabout@ueg.br

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Introduction

Indicators of the scientific, technological, and innovative production can be divided into one of the following four groups: input, output, impact, and processes (Moed, 2017). The input refers to investments done in science and technology (Geisler, 2000), and this component has an important contribution to the development of research stages (Lewison and Dawson, 1998). However, input is highly variable among different countries and scientific fields (May, 1998), a phenomenon that creates asymmetries during the stages of the scientific production and, consequently, on impact indicators, such as the number of: articles produced, citations, and acknowledgments referring to project funding (Fortin and Currie, 2013; Rigby, 2013). Other worldwide studies have also explored citation and co-citation, collaboration among authors, impact factor, and h-index among informetric indicators to evaluate the stages of the scientific process (Bar-Ilan, 2008; Mena-Chalco et al., 2014; Nabout et al., 2015; Parreira et al., 2017). Therefore, an important and crucial step to science relies on understanding how investments made in the scientific process are affecting these parameters in different scales, countries, and fields of knowledge.

Funding resources to scientific research are granted by private or public agencies and sectors; however, investments in basic scientific research for most countries come from public resources (Wang et al., 2012). These funding grants contribute to the formation of human resources via scholarships, improvement of laboratorial infrastructure via acquisition of new equipment, creation of research networks with exchange between researchers, and the development of new technologies and patents. Thus, investments in science, technology, and innovation can directly affect other impact indicators, such as citations (output), and number of co-authors and collaboration (processes; Zhao et al., 2018). This situation reinforces the importance of investigating the impacts of funding on scientific processes.

Studies reporting the influence of funding on output data goes back to 1990s (Lewison and Dawson, 1998; Rigby, 2013), but its main use in the informetric literature increased only in the past few years (Paul-Hus et al., 2016; Tang et al., 2017; Mejia and Kajikawa, 2018). This scenario occurred because information about funding resources related to scientific papers was recently included in different databases (e.g., Scopus and Clarivate Analytics databases). Moreover, the validity and the importance of funding data available in the Web of Science (2009) were reported by several other papers (for more details, see Paul-Hus et al., 2016).

The effect of funding on different impact indicators of the scientific production can be represented following one simple association structure, i.e., the number of funding stimulates the collaboration among scientists (more authors involved in the scientific process), and both funding and collaboration produce more papers with a higher level of citations (see Padial et al., 2010; Tahamtan et al., 2016). Nonetheless, considering that the number of funding granted is dependent of the investment level made in science and technology, this association structure describing the effect of funding on impact indicators of the scientific production may vary among different countries (Wang et al., 2012). In fact, many studies have shown that funding has a positive impact on different impact factors of the scientific production, but this effect is not as strong as expected (Jacob and Lefgren, 2011; Fortin and Currie, 2013; Rigby, 2013; Yan et al., 2018). Therefore, understanding the effects of funding on the collaboration and citations of the scientific production from different countries and research fields is a challenge for current scientometric research field and for science in general. Given that the number of ecological studies has increased in the last decades and its global production is affected by geographical and socioeconomic factors (Parreira et al., 2017), it is fundamental to understand how financial support affects impact factors in this research field and if this relationship follows the same patterns observed for other areas.

The aim of this study was to reveal the effect of the input data (number of funding) on process (collaboration) and output (number of citation) of the ecological research field. Moreover, considering the differences of science and technology investments among distinct countries, we detailed the effect of funding on collaboration and number of citations by each country (based on the nationality of authors). We hypothesized that "if ecological research follows the same patterns observed for other scientific fields, papers with a higher number of funding will present a higher number of authors and citations, but with a weak effect size." Moreover, we also investigated whether the number of authors together with the number of funding can affect directly the number of article citations. For this purpose, we evaluated scientific papers of the ecological research field selected from the WoS database using the structural equation modeling (SEM) approach. Therefore, despite several studies in the scientific literature have investigated the influence of funding on collaboration and number of citations (e.g., Jacob and Lefgren, 2011; Fortin and Currie, 2013; Rigby, 2013; Yan et al., 2018), the new aspects of our study rely on: investigating a new and productive research field; evaluating this relationship considering the nationality of the authors; and applying a new methodological approach to reveal direct and indirect effects of funding.

Material and Methods

Funding data in WoS

Funding data presented in WoS from Clarivate Analytics have three different fields: "Funding Text" (FT), "Funding Agency" (FO), and "Grant Number" (FG). FT returns the full text written by authors in the Acknowledgments section of their article(s). FO gives the name of agencies and organizations cited in the FT field. FG indicates grant numbers, which are associated with both FO and FT fields. Thus, FG represents all kinds of funding received by authors, and sometimes many of these grants are from the same agency. In this study, we used funding data information from the FG field. We choose to use only WoS from Clarivate Analytics because it has a long temporal range for funding information (since 2009), and to standardize this type of data since distinct databases may present a different number of citations for the same paper.

Data collection

We selected all papers published in the category "Ecology" between 2010 and 2016, considering all scientific journals indexed in WoS. We started our search in 2010 because from that year our database was complete (i.e., funding data was available to all papers). We selected Ecology because it is a broad scientific area that is composed of professionals from various subareas with distinct histories and scientific behaviors (e.g., Neff and Corley, 2009; Nabout et al., 2015; Parreira et al., 2017). Moreover, with the growing concern to maintain global biodiversity and sustainable environmental policies, resources from public and private agencies have been allocated to ecological research. Therefore, there is a demand of the civil society for evaluating the effect of scientific investments on the informetric impact indicators (e.g., production of articles, citation, and collaboration, among others) of the ecological research field.

We searched the papers in the WoS from Clarivate Analytics ISI database (searched in December of 2017), using index SCI-Expand and SSCI. For this study, we selected only original articles, and the following data were obtained from each paper:

- number of funding grants, indicated by FG;
- time of publication (number of years after the publication);
- number of authors;
- number of citations;
- nationality of all authors.

For nationality, if all authors were from same country, the paper was classified as national collaboration, and if at least two authors were from different countries the paper was classified as international collaboration. This is especially important to analyze the influence of funding in national collaboration papers (see below). All papers used in this study and their classification (number of funding, number of authors, nationality, etc.) are available in Supplementary file (ESM 1).

Investments in science, technology, and innovation (STI) were obtained for 55 countries of our database (corresponding to 69,430 papers, or 97% of total national collaboration papers). Investments in STI correspond to the investment in dollars by habitants and it was obtained in the database of the Organisation for Economic Co-operation and Development (OECD, www.data.oecd.org). The STI has been used by informetric papers (e.g., Cimini et al., 2016; Dranev et al., 2018), and it usually indicates the national policy of investment in science, including resource to infrastructure and scholarships, among others (OECD, 2017).

Data analysis

We used the SEM to investigate the effects of input indicators on output and processes of indicators, determining their direct and indirect effects. The SEM has been widely used in different research fields of science (e.g., Bag, 2015; Lefcheck, 2016; Shaheen et al., 2017), and, for particular questions of the present paper, the advantage of using SEM, instead the traditional linear regression model or other statistical tests, is because it considers the structural association among predictor variables. This association is based on a conceptual model of the research. We elaborated the conceptual model based on the idea that direct effects are observed from input data on the process and output of literature, and from process on the output (Figure 1). According to this conceptual model, we are capable of identifying relationships among latent variables which can be represented by many observation variables. In the present study, we used three types of observation variables to indicate the input, output, and process latent variables: number of funding, number of citation, and number of authors (indicating scientific collaboration), respectively. For citation, we divided the number of citations of a given paper by the time of publication to control the effect of the time on the number of citations. According to our hypothesis, all coefficients (a, b, and c) in SEM will be positive, indicating a positive effect of the number of funding on the number of authors and citations. Moreover, we expected to find a positive effect of the number of authors on citations. All variables used in SEM were log-transformed (logX+1), and all coefficients were standardized, thus the variables (number of funding, number of authors, and citations) were transformed to variables with mean of zero and standard deviation of one.

The evaluation of SEM was based on Tucker–Lewis Index (TLI), ranged between 0 and 1.0, with best fit found at 1.0. A value of TLI higher than 0.9 indicates an excellent model (Hu and Bentler, 1999). We selected this index because it is independent of the sample size (Bentler, 1990; Fan et al., 2016). Assumptions of the SEM are similar to those made in linear regression models; therefore, it is necessary to deal with normality of variables, independence of sampling unities, and homoscedasticity. Considering that informetric data often have a skewed distribution, we used the bootstrap approach to solve this problem (see Ory and Mokhtarian 2010; Knief and Forstmeier, 2021). In the present study, we used to each SEM 1000 bootstrap and the estimator was the maximum likelihood.

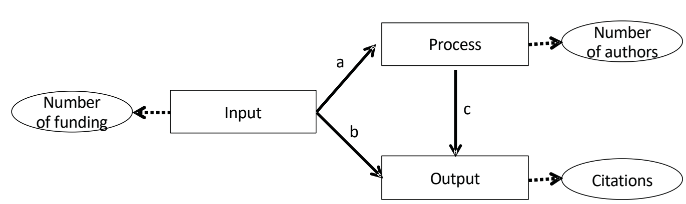

Figure 1 – Structural modeling. Boxes represent latent variables and circles represent observation variables. The relationship is indicated by solid arrows. (A) The input can affect directly the process and (B) the output. (C) The process can affect the output.

In SEM, the main unity of analysis was the paper, and we proposed four SEMs for the following scenarios:

- all papers in the same analysis;
- national papers, performing the analysis with papers where all authors are from same country;
- international papers, performing the analysis with papers where all authors are from different countries;
- papers by country (authors from same country presented in protocol 2).

Posteriorly, we related the coefficients (a, b, and c of the SEM) with the investment in STI of each country.

We performed a linear regression to investigate if the three coefficients described in SEM analyses were associated with the investments in science of evaluated countries. The significance of each regression slope was tested according to a null model using 999 iterations during a Monte Carlo procedure (Manly, 2006).

The SEM was performed using the function "sem" in package "lavaan" (Rosseel, 2012), and for linear regression models was the function "lm" of package "stat," both in software R (R Core Team, 2021).

Results

We found a total of 116,589 papers of Ecology indexed in the WoS, of which 71,028 (61%) of the papers with national collaboration and 45,561 (39%) of the papers with international collaboration. We also found that the number of ecological papers published increased over the years and the growth rate of papers with international collaboration is higher than the observed rate for papers with national collaboration, even though the number of papers with national collaboration was higher (Figure 2).

Our findings demonstrated that approximately 82.8% of all papers published had at least one source of funding, and an increase in the number of papers with funding along the temporal series was considered. For example, in 2010, a total of 78.9% of papers had at least one funding, whereas in 2016, the number of papers with funding increased to 85.1% (Figure 3). Additionally, the temporal trend of papers with more than one funding has increased over the years, whereas the number of papers without funding has decreased (Figure 3).

The SEM using all papers showed that the number of funding has a positive effect on the number of authors and citations (Figure 4A). In details, the number of funding presented a positive direct effect on the number of authors and a positive indirect effect on the number of citations. The direct effect of funding on citations was lower (considering the coefficient), but in general all models presented a low predictive power (R^2, Figure 4A). We divided the dataset into papers with authors from same country (namely, national collaboration) and papers with authors from different countries (namely, international collaboration). Overall, the SEMs for national (Figure 4B) and international collaboration presented the same pattern of global data (Figure 4C).

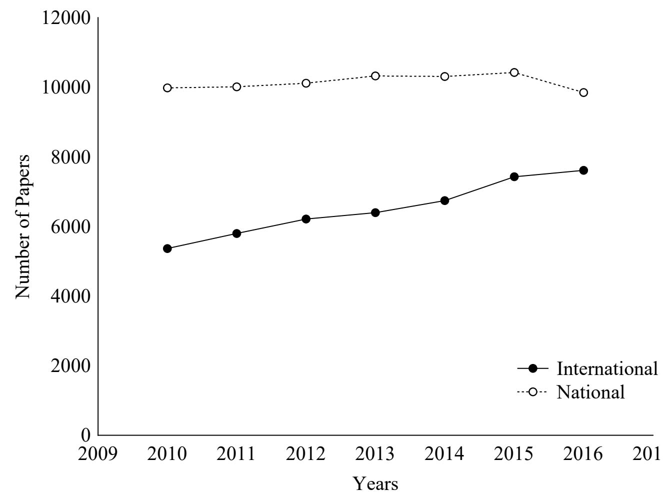

Figure 2 – Number of papers along the years considering the nationality of authors, where "international" indicates authors from different countries, and "national" indicates all authors from the same country.

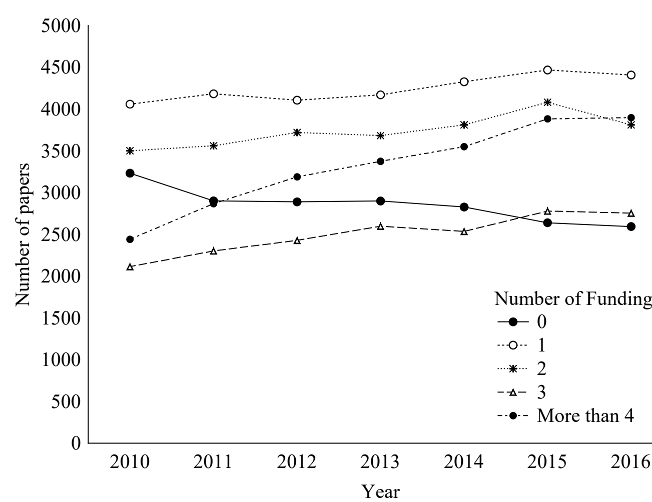

Figure 3 – Number of funding by papers along the years. Scientific papers were divided into five categories, according to the number of funding registered.

However, international collaboration presented a higher R^2, highlighting the importance of international collaboration in these informetric indicators. All SEMs (global, national, and international) presented excellent models (TLI = 1).

We also used SEM to evaluate the effect of the number of funding on number of authors and citations of papers by each country separately (using only papers with authors from the same country). We obtained SEM coefficients (a, b, and c) for the 55 most productive countries evaluated (see the results for each country in the ESM2). For all countries, there was a predominance of positive co-

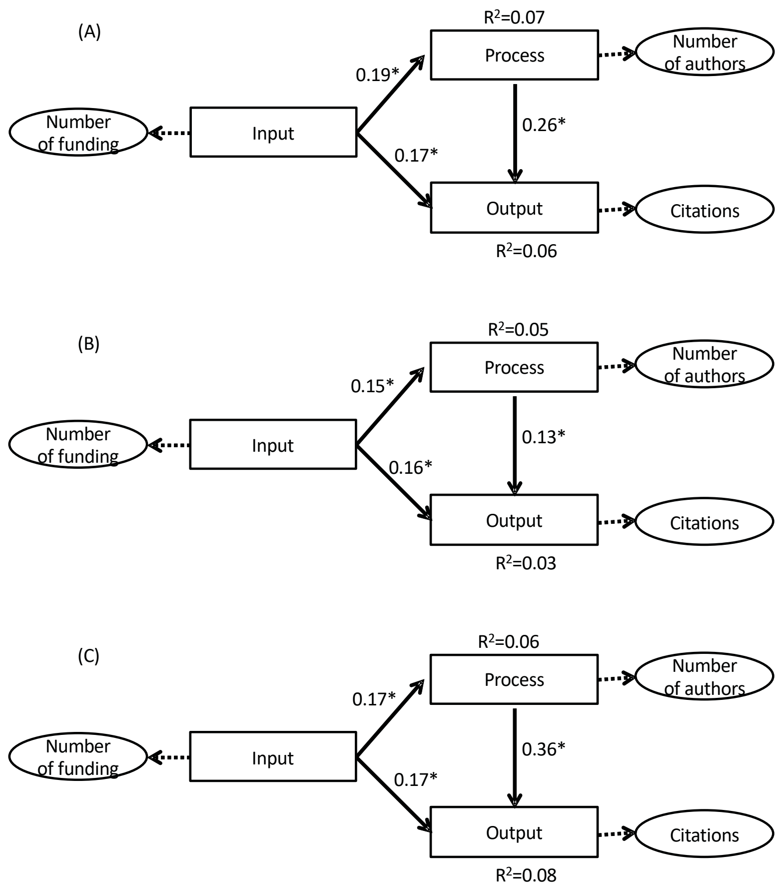

Figure 4 – SEM with standardized coefficient (solid arrows) using all papers. Boxes represent latent variables and circles represent observed variables used in present study. Papers used in SEM were analyzed considering: (A) papers with national (authors from the same country) and international (authors from different countries) collaboration, representing all our dataset; (B) papers with national collaboration; and (C) papers with international collaboration.
*p < 0.001.

efficients; in addition, there was variation in the coefficients among countries grouped based on the categories of investment investigated. For the coefficient a, which measures the influence of the input (number of funding) on the process (number of authors), it was observed that countries with the highest investments presented the highest coefficients a (R^2adj = 0.27; $p < 0.001$; Figure 5A). It means that papers with more authors were those with a greater number of funding, and this fact was more recurrent in countries with higher levels of investment in STI. In contrast, the coefficient b that measures the influence of the input (number of funding) on the output (number of citations) was higher in countries with lower investments in STI, indicated by the negative slope of linear regression (R^2adj = 0.06; $p < 0.03$; Figure 5B). The coefficient c that measures the influence of the process on citations was positive indicating that it is more frequent in countries with high investments on STI that papers with more authors present a greater number of citations (R^2adj = 0.17; $p = 0.001$; Figure 5C). These results showed that funding can have different impacts on informetric indicators, depending on the amount of investments in STI. In countries with high investments in STI, the number of funding affects directly the number of authors and indirectly the number of citations; whereas in countries with low investments in STI, the number of funding affects directly the number of citations of papers.

Discussion

The present study evaluated the influence of the number of funding on the collaboration among scientists and citation of scientific articles in ecological research; in addition, this effect was disentangled based on different countries and their level of investments in STI. Our main results indicate that the number of funding in ecological papers increased along the years, and we also detected a positive effect of the number of funding on number of authors and citations of papers. Nonetheless, deconstructing these effects per country revealed that countries with a higher degree of financial investments in STI maintained a similar relationship with the global data production of papers. In contrast, countries with a lower degree of investments in STI showed

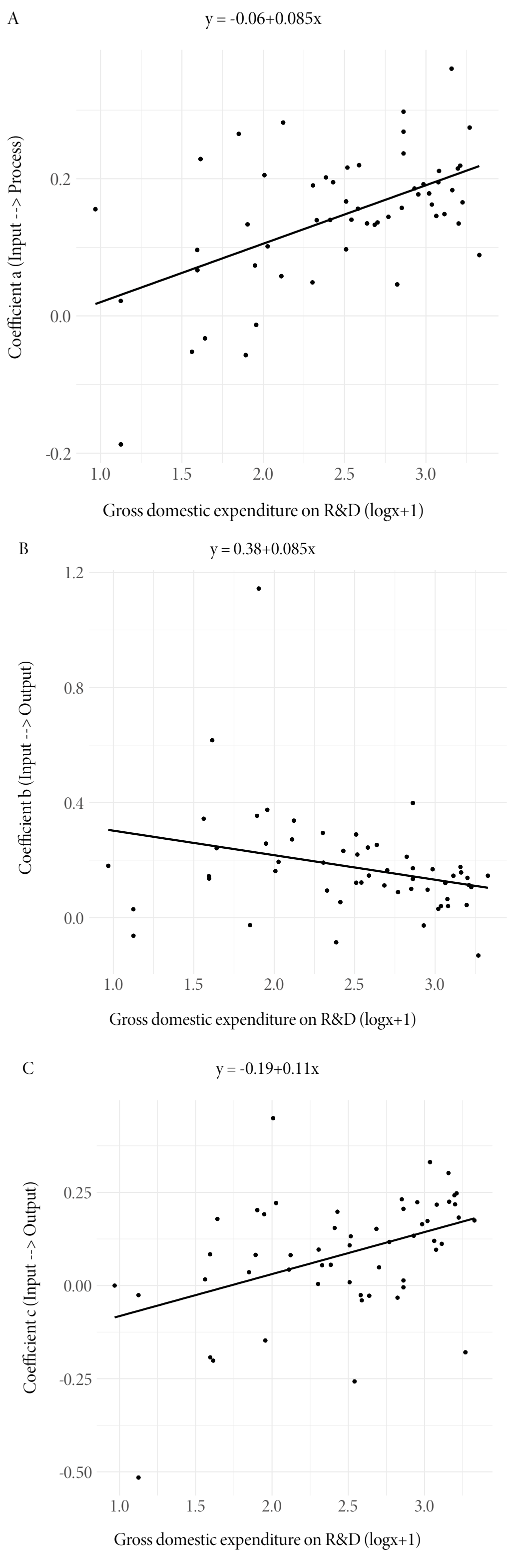

Figure 5 – Scatterplot of each coefficient obtained in SEM and the country investment in science, technology, and innovation. (A) Coefficient a of the SEM, indicating the effect of funding on the number of authors; (B) coefficient b of the SEM, indicating the effect of funding on the number of citations; and (C) coefficient c of the SEM, indicating the direct effect of the number of authors and the indirect effect of the number of funding on the number of citations.

that the number of funding impacts citations positively and directly. Therefore, future papers aiming to investigate the number of funding and its influences on informetric parameters of impact must consider the nationality of co-authors, once funding policies and absolute values invested in STI vary among countries.

Despite the positive impact of research funding on several impact indicators of the scientific production, recent studies also showed that this effect is not high (Jacob and Lefgren, 2011; Fortin and Currie, 2013; Rigby, 2013; Yan et al., 2018). Our findings indicate that this trend is also observed for ecological research, and, additionally, there is a positive relationship between the number of authors and citations, as also found by other authors (Leimu and Koricheva, 2005b; Padial et al., 2010). Several factors, such as presence of positive results (Leimu and Koricheva, 2005b; Fanelli, 2013), larger network of collaboration (Leimu and Koricheva, 2005a; Yu et al., 2014; Parreira et al., 2017), high number of pages (Bornmann et al., 2014), visibility of papers (open-access papers are more cited; Xia et al., 2011), visibility at online social media (Nabout et al., 2018), publication in prestige journals (Vanclay, 2013), among others (see Tahamtan et al., 2016; Bai et al., 2019), may affect the number of citations and authors of a paper. Given that we did not include all these variables in our models, this may explain their low predictive power. Therefore, in absolute values, the R^2 was low; however, considering the few number of variables used, we concluded that the number of funding can be an important variable affecting informetric data.

The number of funding is an important indicator of the input, and it is recognized that the diversity of funding agencies and types of funding (research investments, scholarships, and exchange) can strengthen the scientific research and promotes an increase on the collaboration among authors and citation of articles (Bowen and Casadevall, 2015; Tahamtan et al., 2016). In the same way, the absolute value invested by research or papers can affect other informetric indicators (e.g., Leydesdorff et al., 2019). In fact, in the present study, it is not possible to determine the total value invested on each paper, and thus the metric number of funding is an indicator of the diversity of investments for a given article. Therefore, an article with more funding sources has a greater capacity for authors to raise funds for research. In this sense, we demonstrated that articles with the highest number of funding were those with the highest number of authors and citations.

Investments in science have historically raised knowledge and promoted innovation and social and economic growth (Lane and Bertuzzi, 2011). However, each country has its own idiosyncrasies related to how much it invests in scientific development, reflecting in a different number of researchers per country, and/or in consolidated and stable sources of funds. These differences exist even in time of crisis when each country decides how to invest in science and technology. For example, the European Union countries increase their investment in science during the period of economic crisis (e.g., Makkonen, 2013), while Brazil has experienced an economic recession and political crisis which has impacted in the investments in STI (Angelo, 2019; Thomé and Haddad, 2019). Considering these historical differences among countries, the number of funding (and also the raw amount of resources invested) generates different impacts on science and processes of collaboration and citations of scientific papers. Here, we demonstrated that the number of funding affected positively the number of collaborations in countries with greater investments in STI (usually developed countries), whereas the number of funding was positively related to the number of citations in countries with lower number of investments. These differences influence on the dynamics of science in countries.

In developed countries with greater investments in STI, the competitiveness per resource to promote research is higher. Therefore, larger groups of authors increase the chance of raising funds (Lewison and Dawson, 1998). In contrast, in countries with fewer investments, funding increases the quality of the scientific paper produced, impacting on the number of citations. Evidently, related mechanisms cannot be explained by few variables. The relationship between investments and number of citations can be influenced by several aspects, such as funding sources (national or international), their variety (number of funders), and intensity (Gök et al., 2016). Besides funding, numerous other factors can be determinants for citations (Padial et al., 2010). Therefore, this study took a step forward in detecting the influence of the number of funding on informetric indicators according to countries and their level of investment in STI.

The effect of the number of funding on informetric indicators also highlights the importance of investments in STI to improve indicators of collaboration and citations of papers. Collaboration has been an important element in increasing the quantity and quality of science. In fact, studies have shown that the number of papers with international collaboration has increased over the years (Parreira et al., 2017), and that the mobility of researchers promotes an increase in the quality of the papers produced (Sugimoto et al., 2017). This mobility involves investment; therefore, the lack of investment can limit collaboration between researchers. Some countries have been promoting specific calls for mobility (national and international), for example, the program Erasmus Mundus (Europe Union), British Council with State of Brazilian Government, among others.

Conclusion

The present paper demonstrates that effects at one level of the informetric indicator can affect other indicators and levels. Moreover, we highlight that the impact of the number of funding can vary among countries, therefore, these results are important to the development of national policies and future informetric studies. To national policy, the number of funding can affect directly or indirectly the number of citations and this structure depends of the level of investments in STI made by each country. In countries with higher investments in STI, we found that funding affects directly the number of collaboration and indirectly the number of citation; whereas in countries with fewer investments in STI, funding affects directly the number of citations. To future informetric studies, we recommend the inclusion of author's nationality when investigating the funding effect. Although our conclusions were based on ecological data, we believe that other biological, medical, physic and chemistry areas can presented similar patterns given they present a similar structure of scientific production, collaboration and citations.

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Contribution of authors:

Nabout, J.C.: Conceptualization, Formal Analysis, Writing — first draft, Writing — edition & review. Faquim, R.C.P.: Data curation, Formal analysis, Writing — first draft, Writing — edition & review. Carvalho, R.A.: Conceptualization, Formal Analysis, Writing — first draft, Writing — edition & review. Machado, K.B.: Conceptualization, Formal Analysis, Writing — first draft, Writing — edition & review.

References

Angelo, C., 2019. Brazil's government freezes nearly half of its science spending. Nature, v. 568, 155-156.

Bag, S., 2015. A short review on structural equation modeling: applications and future research directions. Journal of Supply Chain Management Systems, v. 4, (3) 64-69.

Bai, X.; Zhang, F.; Lee, I., 2019. Predicting the citations of scholarly paper. Journal of Informetrics, v. 13, (1), 407-418. https://doi.org/10.1016/j.joi.2019.01.010.

Bar-Ilan, J., 2008. Review Informetrics at the beginning of the 21st century – A review. Journal of Informetrics, v. 2, (1), 1-52. https://doi.org/10.1016/j.joi.2007.11.001.

Bentler, P.M., 1990. Comparative fit indexes in structural models. Psychological Bulletin, v. 107, (2), 238-246. https://doi.org/10.1037/0033-2909.107.2.238.

Bornmann, L.; Leydesdorff, L.; Wang, J., 2014. How to improve the prediction based on citation impact percentiles for years shortly after the publication date? Journal of Informetrics, v. 8, (1), 175-180. https://doi.org/10.1016/j.joi.2013.11.005.

Bowen, A.; Casadevall, A., 2015. Increasing disparities between resource inputs and outcomes, as measured by certain health deliverables, in biomedical research. Proceedings of the National Academy of Sciences, v. 112, (36), 11335-11340. https://doi.org/10.1073/pnas.1504955112.

Cimini, G.; Zaccaria, A.; Gabrielli, A., 2016. Investigating the interplay between fundamentals of national research systems: Performance, investments and international collaborations. Journal of Informetrics, v. 10, (1), 200-211. https://doi.org/10.1016/j.joi.2016.01.002.

Dranev, Y.; Kotsemir, M.; Syomin, B., 2018. Diversity of research publications: relation to agricultural productivity and possible implications for STI policy. Scientometrics, v. 116, (3), 1565-1587. https://doi.org/10.1007/s11192-018-2799-2.

Fan, Y.; Chen, J.; Shirkey, G.; John, R.; Wu, S. R.; Park, H.; Shao, C., 2016. Applications of structural equation modeling (SEM) in ecological studies: an updated review. Ecological Processes, v. 5, (1), 1-12. https://doi.org/10.1186/s13717-016-0063-3.

Fanelli, D., 2013. Positive results receive more citations, but only in some disciplines. Scientometrics, v. 94, (2), 701-709. https://doi.org/10.1007/s11192-012-0757-y.

Fortin, J.-M.; Currie, D.J., 2013. Big science vs. little science: how scientific impact scales with funding. Plos One, v. 8, (6), e65263. https://doi.org/10.1371/journal.pone.0065263.

Geisler, E. 2000. The metrics of science and Technology. Quorum Books, New York.

Gök, A.; Rigby, J.; Shapira, P., 2016. The impact of research funding on scientific outputs: Evidence from six smaller European countries. Journal of the Association for Information Science and Technology, v. 67, (3), 715-730. https://doi.org/10.1002/asi.23406.

Hu, L.T.; Bentler, P.M. 1999. Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives. Structural Equation Modeling, v. 6, (1), 1-55. https://doi.org/10.1080/10705519909540118.

Jacob, B.A.; Lefgren, L., 2011. The impact of research grant funding on scientific productivity. Journal of Public Economics, v. 95, (9-10), 1168-1177. https://doi.org/10.1016/j.jpubeco.2011.05.005.

Knief, U.; Forstmeier, W., 2021. Violating the normality assumption may be the lesser of two evils. Behavior Research Methods, 1-15. https://doi.org/10.3758/s13428-021-01587-5.

Lane, J.; Bertuzzi, S., 2011. Measuring the results of science investments. Science, v. 331, (6018), 678-680. https://doi.org/10.1126/science.1201865.

Lefcheck, J.S., 2016. Piecewise SEM: Piecewise structural equation modelling inr for ecology, evolution, and systematics. Methods in Ecology and Evolution, v. 7, (5), 573-579. https://doi.org/10.1111/2041-210x.12512.

Leimu, R.; Koricheva, J. 2005a. Does scientific collaboration increase the impact of ecological articles? BioScience, v. 55, (5), 438-443. https://doi.org/10.1641/0006-3568(2005)055[0438:DSCITI]2.0.CO;2.

Leimu, R.; Koricheva, J., 2005b. What determines the citation frequency of ecological papers? Trends in Ecology & Evolution, v. 20, (1), 28-32. https://doi.org/10.1016/j.tree.2004.10.010.

Lewison, G.; Dawson, G., 1998. The effect of funding on the outputs of biomedical research. Scientometrics, v. 41, (1-2), 17-27. https://doi.org/10.1007/BF02457963.

Leydesdorff, L.; Bornmann, L.; Wagner, C.S., 2019. The relative influences of government funding and international collaboration on citation impact. Journal of the Association for Information Science and Technology, v. 70, (2), 198-201. https://dx.doi.org/10.1002%2Fasi.24109.

Makkonen, T., 2013. Government science and technology budgets in times of crisis. Research Policy, v. 42, (3), 817-822. https://doi.org/10.1016/j.respol.2012.10.002.

Manly, B.F., 2006. Randomization, bootstrap and Monte Carlo methods in biology (Vol. 70). CRC Press, Boca Raton.

May, R.M., 1998. The scientific investments of nations. Science, v. 281, (5373), 49-51. https://doi.org/10.1126/science.281.5373.49.

Mejia, C.; Kajikawa, Y., 2018. Using acknowledgement data to characterize funding organizations by the types of research sponsored: The case of robotics research. Scientometrics, v. 114, (3), 883-904. https://doi.org/10.1007/s11192-017-2617-2.

Mena-Chalco, J.P.; Digiampietri, L.A.; Lopes, F.M.; Cesar Junior, R.M., 2014. Brazilian Bibliometric Coauthorship Networks. Journal of the Association for Information Science and Technology, v. 65, (7): 1424-1445. https://doi.org/10.1002/asi.23010.

Moed, H.F., 2017. Applied evaluative informetrics. Springer, Amsterdam.

Nabout, J.C.; Parreira, M.R.; Teresa, F.B.; Carneiro, F.M.; Cunha, H.F.; Souza Ondei, L.; Caramori, S.S.; Soares, T.N., 2015. Publish (in a group) or perish (alone): the trend from single-to multi-authorship in biological papers. Scientometrics, v. 102, 357-364. https://doi.org/10.1007/s11192-014-1385-5.

Nabout, J.C.; Teresa, F.B.; Machado, K.B.; Prado, V.H.M.; Bini, L.M.; Diniz-Filho, J.A.F., 2018. Do traditional scientometric indicators predict social media activity on scientific knowledge? An analysis of the ecological literature. Scientometrics, v. 115, (2), 1007-1015. https://doi.org/10.1007/s11192-018-2678-x.

Neff, M.W.; Corley, E.A., 2009. 35 years and 160,000 articles: A bibliometric exploration of the evolution of ecology. Scientometrics, v. 80, (3), 657-682. https://doi.org/10.1007/s11192-008-2099-3.

Organization for Economic Co-operation and Development – OECD. 2017. OECD Science, Technology and Industry Scoreboard 2017: The digital transformation. OECD, Paris (Accessed December 1, 2019) at: http://dx.doi.org/10.1787/9789264268821-en.

Ory, D.T.; Mokhtarian, P.L., 2010. The impact of non-normality, sample size and estimation technique on goodness-of-fit measures in structural equation modeling: evidence from ten empirical models of travel behavior. Quality & Quantity, v. 44, (3), 427-445. https://doi.org/10.1007/s11135-008-9215-6.

Padial, A.A.; Nabout, J.C.; Siqueira, T.; Bini, L.M.; Diniz-Filho, J.A.F., 2010. Weak evidence for determinants of citation frequency in ecological articles. Scientometrics, v. 85, 1-12. https://doi.org/10.1007/s11192-010-0231-7.

Parreira, M.R.; Machado, K.B.; Logares, R.; Diniz-Filho, J.A.F.; Nabout, J.C., 2017. The roles of geographic distance and socioeconomic factors on international collaboration among ecologists. Scientometrics, v. 113, (3), 1539-1550. https://doi.org/10.1007/s11192-017-2502-z.

Paul-Hus, A.; Desrochers, N.; Costas, R., 2016. Characterization, description, and considerations for the use of funding acknowledgement data in Web of Science. Scientometrics, v. 108, (1), 167-182. https://doi.org/10.1007/s11192-016-1953-y.

R Core Team. 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria (Accessed September 19, 2017) at: https://www.R-project.org/.

Rigby, J., 2013. Looking for the impact of peer review: does count of funding acknowledgements really predict research impact? Scientometrics, v. 94, (1), 57-73. https://doi.org/10.1007/s11192-012-0779-5.

Rosseel, Y., 2012. lavaan: An R Package for Structural Equation Modeling. Journal of Statistical Software, v. 48, (2), 1-36. https://doi.org/10.18637/jss.v048.i02.

Shaheen, F.; Ahmad, N.; Waqas, M.; Waheed, A.; Farooq, O., 2017. Structural equation modeling (SEM) in social sciences & medical research: a guide for improved analysis. International Journal of Academic Research in Business and Social Sciences, v. 7, (5), 132-143. http://dx.doi.org/10.6007/IJARBSS/v7-i5/2882.

Sugimoto, C.R.; Robinson-García, N.; Murray, D.S.; Yegros-Yegros, A.; Costas, R.; Larivière, V., 2017. Scientists have most impact when they're free to move. Nature News, v. 550, (7674), 29-31. https://doi.org/10.1038/550029a.

Tahamtan, I.; Afshar, A. S.; Ahamdzadeh, K., 2016. Factors affecting number of citations: a comprehensive review of the literature. Scientometrics, v. 107, (3), 1195-1225. https://doi.org/10.1007/s11192-016-1889-2.

Tang, L.; Hu, G.; Liu, W., 2017. Funding acknowledgment analysis: Queries and caveats. Journal of the Association for Information Science and Technology, v. 68, (3), 790-794. https://doi.org/10.1002/asi.23713.

Thomé, M.T.C.; Haddad, C.F.B., 2019. Brazil's biodiversity researchers need help. Science, v. 364, (6446), 1144-1145. https://doi.org/10.1126/science.aax9478.

Vanclay, J.K., 2013. Factors affecting citation rates in environmental science. Journal of Informetrics, v. 7, (2), 265-271. https://doi.org/10.1016/j.joi.2012.11.009.

Wang, X.; Liu, D.; Ding, K.; Wang, X., 2012. Science funding and research output: a study on 10 countries. Scientometrics, v. 91, (2), 591-599. https://doi.org/10.1007/s11192-011-0576-6.

Web of Science. 2009. Funding Acknowledgements (Accessed December 5, 2017) at: http://wokinfo.com/products_tools/multidisciplinary/webofscience/fundingsearch/.

Xia, J.; Myers, R.L.; Wilhoite, S.K., 2011. Multiple open access availability and citation impact. Journal of Information Science, v. 37, (1), 19-28. https://doi.org/10.1177%2F0165551510389358.

Yan, E.J.; Wu, C.J.; Song, M., 2018. The funding factor: a cross-disciplinary examination of the association between research funding and citation impact. Scientometrics, v. 115, (1), 369-384. https://doi.org/10.1007/s11192-017-2583-8.

Yu, T.; Yu, G.; Li, P.Y.; Wang, L., 2014. Citation impact prediction for scientific papers using stepwise regression analysis. Scientometrics, v. 101, 1233-1252. https://doi.org/10.1007/s11192-014-1279-6.

Zhao, S.X.; Lou, W.; Tan, A.M.; Yu, S., 2018. Do funded papers attract more usage? Scientometrics, v. 115, (1), 153-168. https://doi.org/10.1007/s11192-018-2662-5.

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Virtual water flow and water footprint as optimizer of water resource management in the state of Ceará, Brazil

Fluxo de água virtual e pegada hídrica como otimizadores da gestão dos recursos hídricos no estado do Ceará, Brasil

Ivana Sampaio Leite[1], *Rodolfo José Sabiá*[1], *Andrezza Pereira Matos*[1], *Camila Cavalcante Silva*[1]

ABSTRACT

The water exported indirectly by sending products to other countries, or vice versa, is called a virtual water flow and this can be measured through water footprint (WF) calculations, which represent the embedded water needed to manufacture a product. This present study aims to analyze the virtual water flow and the WF of the main products exported by municipalities in the state of Ceará in the year 2019, in order to enhance the management of the state's water resources. Analytical hierarchy process (AHP), the most commonly used multicriteria decision-making method in the world, was used to determine which product is more sustainably produced by the municipalities of Ceará, with the criteria: WF, price, and volume exported. The alternatives are at least two of the seven categories of products exported by the state where the "fruit or vegetable juices" class was preferred as the most sustainable. It was found that most cities in the state that export agricultural products use only one basin, which can lead to very low reservoir levels, while the other hydrographic basins in the state are underused. It is worth noting that the Metropolitan Basin concentrates on 11 out of 32 municipalities that export abroad and that it is responsible for supplying more than 4,074,730 inhabitants, according to Brazilian Institute of Geography and Statistics (IBGE, 2019).

Keywords: water management; water resources; analytical hierarchy process; hydrographic basins.

RESUMO

A água exportada indiretamente pelo envio de produtos a outros países, ou vice versa, chama-se fluxo de água virtual e pode ser mensurado por cálculos de pegada hídrica, que representam a água embutida necessária para a fabricação de um produto. O presente estudo teve o objetivo de analisar o fluxo de água virtual e a pegada hídrica dos principais produtos exportados por municípios do estado do Ceará no ano de 2019, a fim de potencializar o gerenciamento dos recursos hídricos do estado. Utilizou-se o *analytical hierarchy process* (AHP), método de tomada de decisão multicritério mais usado no mundo, aqui escolhido para determinar qual o produto mais sustentável produzido pelos municípios do Ceará, com os critérios: pegada hídrica, preço e volume exportado. As alternativas são pelo menos duas das sete categorias de produtos exportados pelo estado, e a classe de "sucos de frutas ou vegetais" foi preferida como a mais sustentável. Constatou-se que a maioria das cidades do estado que exportam produtos de origem agropecuária faz uso de apenas uma bacia, o que pode acarretar níveis muito baixos de reservatório, enquanto as outras bacias hidrográficas do estado são subusadas. Vale a pena salientar que a Bacia Metropolitana concentra 11 de 32 municípios que exportam para o exterior e é responsável pelo abastecimento de mais de 4.074.730 habitantes, segundo o Instituto Brasileiro de Geografia e Estatística (2019).

Palavras-chave: gerenciamento da água; recursos hídricos; *analytical hierarchy process*; bacias hidrográficas.

[1]Universidade Regional do Cariri – Juazeiro do Norte (CE), Brazil.

Correspondence address: Ivana Sampaio Leite – Universidade Regional do Cariri – Avenida Leão Sampaio, 107 – Lagoa Seca – CEP: 63041-145 – Juazeiro do Norte (CE), Brazil. E-mail: gabinete@urca.br

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Introduction

Water is the most important natural resource for human, playing a fundamental role in activities of daily living. The indiscriminate uses of water for different purposes began to generate conflicts due to its false abundance. Currently, the approach to limiting water resources has been highlighted (Hoekstra and Chapagain, 2007). Furthermore, the total volume of fresh water that is used to produce the goods and services consumed by the individual or the community is defined as a water footprint (WF) (Hoekstra et al., 2011).

In this way, a country's WF can be directly determined by other factors, such as the volume of consumption (related to gross national income), the consumption pattern (e.g., high versus low meat consumption), the climate (crop growth conditions), and agricultural practice (efficient water use) (Hoekstra and Chapagain, 2007). Therefore, virtual water is described as an instrument for the management of water resources, serving as an indirect measure of the water consumed by a good, product, or service (Guimarães and Xavier, 2008).

It is important to emphasize the concept of virtual water, which refers to the amount of water incorporated in a certain product. We use the term *virtual water* in the international (or interregional) context of virtual water flow; therefore, when a country or region exports or imports a product, it is exporting or importing water in a virtual way (Hoekstra et al., 2011).

In this case, we can speak in a general way about flows or the trade in virtual water. The northeast region of the country is characterized by high temperatures, high evaporations, and scarcity of rain. There is a significant discernment when the WF is compared with the current capacity of these reservoirs, that is, with the amount of water in the hydrographic basins quite reduced in relation to their total capacities. The state of Ceará has the fourth territorial extension of the northeast region and is the 17th among Brazilian states in terms of territorial surface. Ceará borders the states of Pernambuco, Rio Grande do Norte, Paraíba, and Piauí. In addition, it has 184 municipalities and 20 administrative microregions, especially the Metropolitan Regions of Fortaleza, with 19 cities, and Cariri, with 9 cities (IPECE, 2010). The 2019 Brazilian Institute of Geography and Statistics (IBGE) data indicate a territorial area of 148,894,441 km^2 and an estimated population of 9,132,078 people.

The National Water Resources Council is responsible for promoting the planning and management of water resources and their respective hydrographic basins. Hydrographic Basin is an area where all the rain that falls drains, by streams and secondary rivers, to the same main river, located in a lower point of the landscape being separated from the other Basins by a dividing line called water divider (COGERH, 2018).

In this case, according to the State Water Resources Plan (ANA, 2018), the state of Ceará consists of 155 dams and 12 hydrographic basins, which are classified as Coast, High Jaguaribe, Coreaú, Metropolitans, Ibiapaba Hill, Medium Jaguaribe, Salgado, Acaraú, Banabuiú, Crateús Hinterland, Curu, and Low Jaguaribe, comprising a volume of 18,617 hm^3 (FUNCEME, 2019). Furthermore, the volume of the basins has great relevance to calculate the volume of water taken from the state basins for agricultural production using the WF calculation. It is important to note that the volume used in the hydrographic basins varies according to the period under analysis for the calculation of the WF, since the WF depends on the volume of water incorporated, the climatic conditions, and the geographical position in question.

Barreto et al. (2010) and Fiel et al. (2017) highlighted that water is used as a strategy in conflict management and environmental protection, which would justify the establishment of hydrographic basin management through the Hydrographic Basin Committees (CBHs), as it seeks a balance between human demand and consumption, animal intake, and irrigation.

The presence of CBHs in Brazil arises from the far reaching of inhabitants, who need a high amount of water for human and animal consumption, food production, industrial products, recreation, and so on. It creates a very high demand for it, causing water scarcity, in addition to degradation through solid and liquid organic waste, chemicals, and soil erosion, among others. Due to this scarcity of water and lack of water quality, there might be stagnation and even a drop in the economic situation (Fiel et al., 2017).

A survey conducted using water resources as a tool aims to ensure that the quality of the water is compatible with its demand, the framing of the waters, in the hydrographic basins of rivers that are part of the domain of the Union. It also aims to identify the importance of the framework for planning water quality, as well as the difficulties and possibilities of its implementation. An analysis of the most recent plans of the nine basins with constituted committees was made to seek aspects related to the framework and to compose the study method; electronic questionnaires were applied to the committees of the analyzed basins and also to the National Water Agency to diagnose the understanding of the research focus. Based on the results, it was possible to identify and observe the absence of framing according to the current regulation, namely, CONAMA Resolution nº 357/05, in all the situations (Souza and Pizella, 2021).

Kaplowitz and Witter (2008), Mahmoud et al. (2011), and Fiel et al. (2017) pointed out that, with the extent of water scarcity putting pressure on existing water management and distribution systems, it is essential to identify and analyze the factors that can change consumption management for efficient management, including river basins.

The analytical hierarchy process (AHP) is the most commonly used multicriteria decision-making method in the world. In this perspective, for Barker and Zabinsky (2010), this method satisfies the selection of the criteria suggested by it, including adequacy, ease of use, and validation of its results. The AHP method is based on three stages: building hierarchies through structuring the problem, establishing weights for criteria and preference for alternatives, and analyzing the results (Tramarico et al., 2012). In contrast, the AHP turns comparisons, often empirical, into numerical values that are processed and compared.

The weight of each of the factors allows the assessment of each of the elements within the defined hierarchy. This ability to convert empirical data into mathematical models is the main differential of AHP in relation to other comparative techniques (Vargas, 2010). This method represents an improvement in making decisions by managers, who often depend on their experiences or feelings (Silva et al., 2015).

In this way, it can be said that a multicriteria decision problem consists of a situation that there are at least two alternatives of action to choose and that choice is driven by the desire to meet multiple objectives, often conflicting with each other. These objectives are associated with the consequences of choosing the alternative to be followed and variables that represent them and allow the evaluation of each alternative, based on each objective. These variables can be called criteria, attributes, or dimensions (Almeida, 2013).

This study was developed with the objective of analyzing the virtual water flow and the WF of the main products exported by municipalities in the state of Ceará, in order to enhance the management of the state's water resources.

The use of water by culture in the municipalities of Ceará was quantified, calculating the WF and the virtual water flow of the main products exported by the state of Ceará. It was also verified the integrated planning of the hydrographic basins of the state in order to assess the impacts of the WF in the hydrographic basins of Ceará, developing a methodology as a solution through decision-making methods to define the best product to be exported by each municipality in the state of Ceará.

Materials and methods

For this study, we used the exploratory research method, composing a qualitative and quantitative approach, with the development of a bibliographic character, since it succeeded in reviewing articles. In order to emphasize the study, AHP with the multicriteria decision maker was used as attributing continuity to the development of the research. In addition, histogram, which is a column chart used in statistics, is used. It consists of several adjacent rectangles, representing the frequency table with loss of information (values grouped by classes) of a set of values. On the horizontal scale, class intervals are marked, and each interval is the basis of each rectangle or bar; on the vertical scale, the heights of the rectangles or bars are marked, representing the respective absolute frequencies of the classes (Lopes, 1999; Kurokawa and Bornia, 2002).

Study area

The state of Ceará, the target of the research, is highlighted in the agribusiness issue, mainly in the agricultural sector. Given this, the use of water, directly and indirectly, is part of the entire agricultural production process in the state where significant advances have been made in relation to the use of water resources.

Calculation of the export water footprint

The calculated exported WF corresponds to the volume of water exported indirectly from the state of Ceará to other countries, where the exported WF of Ceará is from a geographically delimited region. In addition, the exported WF is related to basic, manufactured, and semi-manufactured products exported by the northeast region. The products exported by Ceará were separated from the entire agricultural sector, separating the quantity (in ton) by the municipalities of the state of Ceará, of each corresponding product. Subsequently, the collection of all products exported by state, obtained the WF exported from the analyzed region, as shown in Equation 1:

$$PH_{EXPORTADA} = PH_{BÁSICOS} + PH_{SEMIMANUFATURADOS} + PH_{MANUFATURADOS}$$
$$PH_{EXPORTADA} = (Q_{PB} * PH_{PROD}) + (Q_{PS} * PH_{PROD}) + (Q_{PM} * PH_{PROD}) \quad (1)$$

Where:

$PH_{EXPORTADA}$ = exported WF, in m³/year;

$PH_{BÁSICOS}$ = exported WF, in m³/year;

$PH_{SEMIMANUFATURADOS}$ = WF exported from semi-manufactured products, in m³/year;

$PH_{MANUFATURADOS}$ = WF exported from manufactured products, in m³/year;

Q_{PB} = quantity of the respective basic product, in kg;

Q_{PS} = quantity of the respective semi-manufactured product, in kg;

Q_{PM} = quantity of the respective manufactured product, in kg;

PH_{PROD} = WF of a product, in l/kg.

All WF data exposed in this article were taken from Hoesktra et al. (2011) with the analysis made for Brazil, as there are no studies of the specific region.

Analytical hierarchy process

AHP methodology allows us to determine which alternative is the most consistent with our criteria following the level of importance we determine. The priority is a score that classifies the importance of the alternative or criterion in the decision, comparisons are made pair by pair, using the fundamental scale with values ranging from 1 to 9, which is called Satty Fundamental Scale, as shown in Table 1.

Furthermore, when using the method, we divide and define the levels according to the AHP methodology in order to determine the most sustainable product produced by the municipalities of Ceará; in the second level, we defined the three criteria: WF, price, and volume, as shown in Table 2.

Finally, the alternatives, which we define as the main products exported from Ceará. Based on the definition of the main objective, criteria, and alternatives, hierarchical modeling was developed to guide the application of the AHP (Figure 1).

Table 1 – Analytical hierarchy process comparison scale.

Score (weight)	Definition
1	Equally important
3	Weak importance
5	Strong importance
7	Very strong importance
9	Absolute importance
2, 4, 6, 8	Intermediate values

Source: adapted from Saaty (1997).

Table 2 – Criteria used in analytical hierarchy process.

Criteria	Function
Water Footprint	Quantitative criterion, with unit of measurement L/kg, which demonstrates the direct and indirect quantity for the production of a certain food, and with the objective of minimizing.
Price	Quantitative criterion, with unit in US$, and with the objective of maximizing.
Volume	Quantitative criterion, of unit in m^3, the objective is to maximize.

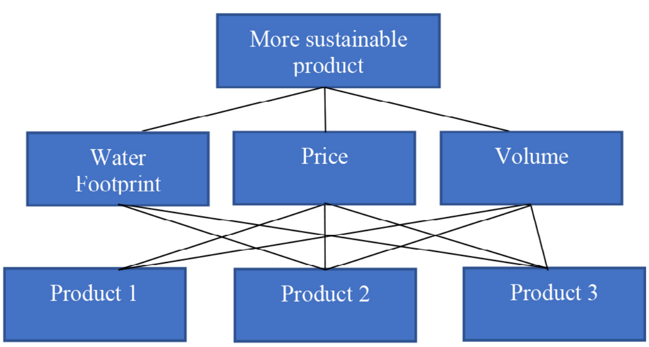

Figure 1 – Hierarchical model used in the problem.

Results

Through the online platform Comex Stat, aggregated to Comex Vis official Brazilian system for consulting foreign trade data, a survey was carried out of the products of agricultural origin that the state of Ceará exports and are organized into categories, as shown in Table 2.

Information on volume exported by product category all over Brazil and the percentage of participation by state was also available. Based on this information, the calculations of the participation in tons of the state of Ceará were carried out, and the equivalent price for the exports of each section was also extracted from the platform, in dollar and Free On Board (FOB), all for 2019 (Table 3).

The WF was also determined for the main exported products; for each category, the footprint that corresponds to the main product produced, in volume, of each section was used. The categories "shoes" and "leather" were used for calculating WF of the leather; "fillets and other frozen, fresh or chilled fish meats" for the lobster; "non-oil fruits and nuts, fresh or dried" used an average of cashew, melon, banana, guava, mango, and papaya footprints. For "other animal or vegetable fats and oils, processed, waxes, mixtures, or non-food preparations," the footprint of natural honey was used. The juice and cotton section made use of their corresponding footprints (Table 4).

In the subsequent stage, a study was carried out of the municipalities in the state of Ceará that export to other countries and their respective hydrographic basins. As in this work we are only attending to products of agricultural origin, a filter was made where we remove cities that export at least one product that is included in the seven types of categories mentioned above (Table 5).

The correlation of the seven categories of agricultural products exported by Ceará with the municipalities that export them is shown in Table 6.

There are 12 basins found in the state of Ceará, as mentioned in the methodology. In order to analyze where the water consumption required for each product category comes from, seven maps were elaborated that show which hydrographic basins the water resource is being used to produce the goods for export.

The sector that produces footwear makes greater use of the Metropolitan Basin, with four of 15 cities being supplied. It is the category that most exports its products. It is then noted when analyzing the map that the northern region of the state has a higher water consumption by the basins (Figure 2).

The "leather" category, the most used basin in this sector is the Metropolitan, with a total of four of seven municipalities. In other words, 57.14% of the water resource comes from just one basin. The concentration of the use of this resource is still found in the northern region of the map (Figure 3).

In the category of "fillets or other frozen, fresh or chilled fish meat," the withdrawal of water is concentrated on the coast of the state, not least because the products of this category are meat of fish, caught in the sea (Figure 4).

The second category that exports the most is "fruit and nuts, non-oil, fresh or dried," with a total of 13 cities. This sector has a more decentralized distribution, with exporting municipalities present in both the north, east, and south of the state of Ceará. This sector makes use of the waters of a greater range of hydrographic basins, although 38.46% of water use in this category comes from only one basin, the Metropolitan Basin (Figure 5).

There are eight municipalities that export the category of "other animal or vegetable fats and oils, processed, waxes, mixtures or non-food preparations," with five corresponding to 62.5% of water withdrawal

Table 3 – Main products exported by the state of Ceará in 2019.

Product category	Tons (total Brazil)	Participation Ceará (%)	Tons Ceará	Price in millions (US$)
Footwear	58,440.34	21.70	12,681.55	236
Leather	471,839.00	4.52	21,327.13	52.3
Fillets or other frozen, fresh or chilled meat	193,269.70	0.94	1,816.73	4.53
Dried fruit and nuts, fresh or dried	947,709.10	17.40	164,901.38	161
Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations	33,500.85	48.90	16,381.92	68.8
Fruit juices or vegetables	2,363,728	2.73	64,529.77	57.6
Cotton fabric, screens (not including tapes or specials)	19,846	26.60	5,279.04	32

Source: Brasil (2020).

Table 4 – Volume of products exported in 2019 and their water footprints.

Product category	Tons annual total	Water footprint(m^3/tons)	Annual water footprint (m^3/year)
Footwear	12,681.55	18,770	238,032,693.5
Leather	21,327.13	18,770	400,310,230.1
Fillets or other frozen, fresh or chilled meat	1,816.73	4,325	7,857,357.25
Dried fruit and nuts, fresh or dried	164,901.38	3,500.6	577,253,770.8
Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations	16,381.92	1,782	29,192,581.44
Fruit juices or vegetables	64,529.77	1,018	65,691,305.86
Cotton fabric, screens (not including tapes or specials)	5,279.04	9,982	52,695,377.28

Source: Hoekstra et al. (2011) and Brasil (2020).

from the Metropolitan Basin. And the concentration of cities by area is in the north of the state (Figure 6).

In the category of "fruit or vegetable juices," as shown in Figure 7, the northern and eastern regions of the state concentrate exporting cities, although the water use required by cities comes from a greater variety of river basins.

The category "cotton fabric, canvas (not including as ribbons or specials)" has fewer cities exporting and all make use of the Metropolitan Basin, so 100% of the cotton fabric sector requires water from only one hydrographic basin (Figure 8).

Discussion

According to Falkenmark and Molden (2008), the economic growth of the population implies an increase in the demand for water and food. The Southeast region of Brazil faces the main problems of water resources related to the scarcity due to pollution and excessive use of water in urban and industrialized areas, its conflicts of use, and the constant flooding (Porto et al., 1999). Barreto et al. (2010) added that the association between water scarcity and disordered economic exploitation causes soil degradation and desertification, in addition to a significant reduction of plant and animal species (Fiel et al., 2017).

With the application of AHP methodology to Excel, the most sustainable product of each municipality for export was analyzed, depending on WF, price, and volume exported, corresponding to the year 2019. The most important criterion is the WF, followed by price and volume (Table 7).

A total of 32 municipalities in Ceará are exporters of agricultural products; of these, an AHP analysis was carried out for decision-making in 21 cities, as the others exported only one type of product category, not making the method feasible. After an initial structuring of the problem, priorities are calculated based on pairwise comparisons, arranged in matrices of order of magnitude from 2×2 to 6×6. The alternatives were the seven categories of products exported by the state, the largest exporting city being the capital, Fortaleza, which exports six of the seven categories.

From the results obtained in the decision-making, a table with the AHP values organized by product category and by the cities that export more than one category is created, with total decimal number of

Table 5 – Products exported by each municipality and its hydrographic basins.

Municipalities	Hydrographic basins	Exported products
Acaraú	Acaraú Basin	Frozen fish; Crustaceans
Aquiraz	Metropolitan Basin	Coconuts, Brazil nuts and cashew nuts; natural honey; vegetable juices and extracts
Aracati	Low Jaguaribe Basin	Footwear with rubber sole, plastic, natural or reconstructed leather outsole, and natural leather uppers; Crustaceans; other vegetable fats and oils (including jojoba oil)
Barbalha	Salgado Basin	Dates, figs, pineapples (avocados), avocados, guavas, mangoes, and mangosteens; coconuts, Brazil nuts and cashew nuts; fruit juices (including grape must) or vegetable juices
Beberibe	Metropolitan Basin	Suitcases and briefcases; dates, figs, pineapples (avocados), avocados, guavas, mangoes, and mangosteens, fresh or dried
Brejo Santo	Salgado Basin	Footwear with rubber sole, plastic, natural or reconstructed leather outsole, and natural leather uppers; footwear with rubber, plastic, natural or reconstituted leather outer soles, and textile uppers
Camocim	Coreaú Basin	Footwear with rubber sole, plastic, natural or reconstructed leather outsole, and natural leather uppers; footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; clothing and clothing accessories of leather or composition leather
Cascavel	Metropolitan Basin	Leathers prepared after tanning or after drying and parchmented hides and skins bovine (including buffalo) or equine; fresh or chilled fish; natural honey
Eusébio	Metropolitan Basin	Dates, figs, pineapples (avocados), avocados, guavas, mangoes, and mangosteens; coconuts, Brazil nuts and cashew nuts; fruit juices (including grape must) or vegetable juices; vegetable waxes (except triglycerides), beeswax or even other insects and spermaceti; cotton yarn (except sewing thread) containing at least 85% cotton by weight
Fortaleza	Metropolitan Basin	Footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; footwear with rubber, plastic, natural or reconstituted leather outer soles and natural leather uppers; Crustaceans; flour, powder and pallets of crustaceans; live fish; Mollusks; prepared and preserved fish, caviar and substitutes prepared from fish eggs; coconuts, Brazil nuts and cashew nuts, fresh or dried; other oil seeds and oleaginous fruits; apples, pears, and quinces; dates, figs, pineapples (avocados), avocados, guavas, mangoes, and mangosteens; grape; melons, watermelons, and papais (papayas); citrus fruit, fresh or dried; tomatoes; other fresh fruits; bananas; coffee; fruits and other edible parts of plants; vegetable waxes (except triglycerides), beeswax or other insect waxes and spermaceti; margarine, mixtures or food preparations of animal or vegetable fats or oils; other vegetable oil fats (including jojoba oil); peanut oil; soy oil; sunflower, safflower, or cotton oil; olive oil; crude glycerol, water and glycerol, glycerol; coconut, palm kernel, or babassu oils; animal or vegetable fats and oils; vegetable juices and extracts; fruit juices (including grape must) or vegetable juices; cotton fabrics containing at least 85% cotton by weight, weighing more than 200g/m^2; woven fabrics of synthetic staple fibers, containing less than 85% by weight of these fibers, combined, mainly or solely with cotton, of a weight not exceeding 170 g/m^2
Horizonte	Metropolitan Basin	Footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; cotton fabrics, containing at least 85% cotton by weight, weighing more than 200 g/m^2; cotton fabrics, containing less than 85% cotton by weight, mainly or solely combined with synthetic or artificial fibers, weighing more than 200 g/m^2
Icapuí	Low Jaguaribe Basin	Frozen fish; Crustaceans; flour, powder and pallets of crustaceans; melons, watermelons, and papayas (papayas); bananas
Itapagé	Curu Basin	Footwear with rubber sole, plastic, natural or reconstructed leather outsole and natural leather uppers; footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials
Itapipoca	Coast Basin	Footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; fruit juices (including grape must) or vegetable juices
Itarema	Coast Basin	Frozen fish; fish fillets and other fish meats; fresh or chilled fish; fruit and other edible parts of plants, prepared or otherwise preserved, with or without added sugar or other sweeteners or alcohol; vegetable waxes (except triglycerides), beeswax or even other insects and spermaceti
Jaguaribe	Middle Jaguaribe Basin	Fruits and other edible parts of plants; fruit, uncooked or uncooked; fruit juices (including grape must) or vegetable juices
Juazeiro do Norte	Salgado Basin	Footwear with outer soles of rubber, plastic, natural or reconstituted leather

Continua...

Table 5 – Products exported by each municipality and its hydrographic basins.

Municipalities	Hydrographic basins	Exported products
Limoeiro do Norte	Low Jaguaribe Basin	Fresh or dried bananas
Maracanaú	Metropolitan Basin	Leathers prepared after tanning or after drying and parchmented hides and skins, of bovine (including buffalo) or equine; tanned or crusted hides and skins of bovine (including buffalo) or equine animals; vegetable waxes (except triglycerides), beeswax or even other insects and spermaceti; cotton fabrics, containing at least 85% cotton by weight, weighing more than 200 g/m^2; cotton fabrics, containing less than 85% cotton by weight, combined, principally or solely, with synthetic or artificial fibers, weighing more than 200 g/m^2; cotton yarn (except sewing thread), containing at least 85% cotton by weight
Maranguape	Metropolitan Basin	Footwear with rubber, plastic, natural or reconstructed leather outsole and natural leather uppers; footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; suitcases and briefcases
Pacajus	Metropolitan Basin	Coconuts, Brazil nuts and cashew nuts, fresh or dried, even shelled or peeled; other nuts; cotton fabrics, containing at least 85% cotton by weight, weighing more than 200 g/m^2; cotton fabrics, containing less than 85% cotton by weight, mainly or solely combined with synthetic or artificial fibers, weighing more than 200 g/m^2
Pacatuba	Metropolitan Basin	Footwear with rubber, plastic, natural or reconstructed leather outsole and natural leather uppers; footwear with rubber, plastic, natural or reconstituted leather outer soles and textile uppers
Paraipaba	Curu Basin	Fruit juices (including grape must) or vegetable juices
Pereiro	Middle Jaguaribe Basin	Fruits and other edible parts of plants; fruit juices (including grape must) or vegetable juices
Quixeramobim	Banabuiú Basin	Footwear with rubber, plastic, natural or reconstructed leather outsole and natural leather uppers; footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; suitcases and briefcases
Quixeré	Low Jaguaribe Basin	Footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; other footwear with outer sole and rubber or plastic upper; melons, watermelons, and papayas (papayas), fresh
Russas	Low Jaguaribe Basin	Vegetable waxes (except triglycerides), beeswax or even other insects and spermaceti
São Gonçalo do Amarante	Curu Basin	Prepared and preserved fish, caviar and substitutes prepared from fish eggs; frozen, fresh or chilled fish
Senador Pompeu	Banabuiú Basin	Footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; footwear with rubber, plastic, natural or reconstructed leather outer sole and natural leather uppers
Sobral	Acaraú Basin	Footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; suitcases and briefcases
Ubajara	Coreaú Basin	Fruit juices (including grape must) or vegetable juices; fruits, uncooked or cooked in water or steam, frozen, whether or not containing added sugar or other sweetening matter
Uruburetama	Coast Basin	Footwear with rubber, plastic, natural or reconstituted leather outer soles and uppers of textile materials; footwear with rubber, plastic, natural or reconstructed leather outer sole and natural leather uppers

Source: Brasil (2020).

1, corresponding to 100%. To use the AHP method, at least two alternatives are necessary, in order to select the most sustainable category for export (Table 8).

The percentage table supported the creation of a histogram to which it is possible to analyze the consistency of the results. This type of graphic allows the preview of the distribution of events (Figure 9).

We can observe from this histogram that the decision percentages are well distributed in relation to the cutoff frequencies calculated. However, more decisions were obtained with the smallest cutoff and less with the largest cutoff values. The lower cutoff value having a higher frequency is also due to the fact that most categories for decision had more than two alternatives, so the categories that were not elected as the most sustainable are distributed in the lowest cutoff values (Figure 10).

By changing the cutoff frequencies calculated by the categories of exported products, we obtained the frequency of decisions by category, which is worth mentioning that each city exports more than one product, with 21 municipalities taking part in AHP decision-making.

Replacing the AHP percentage table with the respective WFs of the evaluated products, a histogram was also made to verify the decision

Table 6 – Categories exported by each municipality.

Product category	Municipalities
Footwear	Aracati, Brejo Santo, Camocim, Fortaleza, Horizonte, Itapajé, Itapipoca, Juazeiro do Norte, Maranguape, Pacatuba, Quixeramobim, Quixeré, Senador Pompeu, Sobral, Uburetama
Leather	Beberibe, Camocim, Cascavel, Maracanaú, Maranguape, Quixeramobim, Sobral
Fillets or other frozen, fresh or chilled meat	Acaraú, Aracati, Cascavel, Fortaleza, Icapuí, Itarema, São Gonçalo do Amarante
Fresh or dried fruit and nuts, fresh or dried	Aquiraz, Barbalha, Beberibe, Eusébio, Fortaleza, Icapuí, Itarema, Jaguaribe, Limoeiro do Norte, Pacajus, Pereiro, Quixeré, Ubajara
Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations	Aquiraz, Aracati, Cascavel, Eusébio, Fortaleza, Itarema, Maracanaú, Russas
Fruit juices and vegetables	Aquiraz, Aracati, Barbalha, Eusébio, Fortaleza, Itapipoca, Jaguaribe, Paraipaba, Pereiro, Ubajara
Cotton fabric, screens (not including tapes or specials)	Eusébio, Fortaleza, Horizonte, Maracanaú, Pacajus

Source: Brasil (2020).

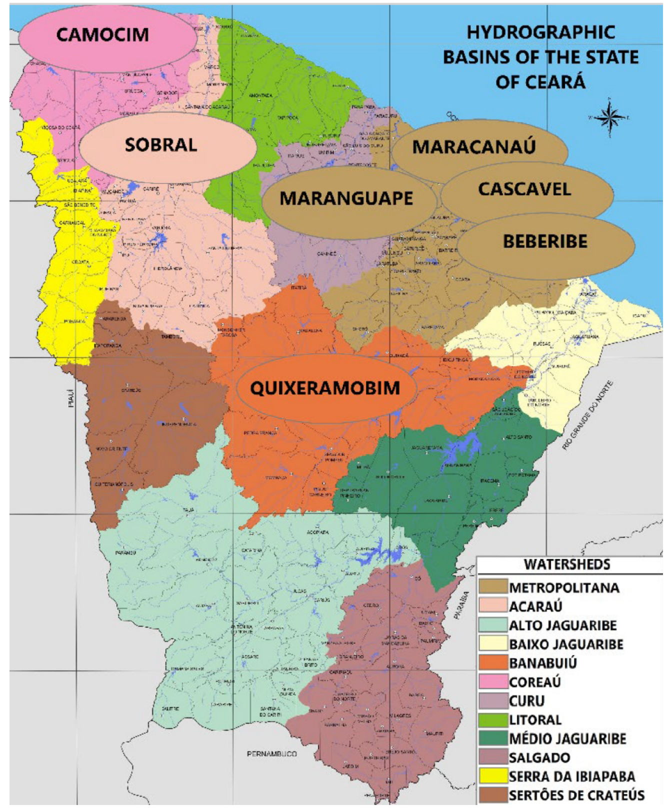

Figure 3 – Map cities and watersheds of the leather category.

Figure 2 – Map cities and watersheds of the footwear category.

Figure 4 – Map cities and watersheds in the category of fillets and other fish meats.

RBCIAMB | v.56 | n.4 | Dec 2021 | 608-620 - ISSN 2176-9478

Figure 5 – Map cities and watersheds of the fruit and nut category.

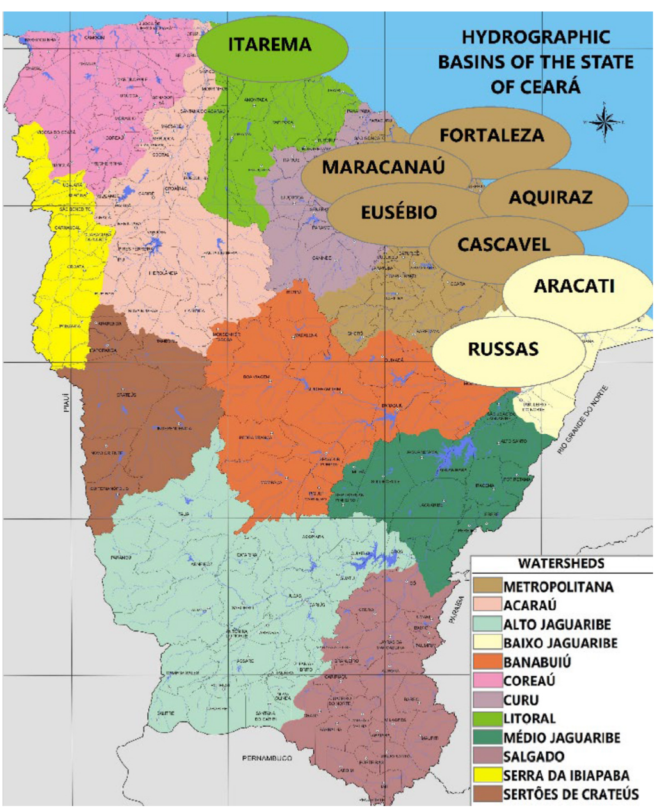

Figure 6 – Map cities and watersheds of the category of other fats and oils.

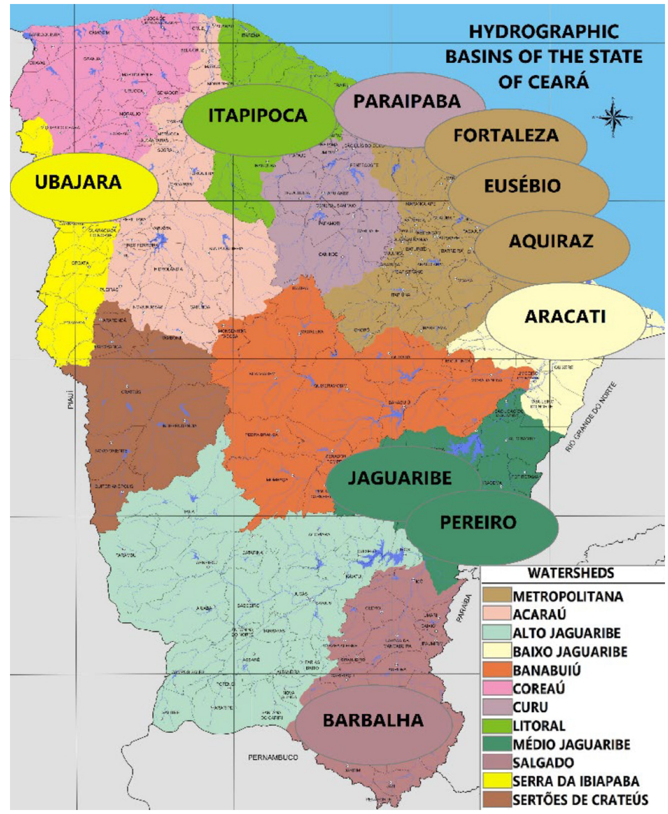

Figure 7 – Map of cities and watersheds in the category of fruit or vegetable juices.

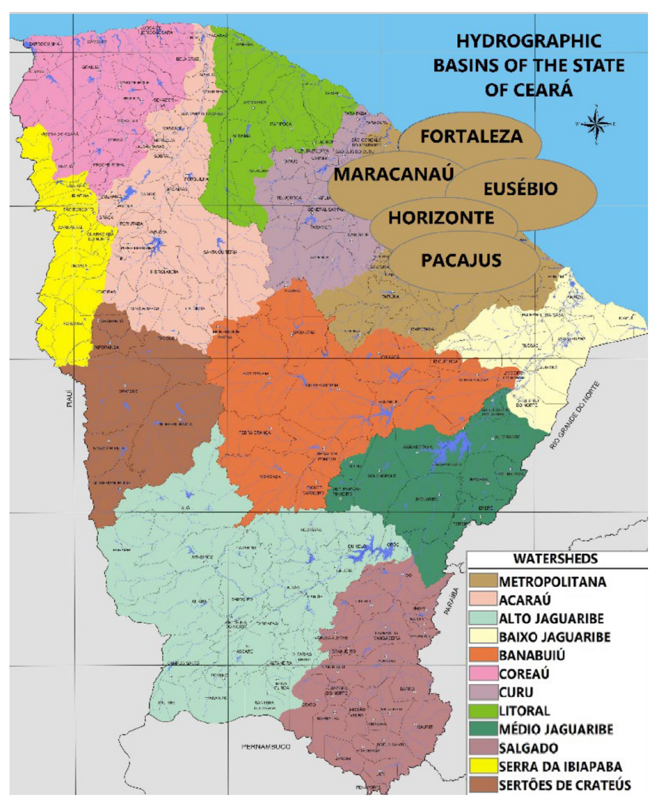

Figure 8 – Map cities and watersheds of the cotton fabric category.

Table 7 – Criteria admitted for the analytical hierarchy process.

Product	Water footprint (m^3/t)	Price in MI (US$)	Tons Ceará
Footwear	18,770	236	12,681.55
Leather	18,770	52.3	21,327.13
Fillets or other frozen, fresh or chilled meat	4,325	4.53	1,816.73
Fresh or dried fruit and nuts, fresh or dried	3,500.6	161	164,901.38
Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations	1,782	68.8	16,381.92
Fruit or vegetable juices	1,018	57.6	64,529.77
Cotton fabric, screens (not including tapes or specials)	9,982	32	5,279.04
	More importance	Medium importance	Low importance

Source: Hoekstra et al. (2011) and Brasil (2020).

Table 8 – Percentage table for analytical hierarchy process (AHP).

FINAL PERCENTAGE TABLE AHP							
Cities	Footwear	Leather	Fillets and others Meats	Fruits and Nuts	Other fats	Fruit na Vegetable Juices	Cotton Fabric
Aquiraz	x	x	x	0.3165	0.2325	0.4499	x
Aracati	0.21238	x	0.1147	x	0.2227	0.4491	x
Barbalha	x	x	x	0.3862	x	0.6128	x
Beberibe	x	0.3061	x	0.6928	x	x	x
Camocim	0.5682	0.4308	x	x	x	x	x
Cascavel	x	0.1397	0.2080	x	0.6512	x	x
Eusébio	x	x	x	0.3963	0.1392	0.0879	0.3756
Fortaleza	0.0783	x	0.0253	0.5009	0.1187	0.2300	0.0468
Horizonte	0.3927	x	x	x	x	x	0.6063
Icapuí	x	x	0.1421	0.8569	x	x	x
Itapipoca	0.3079	x	x	x	x	0.6911	x
Itarema	x	x	0.0585	0.4292	0.5113	x	x
Jaguaribe	x	x	x	0.4020	x	0.5969	x
Maracanaú	x	0.1867	x	x	0.6707	x	0.1410
Maranguape	0.6323	0.3667	x	x	x	x	x
Pacajus	x	x	x	0.8540	x	x	0.1449
Pereiro	x	x	x	0.4259	x	x	x
Quixeramobim	x	x	x	x	x	0.5730	x
Quixeré	0.1331	x	x	0.8658	x	x	x
Sobral	0.6323	0.3667	x	x	x	x	x
Ubajara	x	x	x	0.3882	x	0.6108	x

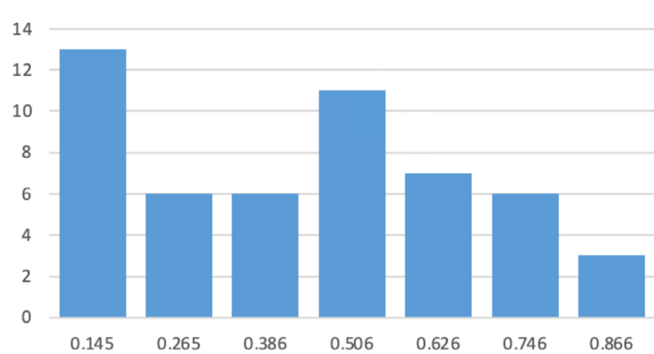

Figure 9 – Histogram of analytical hierarchy process percentages by cutoff frequency.

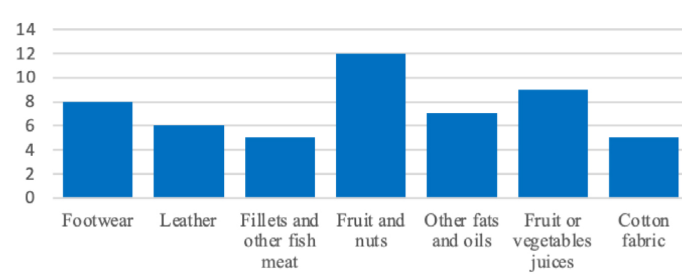

Figure 10 – Histogram of analytical hierarchy process decision percentages by product category.

percentage of the AHP and the WFs of the classes by cutting section of the chosen products (Figure 11).

As previously done, the cutoff frequencies calculated were changed by the WFs of the seven product categories, with the intention of visualizing the distribution of the results of decisions by WF (Figure 12).

The WF of the footwear was admitted to be the same as that of the leather category. Here we are analyzing the cities that entered the AHP decision process, and not the method decision; therefore, the WF that obtained a higher frequency was the leather and footwear sector.

Table 9 summarizes the product category for export selected by the AHP decision-making method for each exporting municipality, including those that did not participate in the decision-making, being the only product that exports the most sustainable.

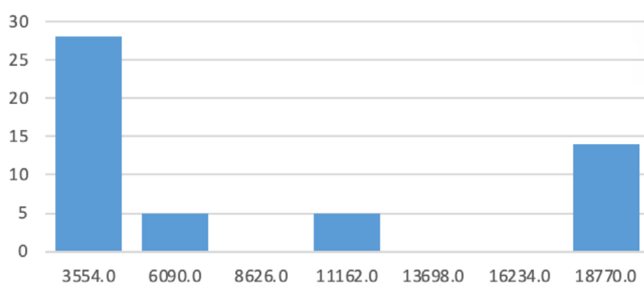

Figure 11 – Histogram of analytical hierarchy process and water footprint decision percentages.

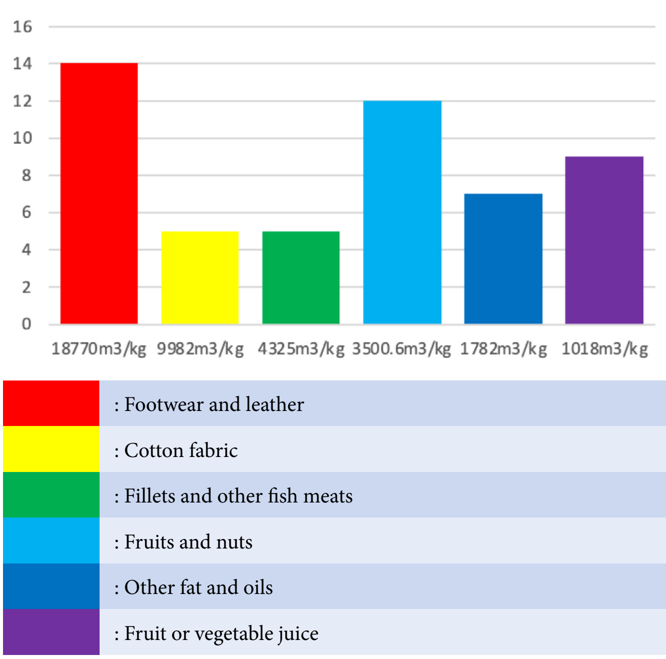

Figure 12 – Analytical hierarchy process decision percentages by water footprint.

Table 9 – Analysis of the most sustainable product for each city to export.

City	More sustainable product
Acaraú	Fillets or other frozen, fresh or chilled meat
Aquiraz	Fruit or vegetable juices
Aracati	Fruit or vegetable juices
Barbalha	Fruit or vegetable juices
Beberibe	Fresh or dried fruit and nuts
Brejo Santo	Footwear
Camocim	Footwear
Cascavel	Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations
Eusébio	Fruit or vegetable juices
Fortaleza	Fruit or vegetable juices
Horizonte	Cotton fabric, screens (not including tapes or specials)
Icapuí	Fresh or dried fruit and nuts
Itapagé	Footwear
Itapipoca	Fruit or vegetable juices
Itarema	Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations
Jaguaribe	Fruit or vegetable juices
Juazeiro do Norte	Footwear
Maracanaú	Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations
Maranguape	Footwear
Pacajus	Fresh or dried fruit and nuts
Pacatuba	Footwear
Paraipaba	Fruit or vegetable juices
Pereiro	Fruit or vegetable juices
Quixeramobim	Footwear
Quixeré	Fresh or dried fruit and nuts
Russas	Other processed animal or vegetable fats and oils, waxes, mixtures or non-food preparations
São Gonçalo do Amarante	Fillets or other frozen, fresh or chilled meat
Senador Pompeu	Footwear
Sobral	Footwear
Ubajara	Fruit or vegetable juices
Uruburetama	Footwear

The result chose, through the objective "more sustainable product," the alternative that is more consistent with the criteria and the importance attributed.

Of the 32 cities in the state of Ceará that export products of agricultural origin, 11 use the reservoirs of the Metropolitan Hydrographic Basin, followed by the Low Jaguaribe Basin with 5, Coast Basin with 4, and Curu and Salgado Basins with 3; Acaraú Basins, Banabuiú, and Middle Jaguaribe with 2 municipalities and Ibiapaba Hill and Coreaú Basin with 1. From this fact, we observe that the water potential of Ceará is not used as it should, as we only use 10 of the 12 hydrographic basins existing in the state and the Metropolitan Basin is the most required and it has the need to supply according to IBGE (2019) more than 4,074,730 inhabitants of the metropolitan region of Fortaleza (Figure 13).

This study focusing on the current debate on the local dimension in water resource governance aims to analyze empirical cases of water management in the Brazilian semi-arid, based on the performance of the intermunicipal consortia and the São Francisco River Basin committee. Abers and Keck (2013) argued that the institutionalization of river basin committees has yielded very heterogeneous results, particularly in relation to the participation of municipalities. Thus, throughout the research, it was seen that, in several surveys, the cases of intermunicipal consortia and river-based committee proved to be opportunities for greater visibility is the action of the local participants. It was found that there is a need for strategies that enable a well-defined organization of cooperation and perception at local levels among the new governance arrangements (Kasahara et al., 2020).

Figure 13 – Map exporting cities of the state of Ceará in 2019 and their hydrographic basins.

Conclusions

The category "fruit or vegetable juices" was deferred by the decision-making method as the most sustainable by the municipalities in the state of Ceará that export to other countries. With the aid of the histograms, it was possible to analyze that the distribution of cutoff values in relation to decision-making proved to be well distributed, although there were few decisions by product classes that obtained about 80% assertiveness in the results. The second highest percentage is of medium cutoff value, showing that the second majority of decisions were elected with 50% assertiveness.

The histogram of the AHP decision percentage and WF has the cutoff frequency calculated by maximum and minimum between the WFs of each product that entered the decision-making process. Thus, Figure 11 shows that the majority of the products chosen or not have the lowest footprints of the study is the most important issue, taking into account the discrepancy between the values of the smallest and largest WF.

The study found that the footwear sector has the greatest economic importance in the state, being the category that exports the most, with 15 cities, and with the highest export price than the other classes. However, due to its high WF, it cannot be elected as the most sustainable product category. Therefore, the most sustainable exported product category chosen is "fruit or vegetable juices," as it is the one that best suits the requirements of WF, price, and volume.

The basin committees in the state of Ceará reflect the same reality observed in the studies that point to an inadequacy of the water framing instrument, making it difficult to control water quality in the gray WF. This scenario of framing is not viable in the Ceará basins because the rivers are intermittent and part of the year is dry. Another important fact is that the need to assume the WF as an instrument for the management of water resources is suggested in order to better control this quality in the face of the difficulties encountered in the basin committees.

When analyzing the water potential of Ceará, we see that there is still a lot to explore as the state's water requirement for the production of goods to be exported is concentrated around 32% only in the Metropolitan Basin. The requirement for water by only one basin can lead to very low levels of reservoirs that may not support the current demand in the future. The other river basins are underused and study with fair logistics is recommended for better management and use of water resources in the state of Ceará, or even create forms of government incentives so that companies further away from the capital can also produce and sell their products at international level.

RBCIAMB | v.56 | n.4 | Dec 2021 | 608-620 - ISSN 2176-9478

Contribution of authors:

Leite, I.S.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Data curation. Sabiá, R.J.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Visualization, Resources, Supervision, Project administration. Matos, A.P.: Formal analysis, Investigation, Validation, Visualization, Data curation. Silva, C.C.: Methodology, Formal analysis, Investigation, Validation.

References

Abers, R. N.; Keck, M. E., 2013. Practical authority: agency and institutional change in Brazilian water politics. Oxford and New York, Oxford University Press.

Agência Nacional de Águas (ANA), 2018. Plano Estadual dos Recursos Hídricos (Accessed September 28, 2020) at: https://dadosabertos.ana.gov.br/datasets/d5c8d1093d0a44d8aa2e36d6d00f4422_0.

Almeida, A., 2013. Processos de decisão nas organizações: construindo modelos de decisão multicritério. Atlas, São Paulo.

Barker, T.; Zabinsky, Z., 2010. Designing for recovery-A solid reverse supply chain can help you recover, renew, recycle. Industrial Engineer, v. 42, (4), 38.

Barreto, J. F.; Neto, J. D.; Farias, S. A. R., 2010. Avaliação socioeconômica e hídrica dos municípios da sub-bacia hidrográfica do rio Taperoá, PB. Qualit@s Revista Eletrônica, v. 9, (1), 1-13. http://dx.doi.org/10.18391/qualitas.v9i1.585.

Brasil. Conselho Nacional do Meio Ambiente – CONAMA. 2005. Resolução n° 357, de 17 de março de 2005 do Conselho Nacional do Meio Ambiente-CONAMA. Dispõe sobre a classificação dos corpos de água. Diário Oficial da União.

Brasil. Ministério da Indústria, Comércio Exterior e Serviços (MDIC), 2020. Comex Vis: Visualizações de Comércio Exterior (Accessed September 12, 2020.) at: http://www.mdic.gov.br/comercio-exterior/estatisticas-de-comercio-exterior/comex-vis.

Companhia de Gestão dos Recursos Hídricos (COGERH), 2018. Bacias hidrográficas (Accessed July 20, 2020) at: https://portal.cogerh.com.br.

Falkenmark, M.; Molden, D., 2008. Wake up to realities of river basin closure. International Journal of Water Resources Development, v. 24, (2), p. 201-215. http://dx.doi.org/10.1080/07900620701723570.

Fiel, A.; Strasburg, V.; Spilki, F., 2017. Variáveis intervenientes na existência de comitês de bacias hidrográficas no Brasil. Ambiente & Água (Online), v. 12, (2), 340-350. https://doi.org/10.4136/ambi-agua.1828.

Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME), 2019. Portal Hidrológico do Ceará – Reservatórios (Accessed July 16, 2020.) at: http://www.funceme.br.

Guimarães, P.; Xavier, Y., 2008. A regulamentação da água virtual nos sistemas ambientais. Ambiente e Sociedade, p. 702-717.

Hoekstra, A.; Chapagain, A., 2007. The water footprints of Morocco and the Netherlands: Global water use as a result of domestic consumption of agricultural commodities. Ecological Economics, v. 64, (1), 143-151. https://doi.org/10.1016/j.ecolecon.2007.02.023.

Hoekstra, A.; Chapagain, A.; Aldaya, M.; Mekonnen, M., 2011. Water footprint assessment manual: setting the global standard. Earthscan, London.

Instituto Brasileiro de Geografia e Estatística (IBGE), 2019. Cidades e Estados. (Accessed February 20, 2020) at: https://www.ibge.gov.br/cidades-e-estados/ce.html.

Instituto de Pesquisa e Estratégia Econômica do Ceará (IPECE), 2010. Ceará em Números (Accessed January 4, 2020.) at: https://www.ceara.gov.br/2010/03/13/ceara-em-numeros/.

Kaplowitz, M. D.; Witter, S. G., 2008. Agricultural and residential stakeholder input for watershed management in a mid-Michigan watershed. Landscape and Urban Planning, v. 84, (1), p. 20-27. http://dx.doi.org/10.1016/j.landurbplan.2007.06.004.

Kasahara, Y.; Sobral, M.; Melo, M., 2020. A dimensão local na governança dos recursos hídricos: a experiência de consórcios e comissões intermunicipais de bacias de rio. Revista Brasileira de Ciências Ambientais (Online), v. 55, (3), 282-297. https://doi.org/10.5327/Z2176-94782020071.

Kurokawa, E.; Bornia, A., 2002. Utilizando o histograma como uma ferramenta estatística de análise da produção de água tratada de Goiânia. XXVII Congresso Interamericano de Ingeniaría Sanitaria y Ambiental, Cancun, México.

Lopes, P. A., 1999. Probabilidades & estatística. R&A, Rio de Janeiro, 174 pp.

Mahmoud, M. I.; Gupta, H. V.; Rajagopal, S., 2011. Scenario development for water resources planning and watershed management: Methodology and semi-arid region case study. Environmental Modelling & Software, v. 26, (7), p. 873-885. http://dx.doi.org/10.1016/j.envsoft.2011.02.003.

Porto, R. L. L.; Filho, K. Z.; Marcellini, S. S., 1999. Escoamento superficial: análise do hidrograma. Departamento de Engenharia Hidráulica e Sanitária, São Paulo.

Saaty, T., 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology, v. 15, (3), 234-281. https://doi.org/10.1016/0022-2496(77)90033-5.

Silva, F. D.; Salgado, M. S.; Silva S. M., 2015. Desenvolvimento de projetos sustentáveis usando a plataforma BIM: estudo de caso na cidade do Rio de Janeiro. Latin American and European Conference on Sustainable Buildings – EURO ELECS, Guimarães, Portugal, v. 2, 1513-1522.

Souza, V.; Pizella, D., 2021. O quadro brasileiro de água doce superficial em rios dominados por sindicatos: desafios e perspectivas para a gestão da qualidade da água. Revista Brasileira de Ciências Ambientais (Online), v. 56, (1), 1-15. https://doi.org/10.5327/Z2176-947820200707.

Tramarico, C.; Salomon, V.; Marins, F.; Muniz Jr., J., 2012. Modelagem com AHP e BOCR para a seleção de prestadores de serviços logísticos. Pesquisa Operacional para o Desenvolvimento, v. 4, (2), 139-159.

Vargas, R., 2010. Utilizando a programação multi-critério (Analytic Hierarchy Process – AHP) para selecionar e priorizar projetos na gestão de portfólio. PMI Global Congress, Washington, D.C.

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Quali-quantitative characterization of biogas with the temporal behavior of organic load on wastewater treatment plant with upflow anaerobic sludge blanket reactors through measurement in full-scale systems

Caracterização quali-quantitativa do biogás e suas relações com o comportamento temporal da carga orgânica em reatores anaeróbios de fluxo ascendente, em escala plena, no tratamento do esgoto sanitário, empregando equipamentos de medição online

Orlando Antonio Duarte Hernandez[1], *Ana Caroline Paula*[1], *Gustavo Rafael Collere Possetti*[2], *Mauricio Pereira Cantão*[1], *Miguel Mansur Aisse*[1]

ABSTRACT

This study aims to present the time behavior of wastewater flow parameters, organic matter, biogas flow, biogas composition, and its relations, measured through online sensors, in a municipal wastewater treatment plant (WWTP) operating full-scale upflow anaerobic sludge blanket (UASB) reactors, installed in the south of Brazil. WWTP has online measurement devices to evaluate some physicochemical variables of the sewage and the biogas. The COD analyzer (UV–Vis probe), ultrasonic flow meter, biogas flow meter, and biogas composition analyzer were the equipment used. The monitoring occurred for two time periods each of 72 h and one time period for 48 h in the year 2018. Data were checked with descriptive statistics, data independence was checked through the autocorrelation Box–Ljung test, normality behavior was checked with several tests (Shapiro–Wilk, Kolmogorov–Smirnov, Lilliefors, Anderson–Darling, D'Agostino K^2, and Chen–Shapiro), and Spearman's correlation coefficient was used to evaluate the correlations among the parameters. The mean sewage flow was 345 ± 120 $L.s^{-1}$; removed organic load was, in average, 48%; biogas quality values were 82.32% ± 3.62% v/v (CH_4), 2.66% ± 1.19% v/v (CO_2), and 3453 ± 1268 ppm (H_2S); and the production per capita

RESUMO

O trabalho teve como objetivo a caracterização qualiquantitativa do biogás e suas relações com o comportamento temporal da carga orgânica em reatores anaeróbios de fluxo ascendente (UASB), em escala plena, no tratamento do esgoto sanitário, empregando equipamentos de medição *online*. O trabalho foi conduzido em uma estação de tratamento de esgotos (ETE) instalada no Sul do Brasil. A ETE possui dispositivos de medição *online* para avaliar algumas variáveis físico-químicas do esgoto e do biogás. Os equipamentos utilizados foram o analisador Demanda Química de Oxigênio (DQO) [sonda ultravioleta visível (UV–Vis)], medidor ultrassônico, medidor de biogás e analisador de composição de biogás. O monitoramento ocorreu por dois períodos de 72 horas cada e um período de 48 horas, no ano de 2018. Os dados foram analisados com estatística descritiva, a independência dos dados foi averiguada por meio do teste de correlação Box-Ljung, a normalidade foi verificada pelos testes Shapiro-Wilk, Kolmogorov-Smirnov, Lilliefors, Anderson-Darling, D'Agostino K2 e Chen-Shapiro, e foi usado o método de Spearman para avaliar as correlações entre os parâmetros. A vazão média de esgoto foi 345 ± 120 Ls^{-1}. A carga orgânica removida foi, em média, 48%. Os valores de qualidade do

[1]Universidade Federal do Paraná – Curitiba, (PR), Brazil.

[2]Companhia de Saneamento do Paraná – Curitiba (PR), Brazil.

Correspondence address: Orlando Antonio Duarte Hernandez – Graduate Program in Water Resources and Environmental Engineering, Department of Hydraulics and Sanitation, Universidade Federal do Paraná – PO Box 19011 – Jardim das Américas – CEP: 81531-990 – Curitiba (PR), Brazil. E-mail: oranduher1@gmail.com

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obtained was 4.51 ± 1.65 $NL.hab^{-1}.d^{-1}$. It was estimated an electric power generation of 3118.6 $kWh.d^{-1}$, which is equivalent to an installed power of 130 KW. The behavior of removed organic load and biogas flow ($Nm^3.h^{-1}$), produced in the treatment plant, showed variable, periodic, and nonstationary time behavior.

Keywords: biogas composition; biogas flow; chemical oxygen demand probe; sewage; ultrasonic flowmeter.

biogás foram, para o metano (CH4), 82,32% ± 3,62% v/v (percentagem volume-volume), para o dióxido de carbono (CO2) 2,66% ± 1,19% v/v e para o sulfeto de hidrogênio (H2S) 3453 ± 1268 ppm. A produção de biogás *per capita* obtida foi 4,51 ± 1,65 $NL.hab^{-1}.d^{-1}$. Foi estimada uma produção de energia eléctrica de 3.118,6 kWh/d, o que é equivalente a uma potência instalada de 130 KW. O comportamento da carga orgânica removida e da vazão de biogás ($Nm3.h^{-1}$) produzida na estação de tratamento, apresentaram um comportamento temporal variável, periódico e não estacionário.

Palavras-chave: composição biogás; esgoto; medidor ultrassônico; sonda demanda química de oxigênio; medidor ultrassônico; vazão biogás.

Introduction

The treatment of sewage in warm regions, such as South America and Caribe, generally occurs via anaerobic technologies, such as upflow anaerobic sludge blanket (UASB) reactors. Von Sperling and Oliveira (2009), Noyola et al. (2012), Chernicharo et al. (2015), and Mainardis et al. (2020) recognized the great advantages of UASB, since it allows the reduction of the costs of implementation, operation, and maintenance of wastewater treatment plants (WWTP); besides, it requires a low initial investment.

UASB reactors are well known for their efficiency on removal of organic matter and solids, low energy demand, and without adding chemicals. The structure of these reactors basically consists of a tank with a bottom layer of biological sludge and a settler and gas deflector on the top container. With the proper operation, a tendency of separation of solid, liquid, and gas phases occurs (Lettinga et al., 1983; Chernicharo et al., 1999). For these authors, among the main parameters related to the design of UASB reactors, hydraulic volumetric rate (HVR), hydraulic retention time (HRT), volumetric organic loading rate (Lv), and upflow velocity should be accounted.

Many studies have been conducted expressing or comparing the mean volumetric organic loading to the efficiencies of UASB reactors in the treatment of sewage. In this regard, volumetric organic loading is recommended to be between 2.5 and 3.5 kg $COD.m^3.d^{-1}$ (Chernicharo et al., 1999; von Sperling and Chernicharo, 2005; Chernicharo et al., 2015). Previous studies from Lettinga et al. (1983) reported lower loads, similar to Aisse et al. (2002), presenting values of 1.80 kg $COD.m^{-3}.d^{-1}$ for the hydraulic retention time of 8 h. Aisse et al. (2002) mentioned the COD of (151 ± 64) $mg.L^{-1}$ in the effluent of a UASB reactor treating urban wastewater. Considering the influent COD of (453 ± 147) $mg.L^{-1}$, the authors obtained the COD efficiency removal of 67%.

The gas phase, inherent to sewage treatment in UASB reactors, represents a great advantage, especially regarding biogas production with elevated methane content. Biogas in UASB reactors, treating municipal and domestic wastewater, presents its composition as follows: methane (70–80%), nitrogen (10–25%), carbon dioxide (5–10%), and H_2S (1,000–2,000 ppm) (Noyola et al., 2006; Possetti et al., 2019). The proportion among these components depends on the type of biological treatment applied and on the substrate, which could be urban solid residues, domestic and municipal wastewater, sludge from municipal wastewater treatment, animal waste, among others (Venkatesch and Elmi, 2013; Mainardis et al., 2020).

Methane is associated with greenhouse gases, with CH_4 global warming potential (GWP) being 28 times superior to CO_2; thus, biogas combustion for energy production could avoid methane emissions and substitute fossil fuels, also reducing the CO_2eq tons released to the atmosphere (IPCC, 2014). Methane has a lower calorific value of 9.9 $kWh.Nm^{-3}$, and its concentration defines the potential of recovering energy from the biogas; electric power production from biogas is an alternative with great expansion potential in Brazil. Biogas production rates, verified by Lobato et al. (2012), from 9.8 to 17.1 $NL.hab^{-1}.d^{-1}$, and Cabral et al. (2017b), from 3 to 138 $NL(CH_4)/kg(COD_{remov})$, have been used by researchers and wastewater treatment plant managers.

Possetti et al. (2013), Waiss and Possetti (2015), and Cabral et al. (2017b) observed a direct correlation between the influent sewage flow and rainfall, with the consequent lowering of HRT and the production of biogas. For Possetti et al. (2018), the rainwater results in sewage dilution (increase of flow and lowering of COD concentration), significantly reducing the biogas production. Mota et al. (2019) studied the variations in the concentration of methane (CH_4), carbon dioxide (CO_2), and oxygen (O_2), during 24-h periods, in a sanitary landfill, located in the Northeast Region of Brazil, with a predominantly hot tropical and mild semi-arid climate. The research area showed no significant seasonal variation, only periods with more or less rainfall. There were few changes in the climate of the semi-arid region of Northeastern Brazil during the year.

Pagliuso and Regattieri (2008) observed that the increasing municipal demand for electric power requires alternative sources, thus making it necessary a deep knowledge of the time behavior of biogas generated in anaerobic WWTP, which is still little used in Brazil. Electricity generation and consumption in the WWTP itself are options used worldwide. Some guidelines on distributed electricity from biogas are available in Rosenfeldt et al. (2015), Cabral et al. (2017a), Gomes et al. (2017), and Possetti et al. (2019).

New technologies rising in the market, especially those related to online and remote sensing, allow measurements *in loco* and in real time of biogas production in UASB reactors. Mota et al. (2019) recommended the development of further research, and estimating the potential biogas is particularly important to assess the feasibility of its exploitation for energy purposes.

In this context, this study aims to present the time behavior of wastewater flow parameters, organic matter, biogas flow, and biogas composition, measured with online sensors, in a municipal wastewater treatment plant operating with UASB reactors, in full scale.

Materials and Methods

This study took place in a medium-size WWTP, installed in the south of Brazil, with a design flow of 420 $L.s^{-1}$ of domestic sewage and serving approximately 180,000 inhabitants. The wastewater pretreatment occurs with two mechanized screens and one grit chamber. The biological treatment is done in six UASB reactors (secondary treatment), and post-treatment of anaerobic effluent occurs in aerated followed by sedimentation ponds. The biogas generated by the UASB reactors at the plant is destroyed in an enclosed flare.

The treatment plant has online measurement devices to evaluate the behavior of some physicochemical variables of the sewage and the biogas (Figure 1). The COD meter (probe) in the sewage, the sewage flowmeter, the biogas flowmeter, and the biogas quality analyzer were the equipment used in this research.

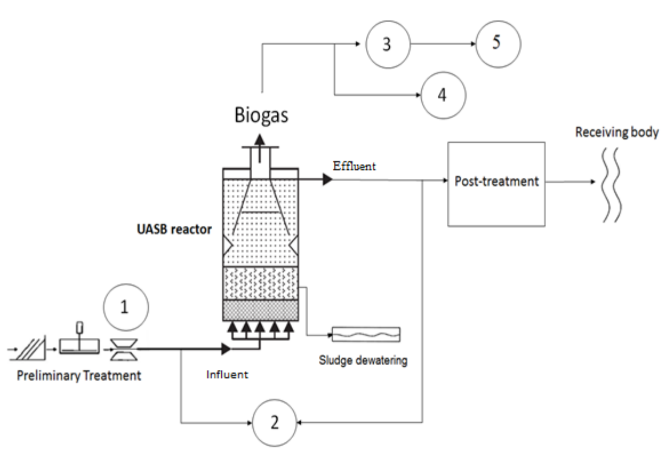

Figure 1 – Flowsheet of WWTP liquid phase and measurement equipment location. (1) Sewage flowmeter; (2) COD concentration meter; (3) biogas flowmeter; (4) biogas quality analyzer; and (5) biogas enclosed flare.

Instrumentation

The COD measurement system is composed of a spectrometer and a control unit; spectrometer probes work according to the principle of UV–Vis spectrometry. The system can determine concentrations between 100 and 3,250 $mg(COD).L^{-1}$. A detailed description of the probe can be found, e.g., in Langergraber et al. (2003) and Hernandez et al. (2018). The probe possesses an uncertainty of 1.8%, for a probability coverage of 95.45% (Hernandez, 2019).

The treatment plant possesses an ultrasound flowmeter, with a resolution of ±0.2%, located over a Parshall flume in the inlet of the treatment plant. The equipment has an output with analog standard 4–20 mA, with an uncertainty of ±0.001%, for a probability coverage of 95.45% (Hernandez, 2019).

The biogas flow was measured with a thermal dispersion transmitter, which is basically formed by two temperature probes (insert in the gas flow) and a heater. The energy required to maintain the sensor warm to a constant temperature is directly proportional to the gas velocity. Hence, correlations between energy and velocity are used to calculate the gas production. In this regard, the uncertainty of the equipment is 10.57% for a probability coverage of 95.45% (Hernandez, 2019).

The gas analyzer is a measurement system composed of a static unity and a portable measurement device, which receives biogas samples collected in the burning line. The biogas analyzer uses selective infrared probes to measure CH_4 (0–100%) v/v and CO_2 (0–100%) v/v, and electrochemical probes to measure O_2 (0–25%) v/v and H_2S (0–5,000) ppm. Regarding the uncertainties, for the infrared probes, it is ± 1.5%, whereas for the electrochemical probes, it was assumed to be ± 0.03% for a probability coverage of 95.45%.

Energy recovery from biogas

The potential of energy generation via the use of the biogas produced in the WWTP was estimated through the following Equation 1 (Cabral et al., 2017a):

$$EP = Q_{CH4} \cdot EC \cdot \eta_{electric} \quad (1)$$

Where:
EP = energy potential ($kWh.d^{-1}$);
Q_{CH4} = methane flow rate ($Nm^3.d^{-1}$);
EC = energetic content of methane (9.9 $kWh.Nm^{-3}$);
$\eta_{electric}$ = electrical efficiency of a combined heat and power engine (36%).

The power of the electric engine is calculated by dividing by 24 h, in case of continuous use.

Statistical evaluation criteria

Temperature and operational data collected in the treatment plant were used, and precipitation data were registered with a pluviometer also located in the plant. In addition, the obtained values were transmitted to a database and subsequently treated in electronic datasheets for the elaboration of the descriptive statistics. The monitoring period occurred hourly for three consecutive days (72 h), in August and in September (samplings 1 and 2); in October, the data were collected for 48 consecutive hours (sampling 3), all in the year 2018. The Spearman's rank correlation coefficient (r_s) was used to evaluate the monotonic correlations among the parameters for the significance level of 0.05.

Rough data were checked with descriptive statistics and analyzed for outliers identification with the interquartile amplitude method. Data independence was checked through the autocorrelation Box–Ljung test (Ljung and Box, 1978), and the normality behavior was verified with the following normality tests: the Shapiro–Wilk test of normality (Shapiro and Wilk, 1965) and the Kolmogorov–Smirnov, Lilliefors, Anderson–Darling, D'Agostino K2, and Chen–Shapiro tests (Adefisoye et al., 2016; Razali and Wah, 2011). If normal distribution and lack of autocorrelation are not to be rejected, for a 0.05 significance level, the *p*-values of the Shapiro–Wilk and Box–Ljung tests are higher than 0.05.

Results and Discussion

The climate of the South Region in Brazil, which is located below the Tropic of Capricorn in a temperate zone, is influenced by the system of disturbed circulation of the south, which produces the rains, mainly in the summer. In the evaluation period, the wastewater collection system was subjected to atmospheric precipitations of up to 38 mm/day. Regarding temperatures, the winter is cool and the summer is hot. The annual medium temperatures range from 14 to 22°C, and in places with altitudes above 1,100 m, it drops to approximately 10°C. Some parts of the southern region also have an oceanic climate. Table 1 shows the meteorological data obtained at the treatment plant.

Organic load

In Figure 2, it is possible to observe the hourly behavior of the organic load, calculated from the relation of the hourly measurements of the ultrasound meter (flow) and spectrometer probe (COD concentration). The probe was used to measure COD in the influent and effluent of the reactor. The reported mean values for the three evaluated periods [sampling 1 (72 measurements), sampling 2 (72 measurements), and sampling 3 (48 measurements)] were 688 ± 243 $mg.L^{-1}$ for the influent and 358 ± 116 $mg.L^{-1}$ for the effluent. The mean sewage flow was 345 ± 120 $L.s^{-1}$, inferior to the design flow. Therefore, the organic influent load in the reactors was 19,782 ± 9,949 $kg.d^{-1}$ and the organic effluent load was 10,133 ± 4,566 $kg.d^{-1}$.

The UASB reactors presented the mean COD removal efficiency of (47.25% ± 12.03%), and the mean removed organic matter was 9,989 ± 5,980 $kg(COD).d^{-1}$. Thus, the removal efficiencies were below the values reported by Aisse et al. (2002) and Oliveira and Von Sperling (2011). The removed organic matter was similar to the mean obtained by Bilotta and Ross (2016) for an equivalent treatment plant. The applied volumetric organic loading rate (Lv) was 1.70 ± 0.81 $kg(COD).m^3.d^{-1}$, which is in accordance with the values reported by Lettinga et al. (1983) and Aisse et al. (2002).

The obtained HRT value of 9.58 ± 2.29 h is coherent with the values reported by Oliveira and Von Sperling (2011), Chernicharo et al. (2015), and Metcalf and Eddy (2016), between 6 and 10 h, in terms of the mean flow, respecting the recommendations of the Brazilian Regulation NBR 12209 (ABNT, 2011).

Characterization and biogas production

Figure 3 presents the behavior of removed organic load ($kg.d^{-1}$) and biogas flow ($Nm^3.h^{-1}$) produced in the treatment plant. The curves present variable, periodic, and nonstationary time behavior, corroborating the biogas production values found by Possetti et al. (2013), Cabral et al. (2017b), and Possetti et al. (2019).

Figure 4A presents the behavior of the hourly biogas concentration (quality) and the histograms of these measurements. The collected values were 82.32% ± 3.62% v/v of methane (CH_4), 2.66% ± 1.19% v/v of carbon dioxide (CO_2), and 3,453 ± 1,268 ppm of hydrogen sulfide (H_2S). In order to complete the 100% v/v in the biogas composition, the difference was attributed to nitrogen (N_2) (~15%) v/v, dissolved in the raw sewage, and removed in the gas phase of the UASB reactor (Noyola et al., 2006).

The presented results indicate that the control and the monitoring of the generated biogas characteristics should be performed continuously, since variation might occur. These variations could occur due to

Table 1 – Meteorological data at the treatment plant.

Day	Temperature* (°C)	Weather	Pluviometry (mm)				
			Day (-1)**	Day (1)	Day (2)	Day (3)	Average (mm)
Sample Collection 1 (August)	17	Dry/cloudy	0	0	0	8	2
Sample Collection 2 (September)	20.1	Dry/rainy	0	2	2	4	2
Sample Collection 3 (October)	16	Rain	16	38	12	12	19.5

*The temperature means of the period evaluated; **the precipitation 1 day before starting the evaluation.

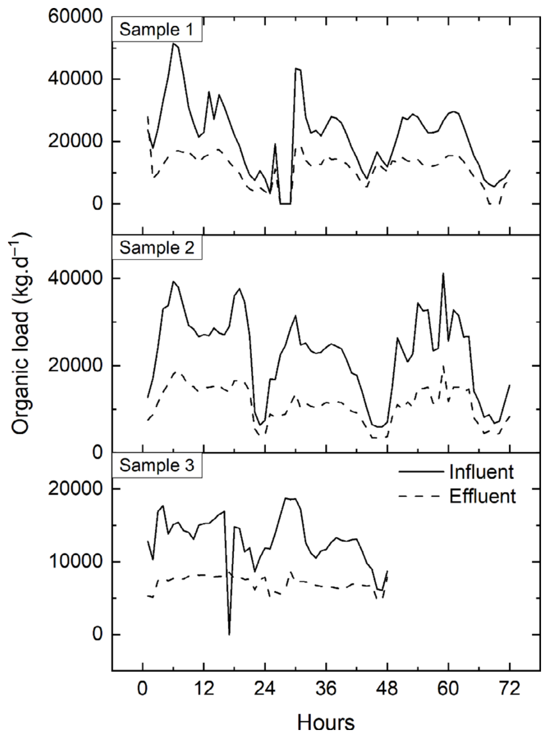

Figure 2 – Organic load at UASB reactors [kg(COD).d-1].

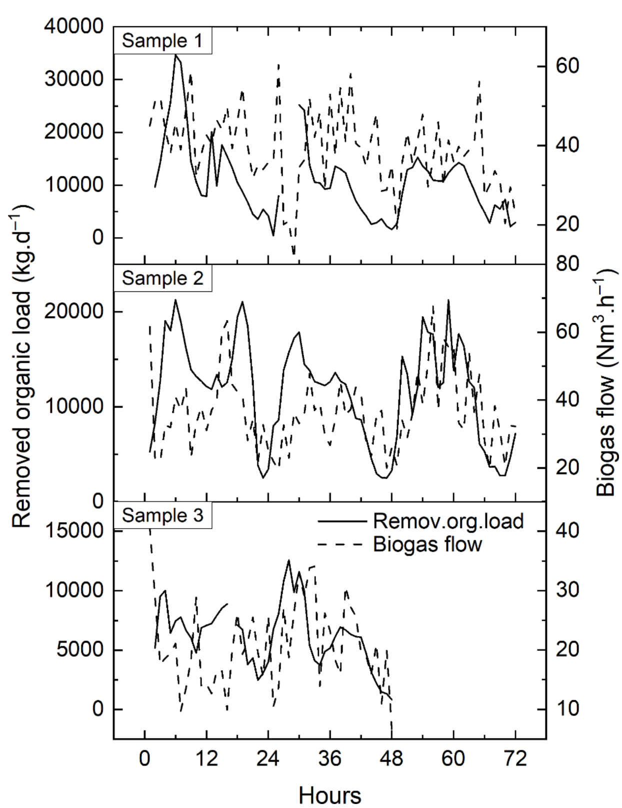

Figure 3 – Removed organic load curve (kg.d-1) and biogas flow curve (Nm³.h-1) as function of time (h).

climate, characteristics of the basin, and population that contributes to the treatment plant or occurrence of disturbances in the process of anaerobic digestion (WEF, 1994, 1998; Brasil, 2017).

Figure 4B shows the histograms of biogas hourly concentration. Regarding H_2S, it was possible to observe greater clusters between 1,700 and 3,700 ppm, highlighting the bimodal feature of the data. For samplings 1 and 2, values ranged mainly between 3,400 and 5,500 ppm, while for sampling 3, the values were located primarily in the interval between 500 and 3,000 ppm (see Figure 4A). The multimodality generally occurs when the data are collected from more than one process or condition. It is believed that rainfall could be the explanation for such behavior. In the period of sampling 3, the mean rainfall was 19.5 mm.d-1, in comparison with samplings 1 and 2, with a mean rainfall of 2 mm.d-1. The gas emission did not show a significant difference between the end of the rainy period and the end of the dry period (Pinheiro et al. 2019).

It is noteworthy that the minimum concentration of H_2S was 130 ppm, and the maximum was 5,457 ppm (Figure 4B). The obtained data could be interesting to adequate, for example, the chemical dosage in the systems for controlling odor, in anaerobic treatment reactors, or to increase the dosage in periods where a greater concentration of H_2S is expected. However, for the use of biogas to generate energy, gas treatment is required. For example, motor-generator groups typically demand concentrations of H_2S below 130 ppm for proper functioning (Soreanu et al., 2011).

Carbon dioxide presented, as seen by Noyola et al. (2006), an asymmetry of the collected data distribution to the left, with the minimum concentrations of 0.7% and maximum concentrations of 6.2% v/v. The histogram also indicates bimodal behavior.

Methane was within the maximum of 94.5% and the minimum of 76.6%. It could be mentioned that in the greater data series, grouping is in the interval between 75 and 87.5%. Moreover, it is evident that the lowest values occurred during sampling 3, rainy period, which is coherent with meteorological conditions (see Table 1) and the data by Possetti et al. (2013) and Cabral et al. (2017b).

The biogas flow showed a relative symmetric distribution, presenting higher frequency in the measurements when the equipment measured between 25 and 45 Nm³.d-1. Figure 4B shows a normal distribution line for the biogas flow; visual inspection indicates possible normality for this parameter but not for the gas concentrations. Biogas flow and removed organic load were tested with the OriginPro© software-based normality tests: Shapiro–Wilk, Chen–Shapiro, Anderson–Darling, Kolmogorov–Smirnov, Lilliefors, and D’Agostino K^2 (omnibus). Each collected sample and the ensemble of all samples were tested, and the results are shown in Table 2.

Razali and Wah (2011) compared the power of the first four tests (Shapiro–Wilk, Anderson–Darling, Lilliefors, and Kolmogorov–Smirnov), verifying that they are in descending order (S–W being the most powerful and K–S the less one). Razali and Wah (2011) also showed that the maximum normality test power occurs for N > 200 for symmetric distributions and N > 50 for asymmetric distributions.

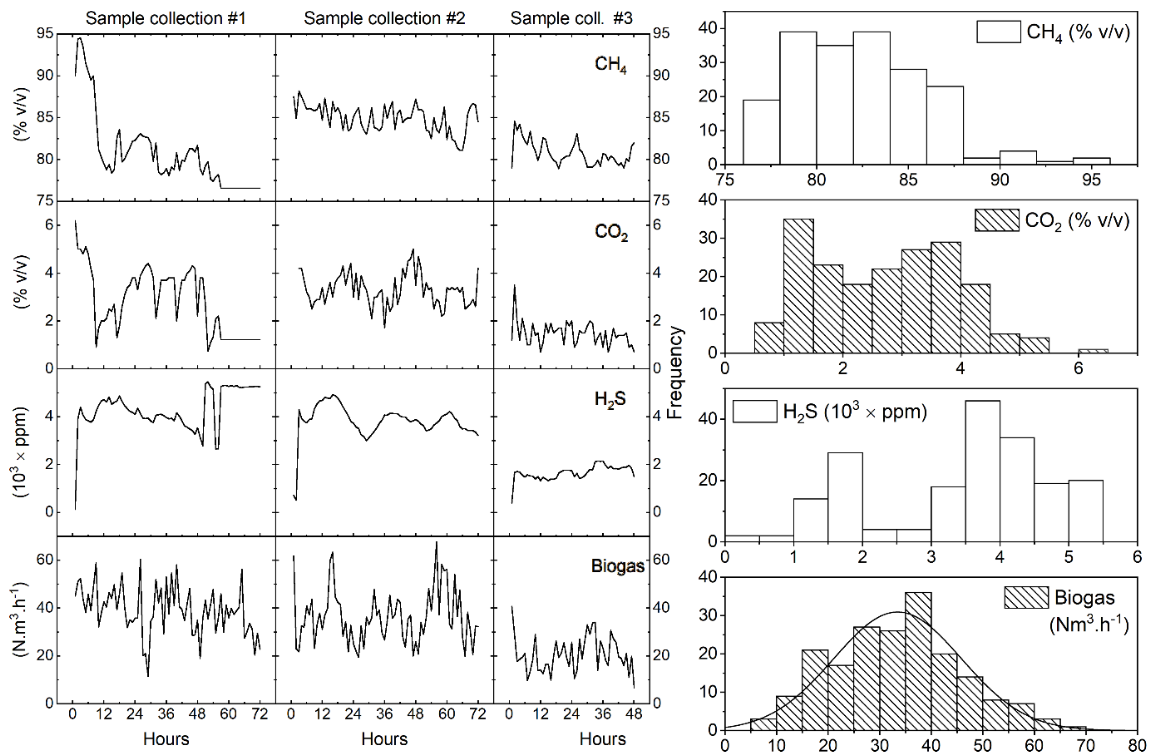

Figure 4 – Behavior of biogas hourly concentration (quality) and the histograms of these measurements. (A) Data distribution of the H_2S, CO_2, CH_4, and biogas flow data for all periods evaluated and (B) behavior of H_2S, CO_2, CH_4, and biogas flow of each period evaluated.

Table 2 – Normality test results for removed organic load and biogas flow.

Normality tests	Removed organic load				Biogas flow			
	Sample #1	Sample #2	Sample #3	All samples	Sample #1	Sample #2	Sample #3	All samples
Shapiro–Wilk	Reject	Reject	Cannot reject	**Reject**	Cannot reject	Reject	Cannot reject	**Cannot reject**
Anderson–Darling	Reject	Reject	Cannot reject	**Reject**	Cannot reject	Reject	Cannot reject	**Cannot reject**
Lilliefors	Reject	Reject	Cannot reject	**Reject**	Cannot reject	Reject	Reject	**Cannot reject**
Kolmogorov–Smirnov	Cannot reject	Reject	Cannot reject	**Cannot reject**	Cannot reject	Cannot reject	Cannot reject	**Cannot reject**
D'Agostino Omnibus	Reject	Reject	Cannot reject	**Reject**	Cannot reject	Reject	Cannot reject	**Cannot reject**
Chen–Shapiro	Reject	Reject	Cannot reject	**Reject**	Cannot reject	Reject	Cannot reject	**Cannot reject**

Table 2 demonstrates that the individual samples and the ensemble of all samples have different behavior. All the tests for the removed organic load sample #3 indicate possible normal distribution, while samples #1 and #2 clearly are not normal. Removed organic load all-samples ensemble reproduces the average behavior of major data. Only biogas flow sample #2 shows non-normal behavior.

Most normality tests show coherent results, the exceptions being Kolmogorov–Smirnov and Lilliefors, which is a modification of the K–S test. Normality test results indicate a non-normality trend for removed organic load and normality trend for biogas flow.

The biogas flow, along with the biogas quality, could be of great help, for example, in the operation of a sludge thermal drying system or the possible implementation of a gasometer, for the storage of biogas generated in the treatment plant.

When comparing the removed organic matter with the flow parameters, CH_4 percentage, CO_2 percentage, and concentration of H_2S,

Table 3 – Matrix of Spearman's correlation coefficient (r_s) between analyzed parameters*.

	Removed organic load	Biogas flow	CH_4	CO_2	H_2S
Removed organic load	1	0.43	0.36	0.29	0.32
Biogas flow		1	0.15	0.30	0.52
CH_4			1	0.57	-0.01
CO_2				1	0.25
H_2S					1

*0.05 significance level.

it was observed that the organic load is positively correlated with the four parameters. The larger correlation coefficients were for removed organic matter *versus* biogas flow (r_s = 0.44) and CH_4 percentage (r_s = 0.34), respectively. Additionally, there is no direct influence between the percentage of CH_4 and H_2S concentration, and a positive correlation of 0.52 was evidenced between biogas flow and H_2S. The correlation coefficients obtained through the Spearman method are presented in Table 3. The correlation varies from negligible ($|r_s|$~ 0) to moderate ($|r_s|$~ 0.6).

Specific biogas production and potential of energy generation

Currently, the treatment plant attends a population of approximately 180,000 inhabitants. Since the average biogas production, in the evaluation period, was 36.46 ± 12.35 $Nm^3.h^{-1}$, the biogas production rate per capita was calculated as 4.51 ± 1.65 $NL.hab^{-1}.d^{-1}$. The biogas production rate with the removal rate was 80.4 ± 29.68 $NL.kg^{-1}$ (COD).

The unitary relations obtained in the studied treatment plant were close to the inferior limit reported by Lobato et al. (2012). When sampling 3 is studied separately, its biogas production rate per capita presents a considerable reduction, with the mean of 2.72 ± 1.03 $NL.hab^{-1}.d^{-1}$. The periods of intense rain resulted in the lowering of biogas production.

Power generation potential estimative based on the average biogas flow and methane content values found during the monitoring period of WWTP was 3,118.6 $kWh.d^{-1}$, which is equivalent to an installed power of 130 KW. According to Rosenfeldt et al. (2015), Cabral et al. (2017a), Gomes et al. (2017), and Possetti et al. (2019), the decision on the best way to use biogas energy depends on the size and operational conditions of each WWTP and on on-site specific requirements, including social and environmental aspects.

Conclusions

The presented results revealed the behavior of different sewage parameters, such as organic load in the influent/effluent and removed organic matter in a wastewater treatment plant implemented, with UASB reactors operating in full scale, including biogas production, and adopting the time behavior in a full-scale approach. Mean hourly values were reported in the evaluation period for COD in the influent sewage, COD in the effluent sewage, sewage flow, biogas flow, and biogas composition (82.32% of methane).

Visual inspection indicates normality for biogas flow, but not for the gas concentrations. Most of the applied normality tests showed coherent results, the exceptions being Kolmogorov–Smirnov and Lilliefors, which is a modification of the K–S test. Normality test results indicate a non-normality trend for removed organic load and a normality trend for biogas flow.

The organic load [kg(COD).d^{-1}] was inferior to design parameters, and the removed organic matter efficiency was, in average, 48%. Both removed organic load and biogas flow ($Nm^3.h^{-1}$), produced in the treatment plant, showed variable, periodic, and nonstationary time behavior. The hourly removed organic matter has shown a positive moderate Spearman's rank correlation coefficient with biogas flow, CH_4 percentage, CO_2 percentage, and concentration of H_2S. Also, it was verified that there are no direct correlations between biogas flow and the concentration of H_2S.

The mean biogas production per capita obtained was 4.51 ± 1.65 $NL.hab^{-1}.d^{-1}$, a value inferior to that reported in the literature. The values of biogas composition (82.32% ± 3.62%) v/v (CH_4) were in accordance with the values mentioned by Noyola et al. (2006), with H_2S resulting in the superior limit reported in the literature (between 1,700 and 3,700 ppm). In the period of sampling 3, the mean rainfall was 19.5 $mm.d^{-1}$, resulting in the reduction of organic load and biogas production. It was estimated an electric power generation of 3,118.6 $kWh.d^{-1}$, which is equivalent to an installed power of 130 KW.

Contribution of authors:

Duarte Hernandez, O.A.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing — original draft; Paula, A.C.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing — original draft; Possetti, C.G.R.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing — original draft; Cantao, P.M.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing — original draft; Aisse, M.M.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing — original draft.

References

Adefisoye, J.O.; Golam Kibria, B.M.; George, F., 2016. Performances of Several Univariate Tests of Normality: An Empirical Study. Journal of Biometrics & Biostatistics, v. 7, (4), 322. https://doi.org/10.4172/2155-6180.1000322.

Aisse, M.M.; Lobato, M.B.; Jürgensen, D.; Além Sobrinho, P., 2002. Tratamento de efluentes anaeróbios com descarga de lodo aeróbio em reatores UASB (Treatment of Anaerobic Effluents with Discharge of Aerobic Sludge to the UASB Reactor). In: VII Taller e Simpósio Latino Americano sobre Digestion Anaerobia. Merida, Mexico.

Associação Brasileira de Normas Técnicas – ABNT, 2011. NBR 12209. Elaboração de projetos hidráulico-sanitários de estações de tratamento de esgotos sanitários. ABNT, Rio de Janeiro.

Bilotta, P.; Ross, B.Z.L., 2016. Estimativa de geração de energia e emissão evitada de gás de efeito estufa na recuperação de biogás produzido em estação de tratamento de esgotos. Revista Engenharia Sanitária e Ambiental, v. 21, (2), 275-282. https://doi.org/10.1590/S1413-41522016141477.

Brasil. 2017. Guia técnico de aproveitamento energético de biogás em estações de tratamento de esgoto (Technical guide on the use of biogas energy in wastewater treatment plants). 2ª ed. Ministério das Cidades, Brasília, 183 pp.

Cabral, B.G.C., Chernicharo, C.A.L., Platzer, C.J., Barjenbruch, M., Belli Filho, P., 2017a. Evaluation of biogas production and energy recovery potential in 5 full-scale WWTPs with UASB reactors. Chemical Engineering and Chemical Process Technology, v. 3, (3), 1043.

Cabral, B.G.C.; Possetti G.R.; Platzer, C.J.; Barjenbruch, M.; Chernicharo, C.A.L., 2017b. Avaliação da produção de biogás em reatores UASB em escala plena tratando esgoto doméstico: correlações a partir de medições em tempo real. In: 29º Congresso Brasileiro de Engenharia Sanitária e Ambiental.

Chernicharo, C.A.L.; van Haandel, A.; Aisse, M.M.; Cavalcanti, P., 1999. Reatores anaeróbios de manta de lodo. (Anaerobic Sludge Blanket Reactors). In: Campos, J.R. (Coord.). PROSAB. ABES, Rio de Janeiro, pp. 55-198.

Chernicharo, C.A.L.; van Lier, J.B.; Noyola, A.; Bressani Ribeiro, T., 2015. Anaerobic sewage treatment: state of the art, constraints and challenges. Reviews in Environmental Science and Bio/Technology, v. 14, 649-679. https://doi.org/10.1007/s11157-015-9377-3.

Gomes, E.C.; Dias, I.A.; Ferreira, L.R.A.; Otto, R.B.; Moreira, H.C.; Possetti, G.R.C.; Wagner, L.G.; Junior, J.A.S.; Zeni, A.L., 2017. Guia técnico sobre geração distribuída de energia elétrica por biogás em ETEs/Probiogás. GIZ/Ministério das Cidades, Brasília.

Hernandez, O.A.D., 2019. Avaliação de sistemas de medição para controle de processo em tempo real em uma estação de tratamento de esgoto sanitário que utiliza reatores UASB. Doctoral Thesis, Programa de Pós-Graduação em Engenharia de Recursos Hídricos e Ambiental, Setor de Tecnologia, Universidade Federal do Paraná, Curitiba. Retrieved 2021-09-29, from http://www.prppg.ufpr.br/ppgerha/es/teses.

Hernandez, O.A.D.; Lisboa, A.M.; Cantão, M.P.; Possetti, G.R.C.; Aisse, M.M., 2018. Assessment of an in situ real time UV/Vis based spectrometry system for chemical oxygen demand measurement in a wastewater anaerobic treatment reactor. In: Matsumura-Tundisi, T.; Tundisi, J.G. (Eds.), Water Resources Management. Scienza, São Carlos, pp. 167-180.

Intergovernmental Panel on Climate Change – IPCC. 2014. Climate change: mitigation of climate change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Langergraber, G.; Fleischmann, N.; Hofstädter, F., 2003. A multivariate calibration procedure for UV/VIS spectrometric quantification of organic matter and nitrate in wastewater. Water Science & Technology, v. 47, (2), 63-71. https://doi.org/10.2166/wst.2003.0086.

Lettinga, G.; Roersma, R.; Grin P., 1983. Anaerobic treatment of raw domestic sewage at ambient temperatures using a granular bed UASB reactor. Biotechnology and Bioengineering, v. 25, (7), 1701-1723. https://doi.org/10.1002/bit.260250703.

Ljung, G.M.; Box, G.E.P., 1978. On a measure of lack of fit in time series models. Biometrika, v. 65, (2), 297-303. https://doi.org/10.2307/2335207.

Lobato, L.C.S.; Chernicharo, C.A.L.; Souza, C.L., 2012. Estimates of methane loss and energy recovery potential in anaerobic reactors treating domestic wastewater. Water Science & Technology, v. 66, (12), 2745-2753. https://doi.org/10.2166/wst.2012.514.

Mainardis, M.; Buttazzoni, M.; Goi, D., 2020. Up-flow anaerobic sludge blanket (UASB) technology for energy recovery: a review on state-of-the-art and recent technological advances. Bioengineering, v. 7, (2), 43. https://dx.doi.org/10.3390%2Fbioengineering7020043.

Metcalf, L.; Eddy, H.P., 2016. Wastewater engineering: treatment and resource recovery. 5ª ed. AMGH, Porto Alegre.

Mota, F.; Monteiro, L.; Silva, W.; Borges, D., 2019. Climatic characteristics and hourly variations in biogas concentration in a sanitary landfill in northeast Brazil. Revista Brasileira de Ciências Ambientais (Online), (54), 1-12. https://doi.org/10.5327/Z2176-94782190077.

Noyola, A.; Morgan-Sagastume, J.M.; Lopez-Hernandez, J.E., 2006. Treatment of biogas produced in anaerobic reactors for domestic wastewater: odor control and energy/resource recovery. Reviews in Environmental Science and Bio/Technology, (5), 93-114. https://doi.org/10.1007/s11157-005-2754-6.

Noyola, A.; Padilla-Rivera, A.; Morgan-Sagastume, J.M.; Guereca, L.P.; Hernandez-Padilla, F., 2012. Typology of municipal wastewater treatment technologies in Latin America. Clean Soil Air Water, v. 40, (9), 926-932. https://doi.org/10.1002/clen.201100707.

Oliveira, S.C.; Von Sperling, M., 2011. Performance evaluation of different wastewater treatment technologies operating in a developing country. Journal of Water, Sanitation and Hygiene for Development, v. 1, (1), 37-56. https://doi.org/10.2166/washdev.2011.022.

Pagliuso, J.; Regattieri, C., 2008. Estudo do aproveitamento da energia do biogás proveniente da incineração do chorume para a geração de eletricidade. Revista Brasileira de Ciências Ambientais (Online), (10), 32-38. Retrieved 2021-05-15, from: http://www.rbciamb.com.br/index.php/Publicacoes_RBCIAMB/article/view/428.

Pinheiro, L.; Cattanio, J. H.; Imbiriba, B.; Castellon, S.; Elesbão, S.; Ramos, J., 2019. Carbon dioxide and methane flux measurements at a large unsanitary dumping site in the amazon region. Revista Brasileira de Ciências Ambientais (Online), (54), 13-33. https://doi.org/10.5327/Z2176-947820190021.

Possetti, G.R.C.; Jasinski, V.P.; Mesquita, N.C.; Kriguel, K.; Carneiro, C., 2013. Medições em tempo real do biogás produzido em reatores UASB alimentados com esgoto doméstico. In: 27º Congresso Brasileiro de Engenharia Sanitária e Ambiental, Goiânia.

Possetti, G.R.C.; Rietow, J.C.; Cabral, C.B.G.; Moreira, H.C.; Platzer, C.; Ribeiro, T.B.; Chernicharo, C.A.L., 2019. Energy recovery from biogas in UASB reactors treating sewage. In: Chernicharo, C.A.L.; Ribeiro, T.B. (Eds.), Anaerobic reactors for sewage treatment: design, construction and operation. IWA Publishing, pp. 194-236.

Possetti, G.R.C.; Rietow, J.C.; Costa, F.J.O.G.; Wagner, L.G.; Lobato, L.C.S.; Ribeiro, T.B.; Melo, D.F.; Reis, J.A.; Chernicharo, C.A.L., 2018. Contribuição para o aprimoramento de projeto, construção e operação de reatores UASB aplicados ao tratamento de esgoto sanitário – Parte 5: Biogás e emissões fugitivas de metano. Revista DAE, v. 66, (214), 73-89. https://doi.org/10.4322/dae.2018.042.

Razali, N.M.; Wah, Y.B., 2011. Power comparisons of Shapiro-Wilk, Kolmogorov-Smirnov, Lilliefors and Anderson-Darling tests. Journal of Statistical Modeling and Analytics, v. 2, (1), 21-33.

Rosenfeldt, S.; Cabral, C.B.G.; Platzer, C.J.; Hoffmann, H.; Araujo, R.A., 2015. Avaliação da viabilidade econômica do aproveitamento energético do biogás por meio de motor-gerador em uma ETE. In: 28º Congresso Brasileiro de Engenharia Sanitária e Ambiental.

Shapiro, S.S.; Wilk, M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika, v. 52, (3-4), 591-611. https://doi.org/10.2307/2333709.

Soreanu, G.; Béland, M.; Falletta, P.; Edmonson, K.; Svoboda, L.; Al-Jamal, M.; Seto, P., 2011. Approaches concerning siloxane removal from biogas: a review. Canadian Biosystems Engineering, v. 53, 8.1-8.18.

Venkatesch, G.; Elmi, R.A., 2013. Economic–environmental analysis of handling biogas from sewage sludge digesters in WWTPs (wastewater treatment plants) for energy recovery: case study of Bekkelaget WWTP in Oslo (Norway). Energy, 58, 220-235. https://doi.org/10.1016/j.energy.2013.05.025.

Von Sperling, M.; Chernicharo, C.A.L., 2005. Biological wastewater treatment in warm climate regions. IWA Publishing, London, 1452 pp.

Von Sperling, M.; Oliveira, S.M.A.C., 2009. Comparative performance evaluation of full-scale anaerobic and aerobic wastewater treatment processes in Brazil. Water Science & Technology, v. 59, (1), 15-22. https://doi.org/10.2166/wst.2009.841.

Waiss, T.C.F.; Possetti, G.R.C., 2015. Influência de eventos de chuva na produção de biogás de reatores anaeróbios alimentados com esgoto doméstico. In: 28º Congresso Brasileiro de Engenharia Sanitária e Ambiental, Rio de Janeiro.

Water Environment Federation – WEF. 1994. Preliminary treatment for wastewater facilities. Manual of Practice OM-2. WEF, Alexandria.

Water Environment Federation – WEF. 1998. Design of municipal wastewater treatment plants. Manual of Practice n. 8, ASCE Manual and Report on Engineering Practice, 76. WEF, Alexandria.

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Sertanejo biodigestor: a social technology, an alternative source of energy

Biodigestor sertanejo: uma tecnologia social, fonte alternativa de energia

Reginaldo Alves de Souza[1], *Marília Regina Costa Castro Lyra*[1], *Renata Maria Caminha Mendes de Oliveira Carvalho*[1], *José Coelho de Araújo Filho*[1]

ABSTRACT

The use of biogas as an alternative to using liquefied petroleum gas (LPG) for cooking food in the context of family farming is something recent and has ample room for growth. The aim of this study was to evaluate the use of the Sertanejo biodigester by farming families as a social technology for cooking gas production, as well as an alternative energy source. It also aimed to identify elements which contribute to disseminating this technology as an alternative to the use of firewood, charcoal and LPG. Quali-quantitative approaches were used following the exploratory method, with interviews and non-probabilistic sampling. A population with 132 units of biodigesters in the Agreste mesoregion of the State of Pernambuco was considered, with 83 interviews being collected. The results indicated that the Sertanejo biodigester social technology provides an increase in the income of farming families, avoids the use of firewood and charcoal for cooking food and produces biofertilizer for crops. They also showed that its non-continuous use or deactivation is related to a lack of raw material and the need for maintenance. Given this scenario, its implementation must consider the availability of a raw material source in the production unit and the potential for biogas production from the existing herd and consumption demand. It is recommended to strengthen arguments of economic and environmental impact for low-income families to disseminate this technology; to encourage the use of biogas associated with other activities in the production system; and to incorporate biodigestor social technology in rural credit financing lines.

Keywords: Family farming; social technology; biogas; National Rural Housing Program; climate changes; semi-arid region.

RESUMO

A utilização do biogás como alternativa ao uso do gás liquefeito de petróleo (GLP) para cocção de alimentos no âmbito da agricultura familiar é algo recente e com amplo espaço de crescimento. O objetivo deste estudo foi avaliar o uso do biodigestor sertanejo por agricultores familiares como tecnologia social para produção de gás de cozinha, como fonte alternativa de energia. Visou, também, identificar elementos que contribuam para a divulgação e a disseminação dessa tecnologia como alternativa ao uso de lenha, carvão vegetal e GLP. Utilizou-se abordagens quali-quantitativas, seguindo o método exploratório, com entrevistas e amostragem não-probabilística. Foi considerada uma população com 132 unidades de biodigestores na mesorregião do Agreste Pernambucano, sendo coletadas 83 entrevistas. Os resultados indicaram que a tecnologia social do biodigestor sertanejo proporciona incremento na renda das famílias agricultoras, evita o uso de lenha e carvão vegetal para cocção de alimentos e produz biofertilizante para os cultivos. Também mostraram que o seu uso não contínuo ou desativação está relacionado à falta de matéria-prima e à necessidade de manutenção. Diante desse cenário, sua implantação deve considerar a disponibilidade de fonte de matéria prima na unidade de produção e o potencial de produção de biogás a partir do rebanho existente e da demanda de consumo. Recomenda-se fortalecer os argumentos de impacto econômico e ambiental para as famílias de baixa renda para a disseminação dessa tecnologia; estimular o uso do biogás associado às demais atividades do sistema de produção e incorporar a tecnologia social biodigestor nas linhas de financiamento de crédito rural.

Palavras-chave: agricultura familiar, tecnologia social; biogás; Programa Nacional de Habitação Rural; mudanças climáticas; semiárido.

[1]Instituto Federal de Educação, Ciência e Tecnologia de Pernambuco – Recife (PE), Brazil.

Correspondence address: Reginaldo Alves de Souza – Rua Visconde de Mamanguape, 40 – Encruzilhada – CEP: 52030-010 – Recife (PE), Brazil. E-mail: alves.reginaldo@gmail.com

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Introduction

The causes and consequences of climate change demand efforts in different sectors and different players. One of these efforts concerns the search for alternatives to the current hegemonic energy matrix. Another refers to the adaptation to ongoing climate processes. In this universe of technological options, the biodigester is considered a social technology for the production of biogas (methane) to supply part of the energy needs of family farming as an alternative to the use of Liquefied Petroleum Gas (LPG), firewood and charcoal.

According to Martins et al. (2010), the ability of family farmers to adapt to climate change cannot be reduced to the possibility of adopting some practices apparently adjusted to a certain abnormal climate phenomenon, but it has to be understood as a result of the learning capacity to deal with the new situation.

Discussions around biogas production are not limited to a technical debate about the fermentation process and the efficiency of biodigester models. It is also associated with the broader debate on environmental sustainability, the growing need for clean energy production, reduced use of natural resources and especially related to a reduction in greenhouse gas (GHG) emissions. In the opinion of specialists regarding this theme, it is important to consider that global warming caused by the increase in the emission of greenhouse gases in the Earth's atmosphere can cause changes to terrestrial ecosystems, modifying global vegetation patterns (Nobre et al., 2007, p. 7). Such threats were recently reaffirmed in the sixth Assessment Report of the Intergovernmental Panel on Climate Change, which reveals that the global surface temperature will continue to increase until at least the middle of the century in all considered emission scenarios (IPCC, 2021, p. 18).

Under this perspective, there is a growing need to move towards expanding the use of renewable, non-polluting or low-emission greenhouse gas sources of energy to the detriment of non-renewable energy, the main GHG emitters. Data presented by the Energy Research Company (EPE) (Table 1) indicate that the participation of renewable sources in the national energy matrix in the period from 2008 to 2018 did not change significantly, varying negatively when evaluating the share of renewable sources, which contributed 45.6% to the national energy matrix in 2008, and represent 45.3% in 2018 (EPE, 2019, p. 56).

However, it can be seen that there are changes to the shares in the scope of renewable sources, with a reduction of 1.5 percentage points (pp) in the use of hydraulic energy, 3.2 pp in the use of firewood and charcoal, and an increase in the share of other renewables of 2.5 pp; furthermore, the contribution of solar energy begins in 2018 with 0.1% of the national energy matrix. Despite the diversification of the national energy matrix, biogas is still not highlighted as a renewable source of large-scale energy potential, being considered by EPE as incipient (EPE, 2019, p. 55-56).

Interest in this research was aroused by the potential that the biodigester has for producing cooking gas associated with a considerable number of farming families that can incorporate this technology into their production processes, and takes the project "Biodigesters, A Social Technology in the National Rural Housing Program (*PNHR*)", implemented by the NGO Diaconia in 2013, as a reference, with the purpose of disseminating the use of biodigesters through training, to produce and manage cooking gas (methane biogas).

One of the main references in the social technologies (ST) registry with a focus on rural development and sustainability is the Bank of Social Technologies (BTS) of *Fundação Banco do Brasil* (*FBB*), where the backcountry biodigester is described as a social technology that produces biogas from animal manure, and is used in stoves to prepare family food (FBB, 2018).

Several authors point out that the emergence of ST is due to an earlier process associated with appropriate technologies. Rodrigues and Barbieri (2008, p. 1071) describe the emergence of this movement in the 1960s and 1970s, according to which – and citing Kaplinski (1990 *apud* Rodrigues and Barbieri, 2008, p. 1071) –, "it would be associated with a reaction to post-war economic growth patterns." In addition to the term ST, the authors retrieved other terms related to the example of the term intermediate technology created by Schumacher (1979 *apud* Rodrigues and Barbieri, 2008, p. 1071), according to the authors, indicating "a technology that combines elements of traditional technologies with those of advanced technologies." The authors also refer to the terms alternative technology, defended by Dickson (1974 *apud* Rodrigues and Barbieri, 2008, p. 1071), and soft technology, proposed by Clarke (1976 *apud* Rodrigues and Barbieri, 2008, p. 1071).

Table 1 – Share of different energy sources in the national energy matrix, from 2008 to 2018.

Energy sources	Share (%)	
	2008	2018
Non-renewable	54.5	54.7
Oil and Derivatives	36.7	34.4
Natural gas	10.3	12.5
Mineral Coal and Coke	5.5	5.8
Uranium (U_3O_8)	1.5	1.4
Other non-renewables	0.5	0.6
Renewables	**45.5**	**45.2**
Biomass (derived from sugarcane)	17.0	17.4
Hydraulics	14.1	12.6
Firewood and charcoal	11.6	8.4
Other renewables	2.8	5.3
Wind	-	1.4
Solar	-	0.1

Source: adapted from EPE (2019).

In this historical review of the emergence of ST, Dagnino et al. (2004, p. 19) refer to the struggle of the Indian people against the British rule, where the reformers of that society had "the rehabilitation and development of traditional technologies practiced in their villages" as a fighting strategy, having as a great reference the spinning wheel machine popularized by Gandhi, recognized as the first technologically appropriate equipment. However, according to the authors, the concept of appropriate technology (AT) was introduced in the Western world as a result of the creation by Schumacher of the Appropriate Technology Development Group and the publication of the book Small in 1973 is beautiful: economics as if people mattered, translated into over 15 languages. For the authors, this movement towards appropriate technology lost momentum in the early 1980s as the neoliberal thought expanded.

Ventura et al. (2012, p. 606) suggest the need to discuss incorporating social technologies to the new institutional framework of the Post-Kyoto climate regime as one of the instruments to combat climate change, in fact contributing to negotiate GHG emission reduction projects in the carbon market, as they not only promote the transfer of technologies, but also the development of technologies suited to each social and environmental reality of the host communities. According to the authors, applying technologies for coexistence with the semi-arid region, especially the biodigester, cisterns and desalination plant, has been characterized as a cultural perspective that guides development with the purpose of improving living conditions and promoting citizenship through socioeconomic and technological initiatives.

In addition, Jiménez and Zambrano (2018) conclude that social technologies present themselves as modern options and adapt to small and medium rural enterprises with a satisfactory cost-benefit ratio that enables the relief of structural problems, thereby allowing the direct participation of rural communities in the implementation process and effectively contributing to develop individual and collective awareness of sustainability in the semi-arid region of the country.

According to Gualdani and Burgos (2020), the concept of ST is quite broad and flexible thanks to its experimentation character and the scope of possibilities for framing different types of solutions to local problems, with ST being defined by several authors as techniques, procedures, processes and methodologies collectively developed in order to solve a problem so as to socially include those involved, ensuring quality of life and environmental gains. They also highlight the low cost usually related to the availability of local materials included in the assembly in this conceptual universe, as labor and time invested must also be considered as social capital employed in its development; replication and reapplication concepts when it comes to reproduction from a step-by-step basis and the reproduction of ST in broader parameters which enable its improvement, including methodological adaptation and incorporating other materials; and that the practices identified as ST consequently have a "step-by-step" process, a development methodology and not necessarily a protocol.

The proposed study was directed to a specific biodigestor model called "sertanejo biodigestor," resulting from an adaptation proposed by the NGO Diaconia to the Indian model with technology used in plate cisterns widely spread across the semi-arid region (Mattos and Júnior, 2011, p. 7).

The innovative aspects proposed by the NGO Diaconia to adapt the technology included the materials for constructing the equipment. However, they must be analyzed from the point of view of construction practicality, results in biogas production and total costs of the equipment. According to the NGO Diaconia (2016), there is a significant number of Sertanejo biodigesters deployed in the Agreste region of Pernambuco, and part of this equipment is totally or partially deactivated. This fact leads to the need for identification of the weaknesses regarding the adaptation to the dynamics of farming families with the technological innovation that gave rise to one of the focuses for research.

In a complementary way, the high cost of LPG can compromise the family income, essentially of the farming families, in view of their non-fixed income associated with the productive processes when it is not linked to social security and complementary programs for income distribution. According to the data presented by the NGO Diaconia, a farming family spends 9.32% of the minimum wage on the purchase of LPG monthly, or collects 21.06 kg of wood to prepare food. It is then a problem related to family income and that the biodigester can effectively contribute with biogas (methane) to the detriment of the use of LPG. However, the question is what is the actual contribution of the biodigester when it comes to increasing family income? In economic terms, it is necessary to check whether the biodigester is really capable of promoting economic gains, considering the references presented by the NGO Diaconia (s.d., p. 8), suggesting that the use of the biodigestor can provide families with savings in monthly expenses equivalent to one and a half canisters of LPG, equivalent to 10% of the minimum wage.

Therefore, the aim of this study was to evaluate the use of the Sertanejo biodigester by farming families in the Agreste region of Pernambuco as a social technology for producing cooking gas, as an alternative source of energy and to mitigate climate change. It also aimed to identify economic and social elements that contribute to disseminating this technology as an alternative for cooking gas production to replace the use of firewood, charcoal and LPG for domestic activities in the context of family farming in the semi-arid region.

The study starts from two basic hypotheses: the use of the biodigester social technology provides an increase in the income of farming families due to a reduction in the use of LPG, avoids the use of firewood and charcoal and contributes to producing biofertilizer for the family's crops; the continuous non-use or deactivation of the biodigester is related to a lack of raw material, requirements in equipment maintenance (which takes a lot of work) and/or the lack of labor to maintain the equipment.

Material and methods

Study area

The study considered the municipalities of Bom Conselho, Caetés, Jupi and São Bento do Una, located in the Agreste mesoregion of Pernambuco as its geographic focus (Figure 1), taking the quantity of biodigesters deployed in that territory belonging to the participating families of the Biodigestor Project as a reference, as executed by the NGO Diaconia.

The Sertanejo Biodigestor (Figure 2) is described by Mattos and Júnior (2011) from the Sertanejo Biodigestor Manual, a component of the Sustainable Land Management Project in Sertão, a publication of the Dom Helder Câmara Project (*PDHC*). Another reference found for this type of biodigester is the NGO Diaconia's booklet, 12 steps to build a biodigestor as a product of the "Biodigestors: A Social Technology in the National Rural Housing Program" project, with support from the Caixa Socioenvironmental Fund (*FSC*). As shown in the two manuals mentioned above, the Sertanejo biodigester adopts the same principles as the Indian model, meaning it is a structure formed by an inlet box (herein referred to as the cargo box), a storage tank (also called the biodigestor tank or main tank), a gas storage hood coupled with a structure to capture the gas produced and a waste outlet box (herein referred to as discharge box). It is observed that the main difference between this model and the others is the type of material used for its construction as a way of adapting to small rural properties. While the Indian and Chinese models use masonry to build the fermentation tanks, in this model the construction is made with cement plates using the same construction principle as the Precast Plate Cisterns in cylindrical shape, according to Figure 3. The cistern is cylindrical in shape, covered and semi-buried. Its operation provides for the capture of rainwater using the roof of the house, which drains the water through gutters (ASA, 2021).

The waste input and output boxes do not differ in the type of material used, only in the format. On the other hand, for the hood or gasometer, which is made of metal in the Indian model and with masonry in the Chinese model, the decision was to adopt a PVC box normally used for water storage in an inverted way in the Sertanejo model, which receives a zinc and earth structure on top to act as a counterweight. The way the gas is captured is another great differential, as a 20-liter bottle adapted to receive and distribute the gas is used.

Figure 2 – Sertanejo biodigester with maximum biogas load. Angico Site, Bom Conselho-PE, by Wanderley Nunes and Cláudio Almeida, 2020.

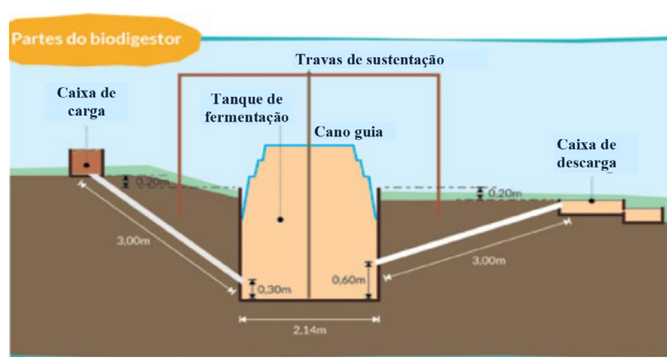


Figure 3 – Parts of the Sertanejo Biodigestor.

Figure 1 – Geopolitical division map of Pernambuco.

By presenting the results of the work developed by the Network of Biodigesters for Latin America and the Caribbean (RedeBioLAC) to identify barriers and mechanisms to overcome them, aiming at the massification and democratization of medium and small scale biodigesters in Latin America and the Caribbean (LAC), Herrero et al. (2016) emphasize the need to adapt the technology to the user (and not the other way around), and that the visibility and dissemination of biodigesters must fully consider their environmental aspects of changing the production and energy matrix and self-sufficiency for the producer.

According to the Diaconia NGO (s.d.), the "Sertanejo Biodigestor" has the following benefits, as shown in Chart 1.

It is important to consider that biofertilizers are a by-product of the effluents from the biodigester, the digestate, which, according to Nicoloso et al. (2019, p. 122), should follow the fundamental principles of fertilizer management and soil fertility already established and constantly refined by research.

The nature of this study

According to the definitions adopted by Gerhardt and Silveira (2009, p. 31), this study is classified as exploratory regarding its objectives, as it is the method which aims to provide greater familiarity with the problem with a view to making it more explicit or build hypotheses. It is configured as qualitative and quantitative in its approach, and documentary and field data were used based on interviews and questionnaires as the data source. Non-probabilistic sampling was also used, defended by Guimarães (2008) as a convenience sample formed by elements that the researchers gathered because they had them, or the researchers makes use of data which are more within their reach, which in this case is access to families with biodigesters.

Chart 1 – Benefits pointed out by the NGO Diaconia with the use of the Sertanejo Biodigestor.

Where	Benefits
In the environment	- Firewood is not taken from the forest for cooking - Contributes to reducing deforestation and the effects of climate change - Prevents methane gas released by the natural combustion of animal manure from being released into the atmosphere
On health	- The biogas produced when used in the stove does not release smoke, preventing respiratory problems - It contributes to the health of animals by collecting waste and cleaning corrals and pigsties, reducing infestation by worms and flies
On the Family income	- Saves a bottle and a half of LPG gas per month - Produces organic fertilizer and biofertilizers
In Agriculture	- Produces natural fertilizers: biofertilizer and tanned manure, which can increase soil fertility and improve production

Source: Diaconia (s.d.).

Sample

The population targeted by this study is part of the universe of farming families residing in houses financed by the *PNHR* of Caixa Econômica Federal (CAIXA), benefiting from the implementation of 395 biodigester units in 39 municipalities of 06 states of the Federation: Bahia, Goiás, Minas Gerais, Pernambuco, Rio Grande do Sul and Santa Catarina. A total of 24 families in Bahia were benefited; 61 in Minas Gerais; 50 in Goiás; 52 in Santa Catarina; 67 in Rio Grande do Sul; and 141 in Pernambuco. The project concentrated its actions in the municipalities of Bom Conselho, Caetés, Jupi and São Bento do Una, in the state of Pernambuco, all belonging to the Agreste mesoregion of Pernambuco, with the goal of implementing 132 units (Diaconia, 2016, p. 8).

From a sampling point of view, a sample based on these data was estimated, which met the expectation of verifying the abandonment rate of using the biodigesters and measuring their impact on family dynamics. Therefore, the finite population of 132 family units of biodigesters implemented in the Agreste mesoregion of Pernambuco was considered, and the probability of continuous non-use or deactivation of the biodigesters was estimated in 15%, with a 95% confidence level, adopting the associated variable of 1.96 and a standard sampling error of 5%. Thus, applying the Equation 1 for sample definition suggested by Meunier et al. (2001), we would need to apply 75 interviews (57% of the total population), and 83 samples were collected during the field visit process, reaching a representation of 63% of the families using the biodigester.

$$n = \frac{N.Z^2.p.(1-p)}{Z^2.p.(1-p) + e^2.(N-1)} \quad (1)$$

Where:

n = calculated sample (size);

N = population (families with biodigesters) (132);

Z = standardized normal variable associated with confidence level - 95% (1.96);

p = probability of biodigester deactivation (%) (0.15%);

e = sampling error (5% standard) (0.05%)

Data used in the study

Semi-structured interviews, systematic observations and photographic records were used as the primary data collection techniques carried out from the field survey. The semi-structured interview was the main instrument to respond to the general objective, as well as to seek subsidies which would allow confirming or denying the presented hypotheses. Thus, data collection took place in the municipalities of Caetés, Jupi and São Bento do Una, maintaining distinct audiences, defined by: families participating in the biodigestor project in the Agreste region of Pernambuco; community leaders; families with consolidated use of the Sertanejo biodigester in the Sertão do Pajeú region, and the NGO Diaconia's technical team members. Descriptive statistics according to Guimarães (2008) were used to treat the collected data.

Results and Discussion

This topic is dedicated to systematizing and interpreting the data generated in the study. The analysis addresses aspects related to the use of technology, economic and environmental impacts, and the role of social organizations in the process of mobilizing families.

Quadros (2009) defends the use of the biodigester in family farming in the Semi-arid region as a means of overcoming energy shortages resulting from economic and environmental impacts as a consequence of the use of firewood and cooking gas. In this perspective, he suggests the biodigester as an alternative to use goat and sheep manure for energy generation (biogas) and fertilizer (biofertilizer), and concludes (among other issues) that it has a high potential for replication in family farming as it has a high cost/benefit ratio with the generation of biogas and organic fertilizer. The data that we will see below corroborates this statement, as they present important subsidies for the debate on using the biodigester in family farming, especially in the semi-arid region, related to the acceptance of the technology, dimensioning biogas production at the expense of the available raw material, in addition to bringing elements related to environmental, economic and social aspects with the use of biodigesters in the family agroecosystem.

It is important to understand that the following data refer to a study dimensioned by three associated variables: family farming, semi-arid and Sertanejo biodigester as a proposal for a technology to produce cooking gas in the context of family farming, therefore constituting a very peculiar context. In any case, based on the work developed by Herrero et al. (2016) with the purpose of giving visibility to the positive impacts of the use of the biodigester in sustainable family, community and productive development, it was possible to identify several experiences in Latin America which corroborate the results presented in this work. In addition, those conducted in the state of Ceará, by Barros et al. (2020) make reference to the work of the NGO Cetra, which built around 300 biodigesters in 20 municipalities in Ceará between 2015 and the first quarter of 2020.

It should be noted that Non-Governmental Organizations (NGOs) play a leading role in the work of multiplying the use of biodigesters for producing biogas in the context of family farming, such as the work developed by Diaconia and Cetra, who, together, are responsible for implementing more than 600 Sertanejo biodigesters, mainly in the semi-arid region of the Northeast.

Implementation and use of the biodigester

The data collected indicate that a considerable part of the families (around 25%) was unable to specify the date that the biodigester was installed on the property. However, it was possible to register that the first units implemented in the surveyed municipalities (about 2%) date from the end of 2014. The vast majority (around 71%) was implemented between the period from January 2015 to October 2016; this means a majority of families had three to four years of experience with the use of this technology, considering the end of 2019 as a reference. One third of the families (32.5%) had their biodigesters deactivated (at the end of 2019) and another group (about 22% of the sample) was not using the produced biogas. Therefore, these numbers can be considered quite expressive, especially when the economic and environmental appeal associated with the biodigester technology is highlighted.

According to Herrero et al. (2016), the work developed by the NGO PROSUCO in Bolivia, with the implementation of 40 biodigesters in 10 municipalities, enabled approximately 50% to be consolidated as a reference in the supply of bio-inputs and in research and innovation. According to Jiménez and Zambrano (2018), the Technological Institute of Costa Rica installed 38 biodigester units in 4 rural communities in the city of Limón in Costa Rica, intended for the treatment of organic waste, mainly from swine, and used only as an energy source for food preparation, where 28 remain active, while 10 units (26%) are disabled due to lack of interest from families or due to system breakdowns.

Aspects related to the advantages and disadvantages of using the biodigester from the perspective of families who deal directly with the technology are diverse, but point to a certain consensus. The data systematized in Table 2 clearly shows how the economic issue stands out as an advantage for the use of the biodigester, being pointed out by 94% of the families as something important, followed by practicality (43%) and abundant production of biogas (12%). This is also the opinion of the reference families of Sertão do Pajeú, where the majority (80% of the sample) claim to have decided to implement the biodigester due to aspects related to reducing expenses with the purchase of LPG gas associated with its high cost.

About 90% of the sample referred to savings or improvement in family income when asked about the advantages of using the equipment. The interviews carried out with community leaders in the municipalities also follow the same opinion. The economic factor stands out as the main advantage for most respondents, in addition to reporting the fact that it is easy to handle and performs well in cooking food.

The opinion of the families in the Pajeú Region does not differ from the narrative presented above, as 90% of them refer to issues related to the economy when justifying that they are no longer able to purchase gas. It was also the reason why 80% of them decided to implement it considering the difficulties of finding firewood, aiming to replace the use of firewood and charcoal, and also considering the fact that it is a clean, non-polluting gas as an advantage.

A work developed by Silva and Correia (2020) in Oeste Potiguar considering a universe of 21 families refers to the degree of acceptability of the Sertanejo biodigester technology used for more than two years, with 42% of them in use for more than five years, and indicating that 100% of the families rated the technology as great or good.

Families point out issues related to work regarding equipment maintenance (28%) and the lack of waste for supply (37%) in the field

Table 2 – Advantages and disadvantages in the use of the biodigester presented by families in the municipalities of Bom Conselho, Caetés, Jupi and São Caetano, 2019.

Evaluated aspects	Absolute Frequency	Percentage
Advantages		
Economical	78	94.0
Pratical	36	43.4
Abundant gas	10	12.0
Disadvantages		
Very hard work	23	27.7
Difficulty collecting waste	31	37.3
Production decreases in winter	2	2

Source: Field research (2020).

of negative aspects. In this sense, the vast majority refers to the labor required for management as the main disadvantage of use, since the search for waste outside the property requires time and competes with other activities in the production system.

In terms of disadvantages, 65% of the families interviewed in Sertão do Pajeú assert that they have no problems or difficulties handling the biodigester. They mention three elements regarding the negative aspects: dryness or cracking in the piping leading the gas to the stove (15% of the sample); water accumulation in the pipe (10%); and a lack of sufficient animals to produce raw material (10% of the sample). On a smaller scale, they cite issues related to insufficient water to feed the equipment, difficulties in transporting the manure and damage to the container for filtering the gas (drying). This last difficulty was the subject of changes proposed by the NGO Diaconia in the filtration system, circumvented by replacing the water canister with more resistant PVC material (Diaconia, 2016).

Knopki (2015) describes that biogas can be used to produce electric, thermal, fuel gas and vehicle fuel, as well as the main characteristic of its flexibility as an advantage, while the disadvantage is due to its complexity related to factors such as controlled production, a value chain which is considered complex, and because it is an explosive combustible gas that requires rigorous control, monitoring and investment in safety issues.

The group of families with deactivated or unused biodigesters basically point to three elements as the cause:

1. that the biodigestor does not work (41%), without specifying the reason;
2. they do not need the biodigester (37%);
3. the supply is low.

Of these aspects, items (a) and (c) are related to surmountable causes; however, item (b) points to something directly related to aspects not identified before the implementation of the biodigester, which is the family's need for the technology.

Community leaders point out possible causes for disabling the biodigester as the lack of interest from the families, the lack of manure to feed the biodigester, the lack of maintenance and the lack of technical assistance. Families interviewed in Sertão do Pajeú (with longer use of biodigesters) highlight two aspects related to not using the biodigester: the lack of interest or commitment, as cited by 65% of respondents; and the fact of not having animals to produce raw material, cited by 40%.

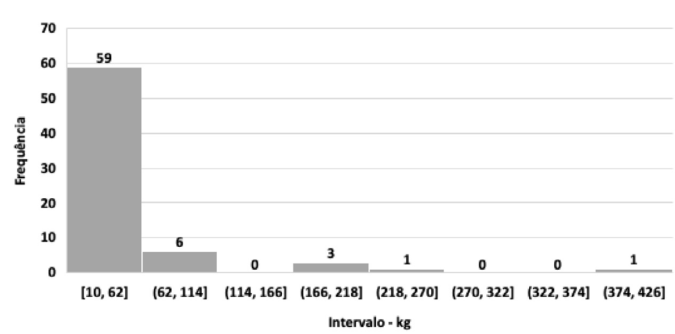
Still regarding item (c), it is observed that the raw material used to supply the biodigester basically has two sources: cattle and swine. Considering that 34% of the families raise goats and sheep, and that 71% declare raising birds, the results clearly indicate that the manure from these animals is not used as raw material for feeding the biodigester. However, it is observed that there is a strong relationship of dependence with raising cattle, as 82% of the families use the manure of these animals as an energy source, with part of them (20%) being associated with swine manure. The latter is responsible for supplying raw material to 7% of the families, and it increases its contribution to 28% in the families when associated with cattle (Table 3).

The amount of raw material (manure and water) used is directly related to the dynamics of household use. Thus, it was possible to identify families using 10 kg to 400 kg of raw material per week, with the majority (84%) using up to 62 kg per week, with an average of 55 kg per family (Graph 1).

Table 3 – Sources of raw material for the biodigester in families in the municipalities of Bom Conselho, Caetés, Jupi and São Caetano, 2019.

Source	Absolute Frequency	Percentage	Accumulated Percentage
Cattle and Swine	17	20.5	
Cattle	50	60.2	
Cattle and Whey	1	1.2	82
Swine	6	7.2	
Uninformed	13	10.8	100

Source: Field research (2020).



Graph 1 – Amount of raw material used to supply the biodigester by families in the municipalities of Bom Conselho, Caetés, Jupi and São Caetano, 2019.
Source: Field research (2020).

An important element in the context of families in the Semi-arid region is the use of water, as the biodigester requires a lot of water for to fully operate, due to the characteristic of biogas production from anaerobic fermentation. Data collected on water use indicate an average of 40 liters per week; however, some families use up to 300 liters of water per week. This indicates a proximity to the ratio of 1 kg of raw material to 1 liter of water, as recommended in the construction manuals for the Sertanejo biodigester.

There is an important competition with the main source for domestic consumption when identifying the water source used, which is the cistern, and occurs in 54% of the families. The other sources are traditionally employed for different uses, especially for animal watering. However, the contradictory fact is that, despite the fact that most families have the cistern as a source of water for feeding the biodigester, only 28% claim that the water used is potable (i.e. suitable for human consumption), while 77% claim to use water for general purposes, although some may fall into both types.

Plate cisterns have recently gained prominence in family agroecosystems, with the implementation of the One Million Cisterns Program (*P1MC*), aiming at capturing and storing rainwater for human consumption. Data indicate that there were 626,791 units implemented in all semiarid states until May/2019 (ASA, 2019) under the *P1MC*. A study evaluating the program in 2010 presents some findings which are in line with the data presented regarding the cistern water use:

- the physicochemical characteristics of the waters stored in the cisterns indicate that these do not come from rainwater collection, but from other alternative sources of supply;
- 79.54% of the samples were considered unrestricted for use by beneficiary families;
- the management is adequate in 82.8% of the interviewed families, while it is inadequate in 15.1%, with the main problem being the poor state of conservation of the cisterns;
- few households (approximately 19.1%) only use the cistern as the main source for domestic water;
- stored water lasts 12 months in just over a third of households (36.4%), while stored water lasts for a maximum of six months for 26.2%.

This last data has an important meaning considering that the more uses that depend on the accumulated water of the cistern, the shorter the available water time (Brasil, 2010, p. 151).

Given the specificities of the Semi-arid region in relation to water availability, any technology that presents a demand for consumption which will effectively compete with water for domestic use must be carefully analyzed. In the specific case of the biodigestor, it deserves technical deepening regarding the possibility of its interconnection to a system for the reuse of greywater, as a water source for the fermentation process, as well as toilet waste as a way to use organic matter for the biodigester.

Part of the water used to facilitate the fermentation process is drained in the form of biofertilizer, which can be used as liquid fertilizer on crops. The data indicate that this guidance was well captured by the set of families, as 84% of the families with a functioning biodigester claim to use the biofertilizer for some type of crop.

Economic and social aspects

It was possible to identify that the biodigesters resulted from the relationship that the families maintain with the local Community Association in 75% of the families, and with the Union of Family Farmers Workers in 64% of the cases, indicating that the relationship with these organizations takes place simultaneously for some. Some families (9%) refer to *Cooperativa de Habitação Rural da Agricultura Familiar, Assentamentos da Reforma Agrária e Comunidades Tradicionais LTDA* (Rural Housing Cooperative of Family Farming, Agrarian Reform Settlements and Traditional Communities LTD) (*ABEMORAR*) the partner organization of the NGO Diaconia NGO that carried out the project in some municipalities.

The biodigester implementation resulted from the action of a project co-financed with public resources through the Caixa Econômica Federal Social and Environmental Fund in all the families surveyed, and they did not imply practically any financial cost. Only a small part claims to have made any investment in paying for the labor of a bricklayer's assistant, with values between R$ 150 and R$ 250. This is also the narrative of the families in the Pajeú Region, where virtually all the biodigesters resulted from the action of the NGO Diaconia. In this case, the families claim to have only contributed with labor help such as digging the hole and building the biodigester.

When asked what the cost of a biodigester would be, 71% of the sample said they did not know and 29% referred to a cost ranging from R$ 2,500 (two thousand five hundred reais) to R$ 8,000 (eight thousand reais), with an average cost of around R$ 3,900 (three thousand nine hundred reais). According to the NGO Diaconia (2020), as indicated in the qualified interview with members of its technical team, the costs of mason labor, digging the hole, installation, materials and technical monitoring for a biodigestor unit are around R$ 4,000 (four thousand reais), meaning they are comparable with the average obtained according to information from the families. Here it is worth noting that a family would take between 48 and 67 months (4 to 5 years) to have the investments reversed at a cost of R$ 65 per LPG gas canister by taking as a reference this cost per biodigester and the equivalent biogas production capacity between 0.92 and 1.28 canisters/month.

The income sources and expenses of families were then analyzed in order to understand the composition of the family income, considering that this is not a deepening of the various elements that make up their income, from the perspective brought by Mattos (2017) when discussing the pluriactivity and multifunctionality of family farming as an important element in aggregating income. Thus, the information collected from the questionnaires enables comparisons and dimensioning of the impact of biogas use on the family economy within the proposed purpose of the work and drawing parallels with the main sources of income, as identified in Table 4.

A first piece of evidence is that the contributions resulting from the *Bolsa Família* Program and the Rural Retirement Program constitute the two main sources of income, since the two do not add up per family. Then there are revenue contributions from agricultural and livestock activities, present in 48.2% of families, especially milk (18% of families). Furthermore, the participation of non-agricultural activities (39.8% of families) is not less important, and is mostly related to renting labor.

The survey on the effective use of income had the purpose of identifying the main expenses of the families, focusing on the main consumption elements and giving total freedom to the families to mention the main expenses with the residence. The results enable us to identify that spending on food is the most cited (95.2% of families), followed by electricity (90.4%) and gas, charcoal and firewood (76%), thus forming the tripod of the main expenditure elements cited by families, followed by transport (19%), health (16%) and other expenses (12%), as shown in Table 5.

The three main energy sources traditionally used for cooking food in addition to biogas were analyzed, introduced as an alternative to the use of LPG gas. It is noteworthy that the use of LPG gas is still dominant even in the context of families who have adopted the Sertanejo biodigester technology for biogas production, as 54% of families still use it as the only source of energy for kitchen activities, while another 25% alternate its use with biogas, which indicates that 79% of families maintain their LPG gas consumption after installing the biodigesters. Thus, the use of biogas as the only energy source for kitchen activities is present in only 17%, but it can be said that 42% of families use this energy source, even if one does that less frequently than another, which will be detailed further on.

The data presented in Table 5 clearly show that the main expenses of families occur with food and health, reaching more than 50% of the monthly average. Expenditures on gas, firewood and charcoal represent only 5% of the average monthly expenditures; however, when related to income transfer, retirement and pension programs (Table 4), these expenditures represent 8.9% of these revenue sources, increasing its impact considerably when compared to the income from the *Bolsa Família* Program, which represented 28.4% of the average obtained. These same data can represent 14% and 25.5% when related to the av-

Table 4 – Main sources of income for families in the municipalities of Bom Conselho, Caetés, Jupi and São Caetano, 2019.

Income source	Absolute Frequency	Relative Frequency	Mean income (by type)	
			Monthly	Annual
Transfer Income/Benefits/Pension	73	95.2%	682.87	8,194.49
Agricultural	40	48.2%	438.23	5,253.80
Non-Agricultural	33	39.8%	239.74	2,876.85
Bolsa Família Program	54	65.1%	215.00	2,795.00
Rural retirement	24	28.9%	998.00	12,974.00
Hired labor	22	26.5%	48.63	583.55
Selling milk	15	18.1%	471.33	5,656.00
Selling cheese	5	6.0%	620.00	7,440.00
Formal employment	3	3.6%	1,154.11	13,849.33
Selling eggs	2	2.4%	57.33	688.00
Cleaning services	1	1.2%	300.00	3,600.00
Selling candy	1	1.2%	100.00	1,200.00
Craftsmanship/handicrafts	1	1.2%	50.00	600.00
Help from relatives	1	1.2%	29.17	350.00
Pension	1	1.2%	998.00	11,976.00

Source: Field research (2020).

Table 5 – Main expenses of families benefiting from biodigesters in the municipalities of Bom Conselho, Caetés, Jupi and São Caetano, 2019.

Type of expense	Absolute Frequency	Relative Frequency	Mean monthly expense	Participation %
Food	79	95.2%	464.94	37%
Electricity	75	90.4%	49.51	4%
Gas/Coal/Firewood	63	75.9%	61.05	5%
Transport	16	19.3%	118.75	9%
Health	13	15.7%	194.62	15%
Clothes	2	2.4%	10.75	1%
Leisure	1	1.2%	30.00	2%
Other expenses	10	12.0%	333.00	26%

Source: Field research (2020).

erage revenue from agricultural activities and non-agricultural activities, and expenses on gas, firewood and charcoal, respectively.

According to Diaconia (2020), each family traditionally spends about 10% of the minimum monthly wage on the purchase of butane gas, which means something around R$ 104.50 in current values. It is therefore assumed that the replacement of these sources with the continuous use of biogas would generate savings for families, and would impact them in different ways according to their revenue composition; however, by following mathematical logic, there would be greater significance for families with a lower monthly revenue average.

The financial impact of using biogas is diluted as alternatives and the mean monthly household income increase. Consequently, the use of biogas in these cases to replace the use of LPG gas, firewood and charcoal generates savings that range from 4 to 5% of the monthly average, which may not be very attractive for introducing a technology such as the biodigester due to its daily management dynamics, as discussed above.

Table 6 also indicates that there is important room for growth in the use of the biodigester from the perspective of reducing expenses on gas, firewood and charcoal for families with little income diversification, but especially for those who depend on the *Bolsa Família* Program. A considerable percentage still uses butane gas as the only source for cooking food, followed by a group of families who associate biogas with LPG gas, and finally a smaller group (16.9%), who only use biogas. It is noteworthy that when excluding families with the biodigester disabled, the percentage of those who only use biogas to cook food rises to 25%. In any case, it is important to highlight that 42% of the total sample uses biogas, and again, the percentage of families with active biodigesters who use biogas in domestic activities increases to 62.5% when extracting the deactivated biodigesters.

The firewood used is removed from the property in 87% of the cases; however, the type of firewood was not studied in depth, although some families insisted on informing that it was forest fragments or dry firewood, without the need for felling trees. Another important element is that 82% of the families say they use firewood weekly, characterizing a very present dynamic in these families. In this sense, a study by Specht (2012) indicates that more than 65% of the respondents use firewood in their homes in different degrees of intensity, at least once a month or every day, and also reveals that 40% of the respondents point to saving gas and money among the reasons chosen for regarding the use of firewood, and another 40% refer to faster cooking due to its high calorific value.

Thus, it is possible to suggest that the best strategy for introducing the technology to families with a higher income range may not be by convincing them of the economic impact, especially if the use of biogas is only associated for cooking food. Therefore, it is necessary to show more forcefully the environmental gains that the technology can offer, and especially to associate other uses of biogas in the production system or in residential activities, which can enable them to expand their participation in the reduction of expenses and consequently contribute to the family income.

By making a comparison with the group of families interviewed in Sertão do Pajeú, it is observed that the association of biogas with other energy sources for cooking food can remain over time, even on a smaller scale. This is because 55% of families say they use firewood or gas occasionally when it comes to the need to use large utensils for cooking food (related to receiving visits), or when there are problems with equipment maintenance, which is treated as an emergency. When it comes to the use of butane gas associated with biogas, there are reports mentioning the use of 1 canister every two or three months, 1 to 2 canisters per year or 1 canister every 4 years. In any case, 20% of

Table 6 – Energy sources used by families in the municipalities of Bom Conselho, Caetés, Jupi and São Caetano, 2019.

Energy source	Unit	Absolute Frequency	Percentage	Mean monthly consumption	Mean monthly expense (R$)
Canister (without Biogas)	Canister	45	54.2%	0.86	52.93
Canister (+ Biogas)	Canister	21	25.3%	0.76	33.13
Only Biogas	Canister	14	16.9%	1.0	-
Coal	Kg	38	45.8%	25.0	22.00
Firewood	m^3	28	33.7%	1.9	-

Source: Field research (2020).

the families claim to use only biogas, which is a number close to that obtained from families in the Agreste region of Pernambuco.

Impact studies of the implementation of 265 biodigesters in the Yucatán Mayan communities in Mexico showed a 97% reduction in the use of firewood in households, placing biogas as the main energy source and identifying an increase in agricultural production by more than 60% of the families, resulting from the use of the biofertilizer. A small milk producer in Costa Rica implemented its biodigester and replaced 40% of the diesel used in its boiler, achieving a return on its investment in less than 2 years. ASPROINCA (*Asociación de Productores Indígenas y Campesinos de Riosucio Caldas*) in Colombia has more than 250 biodigesters installed in its operating territory from its own revolving fund and with the training of Community Promoters (Herrero, 2016).

Work developed by Silva and Correia (2020, p. 8) in Oeste Potiguar found that firewood was the main energy source for 66.7% of the families before the biodigester purchase; 33.3% used cooking gas and another 14.3% used charcoal. This data reveals how much impact introducing the biodigester can have as a gas supplier for cooking food, considerably reducing the use of wood from the caatinga for both direct consumption and for charcoal production, as both were present in 81.9% as power supply.

As shown in Table 7, the average usage time of a gas canister was around 30 days, with this period corresponding to 50% of the families; others (28%) consume the same amount of gas for a period between 45 and 60 days. The unit cost of a gas canister ranged between R$ 60/75 in the studied period (Nov./18 to Jan./20). However, there is an additional cost for 63% of the families, as they buy gas in the city, while 37% buy it in the community and may not have the additional transportation allowance. When asked about the advantages and disadvantages of using LPG gas, practicality and agility are the main advantages for 70% of families; while the high cost is the main disadvantage for 75% of families.

Returning to the study developed by Jiménez and Zambrano (2018), which analyzed biogas consumption, it was observed that the average daily biogas consumption in a universe of 28 biodigesters (active) in rural communities in the evaluated period (110 days of measurement) was 0.37 m^3, with 50% of the consumption data found between 0.2 and 0.5 m^3/day. Regarding the economic impact, the study found that the use of firewood was present in 82% of the families at a cost of USD 19.50, thus obtaining a total annual value for the use of firewood of USD 438.30. Moreover, an investment of USD 306.27 per year occurred in the case of replacement of the LPG gas. Thus, the authors conclude that: obtaining and using biogas as an energy source does not represent a monetary cost for families, but rather some help which enables them to replace previously used fuels and chemical fertilizers, applying biofertilizer to improve income of their crops.

Table 7 – Usage time of the LPG gas canister by families in the municipalities of Bom Conselho, Caetés, Jupi and São Caetano, 2019.

Usage time (days)	Absolute Frequency	Percentage
20	1	1.5
25	1	1.5
30	34	50.0
45	4	5.9
60	15	22.1
90	8	11.8
120	3	4.4
180	1	1.5
365	1	1.5

Source: Field research (2020).

Conclusions and Recommendations

The use of social technologies in rural communities in the semi-arid region can meet immediate needs and promote important economic, social and organizational dynamic impacts on the community, enabling these families to understand and commit to environmental and social issues in their surroundings, making them local references. Training actions in the process of implementing these technologies, with a major role played by NGOs, open spaces for dialogue on practices and use of environmentally sustainable technologies, human rights, gender relations, and social participation, among others. Thus, the decision to use a simple source of clean energy to the detriment of the conventional energy matrix is a political and liberating posture, making its agro-ecosystem increasingly self-sustainable and independent of external resources. In this perspective, the results presented allow us to affirm the hypothesis that the use of the Sertanejo biodigestor social technology provides an increase in the income of farming families, influencing a reduction or even replacement of using LPG, and representing effective gains proportional to the income level of the families, in addition to biofertilizer production used in temporary and permanent crops, notably in forage cactus cultivation.

The hypothesis that the non-use or deactivation of the biodigester is related to the lack of raw material, requirements in equipment maintenance and/or shortage of labor to maintain the equipment is also confirmed, notably in relation to the raw material, as this is the reason most pointed out as the cause of the continuous non-use of the technology.

The existence of technology protection mechanisms is considered important, given the possibility of a loss of confidence in the proposed biodigester model due to its implementation without due care.

Thus, the following is recommended: not to deploy a biodigester in family units without livestock activities, under penalty of creating dependence on external sources; carry out preliminary studies on the family's demand for biogas, relating it to the potential of biogas production from the existing herd in order to establish a dynamic in accordance with the expected consumption; strengthen the arguments of economic impact for low-income families and highlight the arguments of environmental impact for families with more permanent sources of income, especially when not associated with agricultural activities; encourage the use of biogas associated with other activities in the production system, especially those dependent on conventional electricity, considering the construction of a biodigester with greater production capacity and using generators adapted to biogas use; establish dialogues with public agencies for technical assistance and rural extension and credit agents in order to incorporate the biodigester technology in financing lines from the environmental sustainability perspective; and always seek technical guidance for implementing the biodigester. It is a greatly useful device with environmental importance, but it needs to be well dimensioned and the installation of the gas pipes must be done by a professional with technical knowledge in the area.

Contribution of authors:

Souza, R.A.: Conceptualization, Methodology, Validation, Formal analysis, Research, Investigation, Resources, Writing — original draft. Lyra, M.R.C.C.: Supervision, Visualization, Writing — original draft, Writing — review & editing, Project administration, Funding acquisition. Carvalho, R.M.C.M.O.: Supervision, Writing — original draft, Writing — review & editing. Araújo Filho, J.C.A.F.: Conceptualization, Formal analysis, Methodology, Supervision, Visualization, Writing — original draft, Writing — review & editing.

References

Articulação no Semiárido – ASA. 2019. Dados Gerais (Acessed July 7, 2021) at: https://www.asabrasil.org.br/mapatecnologias/.

Articulação no Semiárido – ASA. 2021. Modelo da tecnologia social de acesso à água nº 1. Cisterna de placas de 16 mil litros. Anexo da Instrução Operacional SESAN nº 2, de 8 de agosto de 2017. Programa Cisternas. Recife.

Barros, G.C.; Farias Júnior, M.; Santos, M.N.F.; Nascimento, F.C.; Pascoal, C.D.; Duarte, M.D.S., 2020. Biogás e agricultura familiar no nordeste brasileiro: a experiência da ONG CETRA apoiada pela cooperação internacional no semiárido cearense. Revista RedBioLAC, v. 4, 39-43.

Brasil. 2010. Ministério do Desenvolvimento Social e Combate à Fome (MDS). Avaliação da sustentabilidade do programa cisternas em parceria com a articulação no semiárido brasileiro (ASA). Cadernos de Estudos Desenvolvimento Social em Debate, (13). Ministério do Desenvolvimento Social e Combate à Fome, Brasília, 240 pp.

Dagnino, R.; Brandão, F.C.; Novaes, H.T., 2004. Sobre o marco analítico-conceitual da tecnologia social. In: Tecnologia social: uma estratégia para o desenvolvimento. Fundação Banco do Brasil, Rio de Janeiro.

DIACONIA. s.d. 12 passos para construir um biodigestor. DIACONIA, Recife.

DIACONIA. 2016. Reaplicando o biodigestor a partir da mobilização social. DIACONIA, Recife.

DIACONIA. 2020. Entrevista de Ita Porto e Jucier Jorge concedida a: SOUZA, R. A. In: Souza, R.A. Uso do biodigestor como tecnologia social para produção de gás de cozinha. DIACONIA, Recife.

Empresa de Pesquisa Energética (EPE). 2019. Matriz energética e elétrica. EPE, Rio de Janeiro (Acessed April 9, 2020), at: http://www.epe.gov.br/pt/abcdenergia/matriz-energetica-e-eletrica.

Fundação Banco do Brasil (FBB). 2018. Caminhos e perspectivas para a tecnologia social. Fundação Banco do Brasil, Instituto de Tecnologia Social, Brasília.

Gerhardt, T.E.; Silveira, D.T., 2009. Métodos de pesquisa. Editora da UFRGS, Porto Alegre.

Gualdani, C.; Burgos, A., 2020. Mapeamento de fontes institucionais sobre tecnologias sociais na caatinga. Relatório técnico. Projeto Rural Sustentável Caatinga (PRS Caatinga). Fundação Brasileira para o Desenvolvimento Sustentável (FBDS), Rio de Janeiro.

Guimarães, P.R., 2008. Métodos quantitativos estatísticos. IESDE Brasil, Curitiba.

Herrero, J.M.; Donoso, M.P.; Mendoza, L.G.; Pedraza, G.X.; Jiménez, L.R.; Arias, J.V., 2016. Oportunidades para el desarrollo de un sector sostenible de biodigestores de pequeña y mediana escala en LAC. RedBioLac.

Intergovernmental Panel on Climate Change (IPCC). 2021. Climate change 2021. The Physical Science Basis. Summary for Policymakers. IPCC AR6 WGI. WMO, UNEP.

Jiménez, F.M.; Zambrano, D.A, 2018. Consumo de biogás en hogares rurales y sus implicaciones económicas y ambientales. Caso El Porvenir, Limón. Revista RedBioLAC, v. 2, 54-58.

Knopki, R.H., 2015. Segurança e prevenção de riscos na produção de biogás. Probiogás. Ministério das Cidades, Brasília, 35 pp.

Martins, S.; Schlindwein, S.; D'Agostini, L.; Bonatti, M.; Vasconcelos, A.; Hoffmann, A.; Fantini, A., 2010. Mudanças climáticas e vulnerabilidade na agricultura: desafios para desenvolvimento de estratégias de mitigação e adaptação. Brazilian Journal of Environmental Sciences (Online), (17), 17-27. (Accessed July, 2021) at: http://rbciamb.com.br/index.php/Publicacoes_RBCIAMB/article/view/376.

Mattos, L.C., 2017. Um tempo entre secas: superação de calamidades sociais provocadas pela seca através das ações em defesa da convivência com o semiárido. Doctoral Thesis, CPDA, Universidade Federal Rural do Rio de Janeiro, Seropédica.

Mattos, L.C.; Júnior, M.F., 2011. Manual do biodigestor sertanejo. Projeto Dom Helder Câmara, Recife, 55 pp.

Meunier, I.M.J.; Silva, J.A.A.; Ferreira, R.L.C., 2001. Inventário florestal, programas de estudo. Departamento de Ciência Florestal, Universidade Federal Rural de Pernambuco, Recife.

Nicoloso, R.S.; Barros, E.C.; Wuaden, C.R.; Pigoso, A., 2019. Uso do digestato como fertilizante. In: Kunz A.; Steinmetz, R.L.R.; Amaral, A.C. (Eds.). Fundamentos da digestão anaeróbia, purificação do biogás, uso e tratamento do digestato. Sbera: Embrapa Suínos e Aves, Concórdia, 209 pp.

Nobre, C.A.; Salazar, L.F.; Oyama, M.; Cardoso, M.; Sampaio, G.; Lapola, D., 2007. Relatório nº 6: mudanças climáticas e possíveis alterações nos biomas da América do Sul. CPTEC/INPE, IAE/CTA, São Paulo.

Quadros, D.G., 2009. Biodigestor na agricultura familiar do semiárido. EDUNEB, Salvador, 96 pp.

Rodrigues, I.; Barbieri, J.C., 2008. A emergência da tecnologia social: revisitando o movimento da tecnologia apropriada como estratégia de desenvolvimento sustentável. Revista de Administração Pública, v. 42, (6), 1069-1094. https://doi.org/10.1590/S0034-76122008000600003.

Silva, J.E.; Correia, L.A., 2020. Biodigestor sertanejo como alternativa para a conservação do semiarido potiguar. Holos, v. 6, e10125. https://doi.org/10.15628/holos.2020.10125.

Specht, M.J.S., 2012. Uso de lenha como combustível doméstico: padrões, impactos e perspectivas futuras para conservação da floresta atlântica ao norte do rio são Francisco. Master's Dissertation. Pós-Graduação em Biologia Vegetal, Centro de Ciências Biológicas, Universidade Federal de Pernambuco, Recife.

Ventura, A.C.; Garcia, L.F.; Andrade, J.C.S., 2012. Tecnologias sociais: as organizações não governamentais no enfrentamento das mudanças climáticas e na promoção de desenvolvimento humano. Cadernos EBAPE.BR, v. 10, (3), 605-629. https://doi.org/10.1590/S1679-39512012000300009.

ABES

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Energy potential and economic feasibility of biogas: case study of a landfill in Minas Gerais, Brazil

Potencial energético e viabilidade econômica do biogás: estudo de caso de um aterro sanitário em Minas Gerais, Brasil

Tatiane Leticia de Carvalho Souza[1], *André Luiz Marques Rocha*[1], *Daniel Brianezi*[1]

ABSTRACT

The final disposal of solid waste in landfills may result in the production of a clean and renewable energy through the exploitation of biogas generated in these locations. This study aims to estimate the methane production in a landfill, with a total population of 237,298 inhabitants, and a total generation of waste of 83,561.78 ton/year, in the last year of operation, located in the state of Minas Gerais and evaluate the economic feasibility of a biogas exploitation project in this place, for electrical energy generation. The methane production was estimated by the Intergovernmental Panel on Climate Change (IPCC) methodology, obtaining the maximum methane production value of 6,692,590 m³ in the last year of operation of the landfill. For economic feasibility analysis, the tools, such as net present value, discounted payback, and internal rate of return, were used with values of R$ 1,323,684.90 for 8 years, 4 months, and 12 days, and 9% per annum, respectively, demonstrating that the implementation of the project for the use of biogas at the landfill was viable, with positive economic return.

Keywords: economic analysis; electrical energy; final disposal; methane gas; solid waste.

RESUMO

A disposição final de resíduos sólidos em aterros sanitários pode resultar na produção de energia limpa e renovável por meio do aproveitamento do biogás gerado nesses locais. O objetivo deste estudo foi estimar a produção de metano em um aterro sanitário, com população total atendida de 237.298 habitantes, e uma geração total de resíduos de 83.561,78 t ano^{-1}, no último ano de operação, localizado no estado de Minas Gerais e estudar a viabilidade econômica de um projeto de aproveitamento de biogás no local do aterro, para geração de energia elétrica. Para estimar a produção de metano utilizou-se a metodologia proposta pelo Painel Intergovernamental sobre Mudanças do Clima (IPCC, 1996), obtendo-se o valor máximo de produção de metano igual a 6.692.590 m^3, no último ano de operação do aterro. Para análise de viabilidade econômica, utilizaram-se as ferramentas Valor Presente Líquido (VPL), *payback* descontado e Taxa Interna de Retorno (TIR), com valores encontrados de R$ 1.323.684,90, 8 anos, 4 meses e 12 dias, e 9% a.a., respectivamente, demonstrando que a implantação do projeto de aproveitamento de biogás no aterro foi viável, apresentando retorno econômico positivo.

Palavras-chave: análise econômica; energia elétrica; disposição final; gás metano; resíduos sólidos.

[1]Centro Federal de Educação Tecnológica de Minas Gerais – Belo Horizonte (MG), Brazil.

Correspondence address: Tatiane Leticia de Carvalho Souza – Av. Amazonas, 5253 – Nova Suíça – CEP: 30421-169 – Belo Horizonte (MG), Brazil – E-mail: tatianecsouza14@gmail.com

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Introduction

The increase in the urban population combined with changes in consumption habits caused an increase in the production of urban solid waste (ICLEI, 2009). These residues, when disposed inappropriately, result in public health and environmental problems, such as the proliferation of vectors and diseases and pollution of soil, water, and air (Figueiredo, 2011). Most of the solid waste collected in Brazil is destined for landfills. Between 2018 and 2019, about 59.5% of the total solid waste collected went to landfills (ABRELPE, 2019), which are a form of environmentally appropriate final disposal provided by the National Solid Waste Policy (Brasil, 2010). However, there are some environmental problems related to this form of final disposal, among them is the emission of gases.

According to the Ministry of the Environment (Brasil, 2019), the landfill can be considered a biological reactor in which one of the main products generated are the gases that have mainly methane and carbon dioxide in their composition, which are greenhouse gases, with methane having a potential of causing global warming 21 times greater than carbon dioxide (IPCC, 2013). Therefore, it is clear that biogas generated in landfills can be characterized as a global problem, thus highlighting the importance of using it as an alternative to avoid the emission of this gas and, in return, generate a source of clean energy, because it has a high energy potential and is a renewable, economically viable, and environmentally correct source of energy (Bianek et al., 2018).

The Brazilian energy matrix places the country at an advantage in the generation of renewable energy, as it has one of the cleanest matrices in the world (Freitas and Makiya, 2012). Of the electricity produced in the country, 81.4% comes from renewable sources, while 22.8% of the energy comes from renewable sources and the rest from nonrenewable sources globally. However, most of the renewable energy produced in Brazil comes from hydroelectric power stations (EPE, 2018b). As the Brazilian energy matrix is based on hydropower, the generation of new forms of electrical energy, such as that coming from biogas, is not encouraged with the same intensity (Arcadis, 2010).

According to Durão (2017), Brazil has the potential for generating electrical energy through the use of biogas in landfills, but this energy potential is still very less explored, and the generation corresponds only to 1,22% of the total energy matrix in Brazil (ANEEL, 2020).

Some examples of thermal power stations using biogas in landfills in Brazil are: the Biogas Thermal Power Station at the Solid Waste Treatment Center on BR-040, in Belo Horizonte (MG); the Thermal Power Station at the landfill in Uberlândia, Uberlândia (MG); the ValorGás Thermal Power Station, Juiz de Fora (MG); the Bandeirantes Thermal Power Station, São Paulo (SP); the Biogas Thermal Power Station at the Sítio São João Landfill, São Paulo (SP); the Thermal Power Station of Guatapará, Guatapará (SP); the Termoverde Salvador Power Station, Salvador (BA); the Itajaí Biogás e Energia S.A. Thermal Power Station, Canhanduba (SC); and the Recreio Biothermal Power Station, Minas do Leão (RS). These power stations were implemented between 2004 and 2015 in Brazil and have a total installed potential of 86.3 MW for generating electrical energy, most of which are present in landfills in the Southeast region of the country (Nascimento et al., 2019). In addition, it is worth mentioning Termoverde Caieiras, the largest thermal power plant powered by landfill biogas in Brazil, with an installed power of 29.5 MW (ANEEL, 2020).

Thus, it is clear that there are few biogas projects in operation in the country, although there is potential for its use, and this is explained by the existence of some difficulties mainly related to the economic feasibility and operational problems of the system (Arcadis, 2010).

Therefore, the technical and economic feasibility studies for the implementation of this energy source are important to promote its expansion and the exploitation of this potential available in Brazil, considering the importance of the energy use of biogas in landfills as an alternative for the reduction of greenhouse gas emissions and for the diversification of the Brazilian energy matrix.

Thus, this study aimed to estimate the energy potential of biogas and the economic feasibility of its use for the production of electrical energy in a landfill that serves three municipalities located in the Metropolitan Mesoregion of Belo Horizonte, in the state of Minas Gerais.

Literature review

Quantification of landfill biogas

The quantification of biogas generated in landfills can be done through mathematical models that use data about the landfill, such as precipitation, mass of waste deposited, characteristics of the site and waste, to conduct the theoretical estimate of methane produced (Barros, 2012). Currently, the most commonly used methods are based on first-order decay equations. These models consider that the age of the waste has an influence on the production of biogas and that there is a decrease in production over the years, from a certain amount of waste disposed in the landfill (ABRELPE, 2013).

Among the models that use first-order kinetics, we can mention the methodology proposed by the Intergovernmental Panel on Climate Change (IPCC, 1996), a methodology that is simple to apply to calculate methane emissions. In this method, the amount of degradable organic carbon (DOC) present in solid waste is estimated for specific regions, requiring statistical data on the population and urban solid waste (Vieira et al., 2015).

Energy exploitation of biogas in landfills

According to the Ministry of the Environment (Brasil, 2019), the energy exploitation of biogas aims to transform it into other forms of energy such as electric, steam, fuel for boilers or stoves, vehicle fuel, or for supplying gas pipelines. The energy potential of biogas is due to its high methane content, which makes it suitable for several applications in the field of energy generation (ICLEI, 2009).

In a landfill, this process occurs through the conversion of chemical energy present in organic matter molecules into mechanical energy that activates a generator, thus producing electrical energy. Methane is the constituent of biogas used to fuel engines and generators for the production of electrical energy in landfills, reducing the negative impacts generated by its emission through complete combustion for energy purposes (Landim and Azevedo, 2008).

According to ICLEI (2009), the biogas extraction system has vertical and horizontal drains, blowers, filters responsible for removing particulate material, and condensate separating tanks; and for the generation of electrical energy, generator sets are used, such as microturbines and internal combustion engines, the latter being the most used in projects aimed at generating electrical energy from landfill biogas, due to the compatibility of power with the economic feasibility of the project (Barros, 2012), presenting higher electrical efficiency and lower cost when compared with other technologies (ICLEI, 2009).

According to USEPA (2021), biogas is extracted from landfills using vertical wells, drilled into the residual mass, and connected to horizontal wells and a blower/flare system. The gas is then directed, through this system, to a central point where it can be treated according to its final use, and can be burned or used in energy generation projects.

Economic feasibility of using biogas as electrical energy

The implementation of electrical energy generation systems in landfills requires the execution of technical and economic feasibility studies, in order to verify the potential of biogas generation in the landfill, due to the amount of organic matter present in the waste, and to evaluate the electrical energy generation costs (Van Elk, 2007).

There are some factors that indicate the possibility of a landfill being economically viable or not for the installation of biogas energy exploitation projects. Among them, we can mention the population served of at least 200,000 inhabitants (Arcadis, 2010; Barros et al., 2014), receiving a minimum daily amount of waste of 200 tons and 500,000 total tons in its life span (Johannessen, 1999).

According to Costa (2016), the implementation of inter-municipal consortia makes the implementation of biogas energy exploitation projects viable, since municipalities that meet small demands of inhabitants generate a small amount of energy from biogas, which can make the project hardly viable. The consortia enable the installation of projects of capture, burn, and energy exploitation of biogas for the production of electrical energy, because the greater the volume of organic waste deposited in a single landfill, the greater the generation of methane gas (Arcadis, 2010). Therefore, the formation of consortia is an initiative that should be encouraged and has proven to be efficient, especially for municipalities with populations of less than 100,000 inhabitants (Arcadis, 2010).

Methodology

Description of the study site

The landfill where the study of biogas production and the analysis of the economic feasibility of its use for the production of electrical energy was conducted, is located in the state of Minas Gerais and serves three small- and medium-sized municipalities that dispose their waste to the site through the formation of a consortium. For reasons of confidentiality, the name of the landfill, as well as the municipalities served by it, were omitted. We chose to name them as municipalities A, B, and C. However, the data used are true. Table 1 presents socioeconomic data for municipalities A, B, and C.

The landfill started its operation in August 2014, with a population served, till this year, equals 200,045 inhabitants. The site has a disposal area equal to 14.8 ha and has an expected life span of 15 years.

Figure 1 summarizes the methodological steps used to conduct the calculations in this study.

Step 1: Estimation of the population and generation of solid waste in the municipalities served by the landfill

We used the arithmetic growth methodology to estimate the population projection for all municipalities served by the landfill. This model assumes population growth at a constant rate equal to the growth rate of the last 2 years for which we have data, and is represented by Equations 1 and 2 (Qasim, 1985).

$$P_{(t)} = P_0 + K_a(t - t_0) \quad (1)$$

$$K_a = \frac{P_1 - P_0}{t_1 - t_0} \quad (2)$$

Where:

$P_{(t)}$ = the estimated population in year t (inhab.);

K_a = the coefficient;

t_0 and t_1 = years of the last demographic censuses;

P_1 and P_0 = populations in years t_1 and t_0 (inhab.).

We used the population data from the last two censuses conducted by the Brazilian Institute of Geography and Statistics, corresponding to the years 2000 (IBGE, 2000) and 2010 (IBGE, 2010), referring to the urban population.

Table 1 – Socioeconomic data for municipalities A, B, and C.

	Population (year 2000)	Population (year 2010)	GDP per capita	HDI
A	39,458	47,236	R$ 31,529.18	0.753
B	99,515	111,266	R$ 16,555.58	0.761
C	26,303	31,609	R$ 104,169.26	0.764

Source: IBGE (2000, 2010, 2018) and PNUD (2010).

Once the populations for the municipalities were calculated up to the year the landfill was closed, it was possible to calculate the generation of solid waste disposed each year. For this, we used data on the per capita generation of urban solid waste collected in the state of Minas Gerais, a value equal to 0.831 kg/inhabitant.d (ABRELPE, 2014).

We considered, as proposed by Barros (2012), an increase of 1% over the per capita rate per year, a percentage that considers the trend of increased consumption, and consequently, the generation of solid waste by the population over the years.

Thus, multiplying the total population, referring to the sum of the three municipalities, by the per capita production for that year and by the number of days in the year, we obtained the annual production of solid waste disposed in the landfill.

Step 2: Estimation of the methane gas production in the landfill

We used the method suggested by the IPCC (1996) to estimate the potential for methane gas generation, which is a model that theoretically projects the volume of methane to be generated in a given time. We calculated the methane emission in the landfill from Equation 3.

$$Q_x = K.R_x.L_0.e^{-k(X-T)} \tag{3}$$

Where:
Q_x = the methane emission (m^3/year);
K = the decay constant;
$R_x = R_{(t)}$ = the waste stream of the year (t);
L_0 = the waste methane generation potential (m^3/ton);
X = the current year;
T = the year of disposal of waste in the landfill (start of operation).

The IPCC equation, mentioned above, is applied by the Environmental Company of the State of São Paulo (CETESB, 2006) in the Biogás, generation and energy use—landfills® software and was used to obtain the methane generation curve.

It is necessary to know the methane gas generation potential (L_0) to estimate the methane emission. This parameter depends on the composition of the waste, especially its organic portion, and its value is estimated from the carbon content of the waste and its biodegradable fraction and a factor for the stoichiometric conversion of CO_2 into CH_4 (IPCC, 2006). We made the calculation using the equation proposed by IPCC (2006), represented by Equation 4.

$$L_0 = MCF.DOC.DOC_f.F.\frac{16}{12} \tag{4}$$

Where:
L_0 = the waste methane generation potential (m^3/ton);
MCF = the methane correction factor;
DOC = the degradable organic carbon;
DOC_f = the dissociated DOC fraction;
F = the fraction of methane present in biogas in volume;
(16/12) = the carbon to methane conversion factor.

The variable amount of DOC becomes important to know in order make the calculations regarding the methane generation potential. It represents the organic carbon from waste that is available for biochemical decomposition. Its calculation can be made from Equation 5.

$$DOC = (0.40.A) + (0.17.B) + (0.15.C) + (0.30.D) \tag{5}$$

Where:
A = the fraction of paper, cardboard and textile of waste;
B = the fraction of parks' and gardens' debris of waste;
C = the fraction of food waste;
D = the fraction of wood waste.

The IPCC (1996) suggests, in the case where there is no data referring to the gravimetric composition of the waste from the studied landfill, the DOC value equal to 0.12 to be used for Brazil.

According to Bingemer and Crutzen (1987), the dissociated DOC fraction can be obtained by Equation 6. DOCf corresponds to the fraction of DOC that can decompose in an anaerobic way.

$$DOC_f = 0.014.T + 0.28 \tag{6}$$

Where:
DOC_f = the dissociated DOC fraction;
T = the temperature in the anaerobic zone (°C).

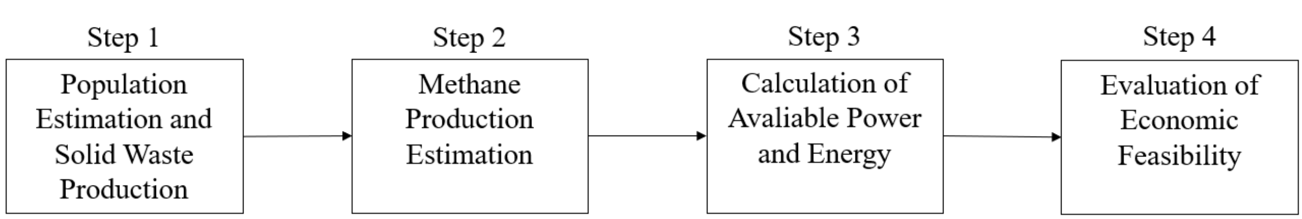

Figure 1 – Flowchart of the calculation methodology used.
Source: Own elaboration (2021).

The value for the MCF, necessary for the calculation of L_0, is related to the conditions of solid waste disposal, the operation control, and the site management. The value of this parameter was adopted according to the default values proposed by IPCC (2006), which are presented in Table 2.

In addition to parameter L_0, the decay constant k is also important. This constant is related to the time required for a portion of DOC present in the waste to decay to half of its initial mass. The constant k was adopted as proposed by IPCC (2006).

Thus, from L_0, the decay constant k and the waste stream in the year, we used Equation 3 to estimate the amount of methane emitted per year in the landfill.

Step 3: Calculation of the power and energy available in the landfill

The calculation of available power was made from Equation 7, modified from CETESB (2006) by Barros (2012).

$$Px = Q_x . E . E_c . P_{cCH_4} . \frac{1}{31{,}536{,}000} . \frac{1}{1{,}000} \quad (7)$$

Where:
P_x = the available power each year (kW);
Q_x = the methane flow each year (m^3/year);
P_{cCH4} = the methane calorific value (J/m^3);
E_c = the biogas collection efficiency (%);
E = the engine efficiency (%);
31,536,000 = the number of seconds in a year;
1/1,000 = for unit transformation from J/s to kW.

Equation 8 was used to calculate the available energy (CETESB, 2006).

$$E = P_x . t, \quad (8)$$

Where:
E = the available energy (kWh/year);
P_x = the available power (kW);
t = the engine operating time (h/year).

Step 4: Evaluating the economic feasibility of the project

We conducted an analysis based on the composition of the cash flow, which includes the project costs, considering the initial investment and expenses with operation and maintenance and the revenue obtained from the sale of electrical energy, in order to evaluate the economic feasibility of the project. We considered the investment costs with the collection system, treatment and purification system, compression, biogas burning, and electrical energy generation, being necessary to know the number of drains and the length of the collection pipe, calculated according to CETESB (2006).

From the composition of the cash flow, we used the net present value (NPV), internal rate of return (IRR), and discounted payback tools to conduct the economic evaluation of the project. These methods, especially IRR and NPV, are the best known and mostly used in investment analysis (Samanez, 2002).

NPV is a technique that explicitly considers the time value of money and was calculated according to Equation 9, modified from Gitman (2010). This method is used with the objective of verifying whether the project will present a greater value to the investor than the cost spent by him (Samanez, 2002).

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1 + MARR)^t} - CF \quad (9)$$

Where:
NPV = the net present value;
n = the discount time of the last cash flow;
t = the discount time for each cash entry;
MARR = the minimum attractive rate of return;
CF_t = the present value of cash flow;
CF_0 = the initial investment.

The results obtained from the calculation of the NPV were analyzed as follows: if NPV > 0, the project must be accepted; and if NPV < 0, the project must be rejected (Gitman, 2010).

In addition, the IRR was calculated, which is a rate that represents the annual return that the company will obtain if it decides to invest in the project (Gitman, 2010). The IRR is calculated by equating the NPV (Equation 9) to 0.

We used the multi-index methodology, which consists of a comparison between the IRR and the MARR (Motta and Calôba, 2002). The MARR is an interest rate that represents the minimum that an investor intends to earn when making an investment and, therefore, is unique for each investor and there is no formula to calculate it, as it can vary over time (Casarotto Filho and Kopittke, 1994). The comparison between the two rates can be made according to Table 3.

Table 2 – Classification of solid waste disposal sites and MCF.

Type	MCF
Managed—anaerobic	1
Managed—semi-aerobic	0.5
Unmanaged—deep (> 5 m of waste) and/or high water table	0.8
Unmanaged—shallow (< 5 m of waste)	0.4
Uncategorized	0.6

Source: translated from IPCC (2006).

Table 3 – Comparison between IRR and MARR.

IRR > MARR	Investment is viable
IRR < MARR	Investment is not viable
IRR = MARR	It is indifferent to invest

Source: Motta and Calôba (2002).

We also calculated the discounted payback, with the objective of verifying the time of return on the investment, being one more way to measure the economic feasibility of the project. This method is based on the time required for the present value of the company's forecast cash flows to equal the value of the initial investment made (Samanez, 2002). We calculated the discounted payback from the present value of the discounted cash flow each year, calculating the balance until it became positive.

Results and Discussion

Step 1: Population estimate and solid waste generation in the municipalities served by the landfill

Using population data from the 2000 and 2010 censuses and the arithmetic growth methodology, Equations 1 and 2, presented in step 1 of the methodology, was possible to calculate the projection for all municipalities served by the landfill for the years 2014–2029. Figure 2 shows the projection for the total population served by the site, equal to the annual sum of the three municipalities, for each year of the landfill's useful life.

Some authors claim in their studies that the minimum population for a biogas project to be economically viable must be equal to 200,000 inhabitants (Arcadis, 2010; Barros et al., 2014), which is met by the present study, demonstrating the tendency to obtain positive results regarding the feasibility of implementing this technology in the studied landfill.

We estimated the annual projection for solid waste disposal, and the total mass for each year, the daily disposal in each year, and the annual accumulation of solid waste are presented in Table 4.

The amount of waste deposited in the landfill increases over the years, with the increase in population, demonstrating the proportionality relationship between these variables. Thus, the consortia are solutions both for the treatment and final disposal of waste and for the gain of scale, as they allow the service to be provided to a greater number of municipalities. Therefore, the consortia collaborate with a better optimization of resources and minimization of environmental impacts.

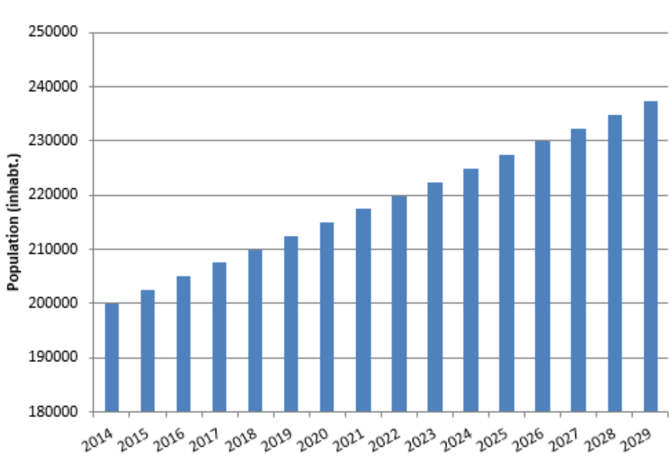

Figure 2 – Population projection for all municipalities served by the landfill.
Source: Own elaboration (2021).

As for the population, there is a minimum amount of waste that the landfill must receive so that it is interesting to implement biogas energy exploitation projects with a positive economic return. According to data provided in studies by Johannessen (1999), this amount equals 200 ton/day. Analyzing the amount of waste received each year, separately, only from the year 2023, the landfill starts receiving the minimum amount of solid waste per day. On the other hand, the landfill will receive the amount of waste over 500,000 tons throughout its useful life, a value also established by the same author.

The daily average of solid waste disposal in the landfill, considering the total value of waste received during its entire useful life, is equal to 196.47 ton/day, and the total accumulation of waste over the 15 years of the landfill's operation is equal to 1,102,014.6 tons.

We considered that all waste collected in the three municipalities is disposed in the landfill, not considering previous stages of treatment. This is due to the fact that the formation of the consortium took place, precisely, to allow the municipalities to have an environmentally adequate final destination, and, consequently, they did not have initiatives such as recycling either. However, it is noteworthy that over the years, other treatments can be adopted by the municipalities, which may lead to changes in the total amount of solid waste disposed at the site and, consequently, in the generation of methane gas.

Step 2: Estimation of the production of methane gas in the landfill

We made theoretical estimate of methane gas generation in the landfill. Therefore, it was necessary to know the potential for L_0 meth-

Table 4 – Total amount of waste disposed in the landfill per year, per day, and annual accumulated.

Year	Daily waste amount (ton/day)	Annual waste amount (ton/year)	Accumulated (ton/year)
2014	166.24	15,293.84	15,293.84
2015	169.98	62,044.23	77,338.07
2016	173.79	63,433.10	140,771.17
2017	177.65	64,843.54	205,614.71
2018	181.58	66,275.84	271,890.55
2019	185.56	67,730.31	339,620.85
2020	189.61	69,207.24	408,828.09
2021	193.72	70,706.93	479,535.02
2022	197.89	72,229.70	551,764.71
2023	202.13	73,775.85	625,540.56
2024	206.43	75,345.70	700,886.26
2025	210.79	76,939.57	777,825.82
2026	215.23	78,557.78	856,383.61
2027	219.73	80,200.67	936,584.27
2028	224.3	81,868.55	1,018,452.82
2029	228.94	83,561.78	1,102,014.60

Source: Own elaboration (2021).

RBCIAMB | v.56 | n.4 | Dec 2021 | 643-653 - ISSN 2176-9478

ane generation and, consequently, the percentage of DOC and the fraction of dissociated DOC.

As the data referring to the gravimetric composition of the landfill were not known, we adopted the DOC value equal to 0.12 (IPCC, 1996).

Considering Equation 6, and assuming an anaerobic zone temperature of 35°C (Bingemer and Crutzen, 1987), we obtained the DOC_f value equals 0.77.

Finally, we calculated the value of L_0 from Equation 4, considering the value of the MCF equal to 1, for anaerobic managed sites, proposed by the IPCC (2006), which is the commonly assigned value to landfills. The fraction of methane present in the biogas (F) was considered equal to 50%, also proposed by the IPCC (2006).

To obtain L_0 in the unit in which it is requested, it was necessary to divide the value found by the specific mass of methane, equal to 0.0007168 ton/m^3 (ICLEI, 2009).

Then, we established the value of the decay constant (k). Considering that the average annual precipitation for the municipality where the landfill is located, with historical data of 30 years, is 1,436 mm/year (Climatempo, 2019) and adopting the values proposed by IPCC (2006), for wet waste, for places with precipitation greater than 1,000 mm/year, tropical climate, with average temperatures greater than 20°C and the type of municipal solid waste as a whole, the value of k used for calculations was equal to 0.170 per year.

Table 5 presents the input data of the Biogás, generation and energy use—landfills® software (CETESB, 2006).

Applying all the data obtained prior to Equation 3 through the Biogas, generation, and energy use—landfills® software (CETESB, 2006), we obtained the methane flow values presented in Figure 3.

In Figure 3, we observed that the production of methane increases over time, as solid waste is disposed in landfill and decays after its closure, reaching its maximum value in the year of closure of receiving waste with value of 6,692,590 m^3 of methane generated. Since then, there is a decrease in methane generation, which is mainly due to the cessation of waste accumulation at the site.

Considering the minimum amount of daily waste that must be disposed in the landfill in order to obtain a viable project for the exploitation of biogas equal to 200 tons (Johannessen, 1999), adopting the same characteristics of the studied landfill, with values of L_0 equal to 85.94 m^3/ton and k = 0.170 per year and applying Equation 3, we can say that the minimum methane flow for the project to exploit biogas for commercialization to be economically viable is equal to 1,066.515 m^3/year. As shown in Figure 3, it is noteworthy that this value is met from 2015 to 2039 and, therefore, we believe that the implementation of a project within this time interval can bring positive economic return for the landfill.

It is noteworthy that not all biogas produced in the landfill will be captured and used. When landfills have well-designed, constructed, and operated collection systems, the collection of biogas can be ≥ 75% (World Bank, 2004; CETESB, 2006). However, considering that there may, for example, be possible operational problems and losses with fugitive emissions and oxidation by the cover layer (Silva et al., 2013), and to bring greater financial reliability to the project, we adopted in this study a value of 65% of efficiency in capturing biogas.

Table 5 – Input parameters of biogas, generation, and energy use—landfills software.

Parameter	Input
Opening year of the landfill	2014
Closure year of the landfill	2029
k (per year)	0.170
L_0 (m^3/ton)	85.94
Concentration of CH_4 in biogas (%)	50
Mass of waste disposed per year (ton/year)	Table 3

Source: Own elaboration (2021).

Step 3: Calculation of the power and energy available in the landfill

We used Equation 7 to estimate the available power, adopting the values of 65% of biogas collection efficiency, methane calorific value equal to 35.53 × 10^6 J/m^3 (CETESB, 2006), efficiency of internal combustion engine equal to 33% (World Bank, 2004), and methane flow each year according to Figure 3.

Then, we calculated the available energy from Equation 8, using the data obtained for the powers each year and considering that the operation will take place 24 h/day for 365 days. Figure 4 demonstrates the behavior of the power and energy curve over the years of the estimate.

We observed that both power and available energy increased over the years of landfill's operation, reaching maximum values of 1,617.37 kW and 14,168,185.14 kWh, respectively, in the same year in which the peak of biogas generation occurs. The average power and energy found, according to the estimate, were equal to 796.89 kW and 6,980,713.18 kWh, respectively.

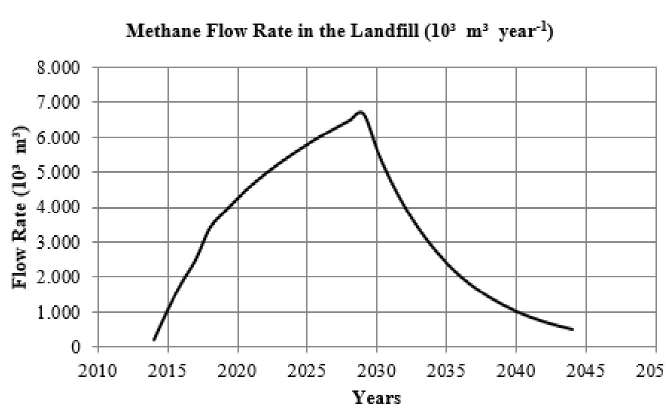

Figure 3 – Methane generation curve in the landfill.
Source: Own elaboration (2021).

Considering that all the power produced annually in the landfill is used to generate electrical energy and knowing that the mean consumption per residence in Brazil is approximately 123.6 kWh/month (EPE, 2018a), we can say that the energy generated by the studied landfill, in the year with the highest peak, would be able to supply approximately 9,550 residences. With this, we perceived the existing potential in the place for the generation of electrical energy through the methane produced from the solid waste disposed in the landfill.

As observed in Figure 4, the power produced varies over the years in the landfill, but not all the power produced will be used, as an initial investment must be made in which the power station is sized for a constant biogas flow, or with a known range. So, it becomes necessary to choose a power for the implementation of the station, as well as the number of generator sets. The choice of the power to be installed, which generates a maximum benefit, is still not much discussed in the current literature when referring to energy exploitation of biogas and, in most cases, it is done arbitrarily, without a defined methodology (Santos, 2015).

In the present work, we proposed the use of a single generator set with fixed power of 1,200 kW, capable of operating for 9 years, meeting the power demand from the year 2022 to 2030. The choice of the proposed power can be justified by the existence of motor-generator groups in the market powered by biogas with power compatible with this generation, and the higher percentage of use of the methane generated when compared with other powers for the same period, equal to 71.94%, with the best cost–benefit ratio.

The acquisition of a new generator set for the years after 2030, to meet the power of the period, was not considered, as, in line with what is described by ABRELPE (2013), as the methane flow tends to decrease after 2029, and, consequently, present a decreasing potential for using the biogas generated, acquiring a new generator set would greatly increase the costs for an exploitation that would be declining and no longer profitable.

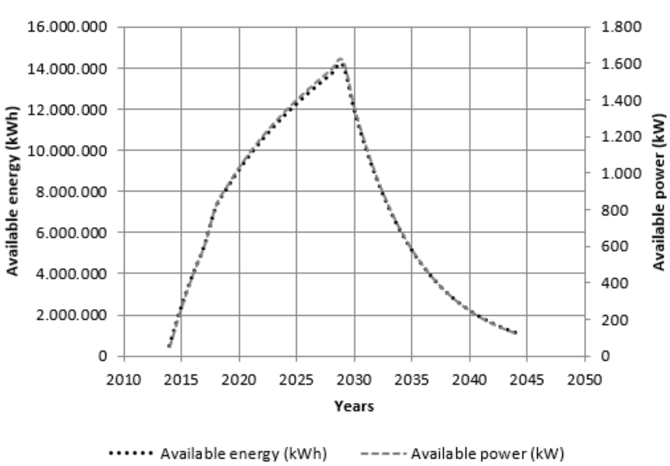

Figure 4 – Power and energy available in the landfill.
Source: Own elaboration (2021).

The exploitation of biogas generated using 1.2 MW power for the period from 2022 to 2030 comprises 71.94% of the total methane produced. The energy equivalent to this power, calculated through Equation 8, is equal to 10,512 MWh per project year and the corresponding flow, calculated from Equation 7, is equal to 368.45 m^3/h.

Step 4: Evaluating the economic feasibility of the project

Applying the methodology proposed by the manual presented by CETESB (2006), we obtained the values for the sizing and exploitation of biogas system components, as shown in Table 6.

The project's investment cost presented a final value equal to R$ 7,432,692.97. We adopted the values referring to the operation and maintenance costs of each of the systems in accordance with what is proposed by ICLEI (2009), which uses the value of 3% and 2% of the total investment value for expenses with the maintenance of the wells and expenses with the maintenance of the flare and extraction system, respectively. In addition, we adopted a value of 5% of the initial investment for maintenance expenses for the electrical energy generator engine (Santos, 2015). Therefore, operating and maintenance costs, considered fixed for all years, were R$ 743,269.30. Operator, management, and administration salary costs were not considered.

Revenues accounted from the sale of biogas, for the calculated value of 10,512 MWh per year, considering the energy sale tariff equal to R$ 187.9 per MWh, value obtained in the A-6 energy auction of the Brazilian Electricity Regulatory Agency for new projects of energy source from thermal to biomass (ANEEL, 2016), presented an annual value equal to R$ 1,975,204.80, which was considered fixed for all years of the project. It is important to highlight that the tariff with the sale of electrical energy was considered constant for all years of the project, but it varies according to the auctions conducted, and in this work, the value of the most recent auction developed by ANEEL in the year of 2019 is considered.

Table 7 presents the results obtained in the economic feasibility analysis, which will be described.

In order to conduct the investment analysis of the project, we compared the IRR to the Selic rate (Special Clearance and Escrow System), which is the most conservative opportunity cost in the Brazilian economy, defined by Bank of Brazil, representing the interest rate of the expected return of a low-risk investment fund in Brazil and, according to ABRELPE (2013), it is applicable for investments in biogas energy exploitation.

The value of the most recent Selic rate, on the date of this study, referring to November 2019, is equal to 5% p.a. (BACEN, 2019b). This rate was also used to calculate the present value of the cash flow, to obtain the discounted payback and to apply Equation 9, which refers to the NPV. For the calculating purposes of this study, the Selic rate was considered fixed, but it varies frequently and this fluctuation can directly influence the economic feasibility of the project, since very high values for this rate can make investment projects unfeasible.

We calculated the cash flow, for the 9 years of the project, considering the revenues subtracted from the costs listed above, obtaining a value for the NPV, from the application of Equation 9, equal to R$ 1,323,684.90. Therefore, as NPV > 0, the project must be accepted, that is, it is viable to invest in it.

The IRR presented a value equal to 9% p.a., therefore, considering the MARR equal to the Selic rate, 5% p.a., and applying the multi-index methodology, we can consider that the investment is viable, since the following relationship is true: IRR > MARR.

We also calculated the discounted payback with the objective of knowing the time of return on the investment made. For this, it was necessary to calculate the discounted cash flow, bringing it to the present value, thus obtaining the balance each year until the value becomes positive. The time required for the investment in the project to be paid is equal to 8 years, 4 months, and 12 days, which corresponds to the year of 2029. Figure 5 shows the year in which the balance becomes positive.

It is important to emphasize that a simplified analysis of investment, operation, and maintenance costs was conducted, considering only the main components of the biogas energy exploitation system for the purpose of producing electrical energy. In more in-depth studies, it should be considered other factors such as those cited by USEPA (2008), which include in the initial investment costs with engineering, legal, commercial, accounting, and other professional services, transport, and delivery of equipment and interconnection with the electrical network; and annual costs, which include, in addition

Table 7 – Results obtained for IRR, NPV, and discounted payback.

Parameter	Result obtained
IRR	9% p.a. > MARR (= 5% p.a.)
NPV	R$ 1,323,684.90
Discounted payback	8 years, 4 months and 12 days

Source: Own elaboration (2021).

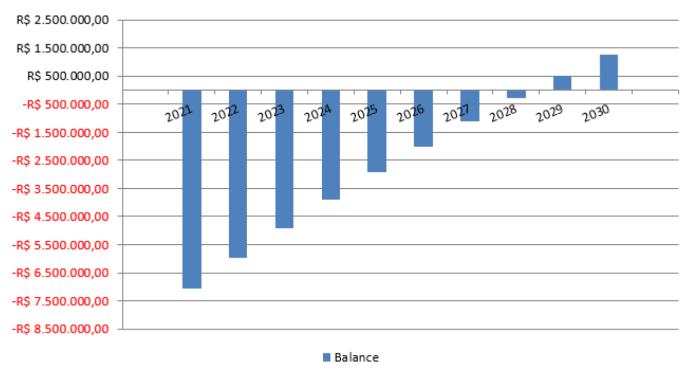

Figure 5 – Project return on investment.
Source: Own elaboration (2021).

Table 6 – Cost of the main components of the sizing system for the exploitation of biogas in landfills.

Collection system			
Component	Amount	Cost*	Total
Drains	76 units	R$ 2,199.04/unit	R$ 167,127.04
Pipe	3,750 m	R$ 549.76/m	R$ 2,061,600.00
Treatment and purification system			
Component	Amount	Cost	Total
H_2O coalescent filter	29,048.3 10^3 m^3	R$ 0.02/m^3	R$ 580,966.66
H_2S/Siloxin	29,048.3 10^3 m^3	R$ 0.02/m^3	R$ 580,966.66
CO_2	29,048.3 10^3 m^3	R$ 0.02/m^3	R$ 580,966.66
Compression			
Component	Amount	Cost	Total
Low compression	368.45 m^3/h	R$ 1,092.35 per m^3/h	R$ 402,472.69
Burner			
Component	Amount	Cost	Total
Flare	1 unit	R$ 436,941.26/unit	R$ 436,941.26
Electrical energy generation			
Component	Amount	Cost	Total
Motor-generator set	1,200 kW	R$ 2,184.71/kW	R$ 2,621,652.00
Grand total			R$ 7,432,692.97

*The values were corrected using the Central Bank of Brazil citizen calculator (BACEN, 2019a), from June 2016 (CETESB, 2006) to September 2019.
Source: Own elaboration (2021).

to those accounted for in this study, operational labor and security, management and administration, insurance, licenses, fees and professional services, for example. We suggest that in future studies all these and other factors that generate costs and revenues for the project should be analyzed.

Therefore, for the purposes proposed for this study, considering the costs and revenues evaluated and related to the implementation of the project in the studied landfill, the economic return will be positive and we suggest, then, that energy exploitation should be adopted on site. However, it is noteworthy that more in-depth and detailed studies, with regard to the project's costs and revenues, must be prepared in order to establish whether such additional values would make the project unfeasible.

Conclusions

The solid waste disposed each year in the landfill, according to the projection made, was able to provide enough biogas exploitation to generate electrical energy, in which, in the year with the highest peak of methane production, it can contribute to the consumption of approximately 9,550 residences. The biogas utilization project, with a duration of 9 years and available power equal to 1,200 kW/year, proved to be viable according to the criteria used, even if not all the power available in the period has been used.

The importance of using biogas in landfills is highlighted as an environmentally adequate alternative, which conciliates both the final destination provided by Brazilian legislation for solid waste, and the use of gas generated by the mass of waste to generate a source of clean energy, bringing the possibility of diversifying the Brazilian energy matrix, and avoiding the emission of gases that aggravate the greenhouse effect.

The formation of consortia between small- and medium-sized municipalities is essential, as they collaborate with a better optimization of resources and minimization of environmental impacts. Studies like this one, which economically evaluates the implementation of biogas energy utilization projects in Brazilian landfills, are essential to demonstrate the economic and environmental benefits of adopting this practice, contributing, for example, to meeting the sustainable development goals and for the Brazilian nationally determined contribution.

Contribution of authors:

Souza, T.L.C.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft. Rocha, A.L.M.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft. Brianezi, D.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft.

References

Agência Nacional de Energia Elétrica – ANEEL. 2016. Resultados de leilões (Accessed October 25, 2019) at: https://www.aneel.gov.br/pt/resultados-de-leiloes.

Agência Nacional de Energia Elétrica – ANEEL. 2020. Sistema de Informações de Geração da ANEEL – SIGA (Accessed June 24, 2021) at: https://www.aneel.gov.br/siga.

Arcadis, T., 2010. Estudo sobre o potencial de geração de energia a partir de resíduos de saneamento (lixo, esgoto), visando incrementar o uso de biogás como fonte alternativa de energia renovável. Programa das Nações Unidas para o Desenvolvimento (PNUD) e Ministério do Meio Ambiente (MMA), São Paulo, 56 pp.

Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais – ABRELPE. 2013. Atlas brasileiro de emissões de GEE e potencial energético na destinação de resíduos sólidos. ABRELPE, São Paulo, 172 pp.

Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais – ABRELPE. 2014. Panorama dos resíduos sólidos no Brasil. ABRELPE, São Paulo, 120 pp.

Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais – ABRELPE. 2019. Panorama dos resíduos sólidos no Brasil. ABRELPE, São Paulo, 74 pp.

Banco Central do Brasil – BACEN. 2019a. Calculadora do cidadão (Accessed October 10, 2019) at: https://www3.bcb.gov.br/CALCIDADAO/publico/exibirFormCorrecaoValores.do?method=exibirFormCorrecaoValores.

Banco Central do Brasil – BACEN. 2019b. Taxa Selic (Accessed November 8, 2019) at: https://www.bcb.gov.br/controleinflacao/taxaselic.

Barros, R.M. 2012. Tratado sobre resíduos sólidos: gestão, uso e sustentabilidade. Interciência, Rio de Janeiro; Acta, Minas Gerais, 374 pp.

Barros, R.M.; Tiago Filho, G.L.; Silva, T.R. 2014. The electric energy potential of landfill biogas in Brazil. Energy Policy, v. 65, 150-164. https://doi.org/10.1016/j.enpol.2013.10.028.

Bianek, J.; Schirmer, W.N.; Cabral, A.R.; Mayer, C.L.D.; Eurich, P.H.M.; Martins, E.H., 2018. Comparação entre metodologias USEPA e IPCC para estimativa teórica de produção de biogás em aterro municipal. Biofix Scientific Journal, v. 3, (1), 34-40. http://dx.doi.org/10.5380/biofix.v3i1.56038.

Bingemer, H.G.; Crutzen, P.J. 1987. The production of methane from solid wastes. Journal of Geophysical Research, v. 92, (D2), 2181-2187. https://doi.org/10.1029/JD092iD02p02181.

Brasil. 2010. Lei nº 12.305, de 2 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos; altera a Lei no 9.605, de 12 de fevereiro de 1998; e dá outras providências. Diário Oficial da União.

Brasil. Ministério do Meio Ambiente. 2019. Aproveitamento energético do biogás de aterro sanitário (Accessed April 5, 2019) at: http://www.mma.gov.br/cidades-sustentaveis/residuos-solidos/politica-nacional-de-residuos-solidos/aproveitamento-energetico-do-biogas-de-aterro-sanitario.

Casarotto Filho, N.; Kopittke, B.H. 1994. Análise de investimentos. Atlas, São Paulo, 447 pp.

Climatempo. 2019. Climatologia (Accessed October 22, 2019) at: https://www.climatempo.com.br.

Companhia Ambiental do Estado de São Paulo – CETESB. 2006. Manual do usuário do programa de computador Biogás: geração e uso energético – aterros – versão 1.0. CETESB, Secretaria de Meio Ambiente, Ministério da Ciência e Tecnologia, São Paulo, 61 pp.

Costa, T.S. 2016. Estimativa de geração de biogás no aterro sanitário da bacia leiteira do estado de Alagoas. Master's dissertation, Centro de Ciências Agrárias, Universidade Federal de Alagoas, Rio Largo. Retrieved 2019-10-11, from https://ceca.ufal.br/pt-br/pos-graduacao/energia-da-biomassa/documentos/dissertacoes-ppgeb/dissertacoes-ppgeb.

Durão, J.V. 2017. Transição para o uso do biogás no brasil: análise baseada na perspectiva multinível. Doctoral Thesis, Instituto de Economia, Universidade Federal do Rio de Janeiro, Rio de Janeiro. Retrieved 2019-04-03, from https://www.ie.ufrj.br/pos-graduacao-j/pos-graduacao-em-politicas-publicas/dissertacoes-e-teses.html#doutorado.

Empresa de Pesquisa Energética – EPE. 2018a. Anuário Estatístico de Energia Elétrica: ano base 2017. Ministério de Minas e Energia, Rio de Janeiro, 249 pp.

Empresa de Pesquisa Energética – EPE, 2018b. Balanço Energético Nacional 2018: ano base 2017. Empresa de Pesquisa Energética, Ministério de Minas e Energia, Rio de Janeiro, 294 pp.

Figueiredo, N.J.V. de. 2011. Utilização de biogás de aterro sanitário para geração de energia elétrica – estudo de caso. Master's dissertation, Energia, Universidade de São Paulo, São Paulo. doi:10.11606/D.86.2011.tde-11082011-092549. Retrieved 2019-03-03, from www.teses.usp.br.

Freitas, C.O.; Makiya, I.K. 2012. Potencial energético a partir do biogás proveniente de aterros sanitários do Estado de São Paulo. In: Anais do XXXII Encontro Nacional de Engenharia de Produção. Desenvolvimento sustentável e responsabilidade social: as contribuições da engenharia de produção. Bento Gonçalves.

Gitman, L.J. 2010. Princípios da administração financeira. 12. ed. Pearson Prentice Hall, São Paulo, 801 pp.

Governos Locais pela Sustentabilidade – ICLEI. 2009. Manual do aproveitamento do biogás. Secretariado para a América Latina e Caribe, Escritório de Projetos no Brasil, São Paulo, v. 1, 80 pp.

Instituto Brasileiro de Geografia e Estatística – IBGE. 2000. Censo Demográfico: Tabela 200 – população residente, por sexo, situação e grupos de idade – amostra – características gerais da população (Accessed October 2, 2019) at: https://sidra.ibge.gov.br/tabela/200.

Instituto Brasileiro de Geografia e Estatística – IBGE. 2010. Censo Demográfico: Tabela 200 – população residente, por sexo, situação e grupos de idade – amostra – características gerais da população (Accessed October 2, 2019) at: https://sidra.ibge.gov.br/tabela/200.

Instituto Brasileiro de Geografia e Estatística – IBGE. 2018. Produto interno bruto dos municípios (Accessed April 15, 2021) at: https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9088-produto-interno-bruto-dos-municipios.html?=&t=o-que-e.

Intergovernmental Panel on Climate Change – IPCC. 1996. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC, United Kingdom (Accessed May 2, 2019) at: https://www.ipcc-nggip.iges.or.jp/public/gl/invs6.html.

Intergovernmental Panel on Climate Change – IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IGES, Japan (Accessed May 20, 2019) at: https://www.ipcc-nggip.iges.or.jp/public/2006gl/spanish/vol5.html.

Intergovernmental Panel on Climate Change – IPCC. 2013. Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 1552 pp.

Johannessen, L.M. 1999. Guidance note on recuperation of landfill gas from municipal solid waste landfills. The World Bank, Washington, D.C., 34 pp.

Landim, A.L.P.F.; Azevedo, L.P. 2008. O aproveitamento energético do biogás em aterros sanitários: unindo o útil ao sustentável. BNDES Setorial, (27), 59-100 (Accessed Apr 6, 2019) at: http://web.bndes.gov.br/bib/jspui/handle/1408/2433.

Motta, R.R.; Calôba, G.M. 2002. Análise de investimentos: tomada de decisão em projetos industriais. Atlas, São Paulo, 392 pp.

Nascimento, M.C.B.; Freire, E.P.; Dantas, F.A.S.; Giansante, M.B. 2019. Estado da arte dos aterros de resíduos sólidos urbanos que aproveitam o biogás para geração de energia elétrica e biometano no Brasil. Engenharia Sanitária e Ambiental, v. 24, (1), 143-155. https://doi.org/10.1590/S1413-41522019171125.

Programa das Nações Unidas para o Desenvolvimento – PNUD. 2010. Ranking IDHM Municípios 2010 (Accessed April 15, 2021) at: https://www.br.undp.org/content/brazil/pt/home/idh0/rankings/idhm-municipios-2010.html.

Qasim, S.R., 1985. Wastewater treatment plants: planning, design and operation. Holt, Rinehart and Winston, New York, 608 pp.

Samanez, C.P., 2002. Matemática financeira: aplicações à análise de investimentos. 3. ed. Prentice Hall, São Paulo, 380 pp.

Santos, I.F.S. 2015. Proposta de um método escalonado para a motorização do aproveitamento do biogás gerado por aterros sanitários para fins de geração de energia elétrica. Master's dissertation, Engenharia de Energia, Universidade Federal de Itajubá, Itajubá. Retrieved 2019-10-12, from https://repositorio.unifei.edu.br/jspui/handle/123456789/162.

Silva, T.N.; Freitas, F.S.N.; Candiani, G. 2013. Avaliação das emissões superficiais do gás de aterros sanitários de grande porte. Engenharia Sanitária e Ambiental, v. 18, (2), 95-104. https://doi.org/10.1590/S1413-41522013000200001.

United States Environment Protection Agency – USEPA. 2008. Final assessment report: landfill biogas recovery and utilization at the solid waste treatment center BR-040 Belo Horizonte, Brazil. Eastern Research Group, Inc. and MGM International Group, LLC, 35 pp.

United States Environment Protection Agency – USEPA, 2021. Landfill Methane Outreach Program (LMOP): basic information about landfill gas (Accessed April 16, 2021) at: https://www.epa.gov/lmop/basic-information-about-landfill-gas.

Van Elk, A.G.H.P. 2007. Redução de emissões na disposição final. Ibam, Rio de Janeiro, 44 pp.

Vieira, G.E.G.; Campos, C.E.A.; Teixeira, L.F.; Colen, A.G.N. 2015. Produção de biogás em áreas de aterros sanitários: uma revisão. Revista Liberato, v. 16, (26), 193-204. http://doi.org/10.31514/rliberato.2015v16n26.p193.

World Bank. 2004. Energy Sector Management Assistance Programme. Handbook for the preparation of landfill gas to energy projects in Latin America and the Caribbean. World Bank, Conestoga-Rovers & Associates, 236 pp.

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Evaluation of generalized extreme value and Gumbel distributions for estimating maximum daily rainfall

Avaliação das distribuições generalizada de valores extremos e Gumbel para a estimativa de chuvas máximas diárias

Álvaro José Back[1], *Fernanda Martins Bonfante*[2]

ABSTRACT

Extreme rain events can cause social and economic impacts in various sectors. Knowing the risk of occurrences of extreme events is fundamental for the establishment of mitigation measures and for risk management. The analysis of frequencies of historical series of observed rain through theoretical probability distributions is the most commonly used method. The generalized extreme value (GEV) and Gumbel probability distributions stand out among those applied to estimate the maximum daily rainfall. The indication of the best distribution depends on characteristics of the data series used to adjust parameters and criteria used for selection. This study compares GEV and Gumbel distributions and analyzes different criteria used to select the best distribution. We used 224 series of annual maximums of rainfall stations in Santa Catarina (Brazil), with sizes between 12 and 90 years and asymmetry coefficient ranging from -0.277 to 3.917. We used the Anderson–Darling, Kolmogorov-Smirnov (KS), and Filliben adhesion tests. For an indication of the best distribution, we used the standard error of estimate, Akaike's criterion, and the ranking with adhesion tests. KS test proved to be less rigorous and only rejected 0.25% of distributions tested, while Anderson–Darling and Filliben tests rejected 9.06% and 8.8% of distributions, respectively. GEV distribution proved to be the most indicated for most stations. High agreement (73.7%) was only found in the indication of the best distribution between Filliben tests and the standard error of estimate.

Keywords: heavy rain; drainage; probability; territorial management.

RESUMO

Eventos extremos de chuvas podem causar impactos sociais e econômicos em vários setores. Conhecer o risco de ocorrência de eventos extemos é fundamental para o estabelecimento de medidas mitigadoras e para a gestão de riscos. A análise de frequências de séries históricas de chuva observadas por meio de distribuições teóricas de probabilidades é o método mais usado. As distribuições de probabilidade generalizada de valores extremos (GEV) e Gumbel destacam-se entre aquelas aplicadas à estimativa das chuvas máximas diárias. A indicação da melhor distribuição depende das características da série de dados usada no ajuste dos parâmetros e do critério utilizado para a seleção. Este trabalho teve como objetivo comparar as distribuições GEV e Gumbel e analisar os critérios usados para a seleção da melhor distribuição. Foram empregadas 224 séries de máximas anuais de estações pluviométricas de Santa Catarina, com tamanho entre 12 e 90 anos e coeficiente de assimetria variando de -0,277 a 3,917. Adotaram-se os testes de aderência de Anderson–Darling, Kolmogorov-Smirnov e Filliben. Para a indicação da melhor distribuição foram usados o erro padrão de estimativa, o critério de Akaike e o *ranking* com os testes de aderência. O teste Kolmogorov-Smirnov mostrou-se pouco rigoroso e somente rejeitou 0,25% das distribuições testadas, enquanto os testes de Anderson–Darling e de Filliben rejeitaram 9,06 e 8,8% das distribuições, respectivamente. A distribuição GEV mostrou-se a mais indicada na maioria das estações. Somente foi constatada alta concordância (73,7%) na indicação da melhor distribuição entre os testes de Filliben e o erro padrão de estimativa.

Palavras-chave: chuvas intensas; drenagem; probabilidade; gestão territorial.

[1]Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina – Urussanga (SC), Brazil.

[2]Universidade do Extremo Sul Catarinense – Criciúma (SC), Brazil.

Correspondence address: Álvaro José Back – Rodovia SC 108, km 353, 1563 – Caixa Postal 49 – Estação – CEP: 88840-000 – Urussanga (SC), Brazil. E-mail: ajb@epagri.sc.gov.br

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Introduction

The study of intense rainfall events is important for understanding the climatic reality of a place and for understanding and evaluating the consequences of the impacts they generate on different sectors of society. Selge et al. (2015) showed a high vulnerability of agricultural production and regional income due to the low adaptation to local climate conditions.

Most of the extreme rain events when they reach occupied areas, especially urban areas, negatively impact the socioeconomic system of these locations (Souza et al., 2014). Fernandes and Valverde (2017) highlighted that located and extreme climatic events impact, especially, the most socioeconomically susceptible populations, with higher levels of exposure and less resilience. From a social point of view, extreme events are considered as those episodes of rain in which material, human, and economic damage of great importance occurs and in which vulnerability and resilience play an important role in the analysis of the extreme event (Monteiro and Zanella, 2017).

Impacts related to extreme rainfall events cause a huge number of disorders and loses (Bork et al., 2017). Investigation of spatial and temporal distributions of heavy rains provides information for planning actions to prevent and minimize their impact.

Risk assessment is an important tool in natural disaster management. According to Mouri et al. (2013), risk assessment of natural disasters is defined as the assessment of both the probability of natural disaster occurrence and the degree of damage caused by natural disasters. Recently, many studies have focused on natural disaster risk analysis with probability distributions based on historical data, which are usually converted to frequencies. Regarding frequency analysis, particularly for extreme events, the objective is to define the events associated with a return period that provide information to carry out the design of hydraulic works, decreasing the uncertainty of the forecast (Molina-Aguilar et al., 2019).

Costa et al. (2018) commented that studies about the risks of extreme events enable the development of actions that minimize the effects of these events, thus strengthening the resilience of the affected communities, which generally have low technological development to overcome the damage triggered during disasters.

Water resource analysis using a statistical approach can increase our understanding of environmental contexts. These approaches have played important roles in disaster prevention, the environment, and climate change prediction. In some communities, extreme flood events no longer result in disasters because prevention strategies such as the construction of structured rivers and levees have been implemented (Mouri et al., 2013).

For insurance and indemnity matters, it is necessary to define the expected indemnity or the insured amount, which depends, of course, on the probability of an extreme event occurring. For this, it is necessary to adequately estimate the risks of extreme events, which requires the use of an appropriate probability distribution. Skees (2010) pointed out that ignoring this limitation can lead professionals to believe that they accurately accounted for exposure to catastrophic risk when this may not be true. A limited probability distribution adjustment in the sample data may underestimate or overestimate exposure to catastrophic risk.

Knowledge of extreme rainfall events is a requirement in drainage, waterproofing, and other engineering works, whether in urban or rural areas, because it allows the designer to consider the existing risks with the execution of the work and associate it with the best alternative, from an economic point of view, without disregarding technical issues of performance and safety (Souza et al., 2014). It is also important for proper soil management and prevention of water erosion (Santos et al., 2010). Maximum rainfall estimation with a given return period is essential for dimensioning hydraulic works such as drainage channels, manholes, storm drain, bridges, and dams (Almeida et al., 2015). The procedure adopted normally consists of using a theoretical distribution of probabilities, which must have its parameters previously adjusted based on the historical series of the annual maximums observed (De Paola et al., 2018).

There are several probability distributions, such as type I and type II extreme distributions, generalized extreme value (GEV), Pearson Type III, and Log-Pearson type III distributions, that can be used (Vivekanandan, 2015a). The type I extreme or Gumbel distribution and extensions have been applied to different areas of scientific knowledge such as hydrology, meteorology, climatology, insurance, finance, and geology, among many others (Nanvapisheh, 2021). The Gumbel distribution has been widely used to study maximum rainfall (Marques et al., 2014; Affonso et al., 2020).

The GEV distribution is widely employed for modeling the extreme precipitation in the environmental sciences and many other fields (Bella et al., 2020). GEV distribution has recently been indicated and is being widely used for precipitation frequency analysis for its capacity to include all three types of asymptotic distributions of extreme values (Gumbel, Fréchet, and Weibull).

In recent decades, many studies have been performed on the best fit of probability distributions for hydrological series. In addition, many countries use specific probability distributions to analyze maximum hydrologic events. Pearson type III distribution is recommended in China (Rizwan et al., 2018), while the United States adopted the Log-Pearson type III distribution (USWRC, 1981). Gumbel distribution is recommended in Canada (Das and Simonovic, 2011). Marra et al. (2017) highlighted that GEV is a three-parameter distribution of extreme values used worldwide to model rainfall extremes. Several European countries, such as Austria, Germany, Italy, and Spain, recommend the use of GEV distribution in studies of extreme events, such as rain and flood (Salinas et al., 2014).

Several studies in the literature have investigated probability distribution models for extreme values of climatic variables, mainly Gumbel and GEV models, which are currently the best-fits models, with best performance (Das and Simonovic, 2011; Marques et al., 2014; Pérez-Sánchez and Senent-Aparicio, 2017; Alam et al., 2018; Yuan et al., 2018; González-Álvarez et al., 2019). Many studies indicate Gumbel distribution as the most suitable method (Almeida et al., 2015; Vivekanandan, 2015b; Cremoneze et al., 2017; Mistry and Suryanarayana, 2019), while others cite GEV distribution as the superior method (Das and Simonovic, 2011; Beskow et al., 2015; Namitha and Vinothkumar, 2019).

Besides the distribution to be used, the method to adjust parameters can interfere in the evaluation of distribution (Marques et al., 2014). Among methods for adjusting probability distribution parameters, we highlight the method of moments (MM), the method of maximum likelihood (ML), and the method of L-moments (LM) (Hosking, 1990). The method by Chow (1964) is still often used in Gumbel distribution, with this distribution being known as Gumbel–Chow (Back and Cadorin, 2020). The method of moments is considered simpler, but also less precise when compared with other procedures, such as the method of maximum likelihood (Vivekanandan and Shukla, 2015). The ML method is considered to maximize the plausibility of a given distribution to be represented by the parameters estimated. However, in some cases, small samples can produce estimators comparable or even inferior to other methods. The ML method also has the drawback of increased complexity in calculation routines to estimate parameters, as is the case of GEV distribution. Naghettini and Pinto (2007) highlighted that the method of moments can produce low-quality estimates compared with the ML method, especially when the distribution has three or more parameters. The authors highlighted that the LM method results in estimates comparable in quality with those of ML, being often more precise for samples with small number of observations. Hosking (1990) highlighted that the LM method is less affected by extremes in the data series.

Maximum precipitation series can be represented by more than one probability distribution, and it is important to select the best distribution to be used (Zhang et al., 2002; Mandal and Choudhury, 2015; Vivekanandan, 2015a; Feyissa and Tukura, 2019). We can select the best model based on tests comparing observed frequencies with theoretical frequencies. The adhesion tests most used in hydrology are the Kolmogorov–Smirnov (KS), Anderson–Darling (AD), chi-square, and Filliben correlation (Rf) tests.

The distribution to be adopted depends on the characteristics of the hydrological series, the method for parameter adjustment, and the criterion to be adopted in the selection of probability distribution. Numerous studies performed by different researchers show that the best distribution can be defined based on the analysis of adhesion distribution adjusted to the observed data. Therefore, no distribution should be indicated according to region or country (Vivekanandan and Shukla, 2015). Thus, identifying the most adequate probability distribution to the extreme events observed, as well as adjusting its parameters and evaluating the quality of this adjustment, is challenging in the study of extreme events.

Leite and Virgens Filho (2011) highlighted that an error can occur in data analysis because of disregarding the characteristics of the most appropriate probability distribution for the data under study. The authors stated that mistakes may result in the unnecessary use of a more complex and laborious model, as well as in the use of a simplified model, which would result in wrong conclusions, if the data do not adhere to this distribution. However, we observe that most studies show only the best fit obtained, while in many cases, two or more models fit properly, with very small differences, and often less laborious and sometimes equally efficient model options are not shown.

Feyissa and Tukura (2019) highlighted that the proper evaluation of flood frequency distribution is one of the main problems faced by hydrologists. This issue is very important as different distributions can produce significantly different estimates for the same return period (Coulson, 1991). Thus, this study evaluates Gumbel and GEV distributions with parameters estimated by different methods for the series of annual maximum daily rainfall in Santa Catarina.

Materials and Methods

Data

We analyzed daily rainfall data from rainfall stations located in the state of Santa Catarina, Brazil. We used rainfall stations belonging to the Hydrometeorological network of the National Water Agency (ANA, 2020) and the network of rainfall stations from the Santa Catarina Agricultural Research Company (EPAGRI, 2020). For each rainfall station, we determined the series of annual maximums between 1912 and 2019. We selected stations with series over 10 years, excluding years with failures in observations. We selected 224 rainfall stations with these criteria, with 201 stations from ANA and 23 stations from Epagri, whose spatial distribution can be observed in Figure 1.

Probability distributions tested

The GEV distribution incorporates three asymptotic forms of maximum extreme values in a single expression. The probability density function is given by Equation 1:

$$f(x) = \frac{1}{\alpha}\left[1 - k\left(\frac{x-\beta}{\alpha}\right)\right]^{\left(\frac{1}{k-1}\right)} \exp\left\{-\left[1 - k\left(\frac{x-\beta}{\alpha}\right)\right]^{1/k}\right\}, \quad (1)$$

Where:
α = scale parameter.
β = position parameter.
k = form parameter.

The value of signal k determines the asymptotic form of maximum extreme values, that is, if $k < 0$, GEV represents type II distribution, defined only for $X > (\beta + \alpha)/k$. If $k > 0$, GEV represents type III distribution, defined only for $X < (\beta + \alpha)/k$. If $k = 0$, GEV corresponds to Gumbel distribution with scale (α) and position (β) parameters. Fréchet and Weibull extreme value distributions correspond to the particular cases in which $k > 0$ and $k < 0$, respectively.

Type I extreme distribution, also known as Gumbel distribution, has its probability density function given by Equation 2:

$$f(x) = \alpha \exp\{-\alpha(X-\beta) - \exp(-\alpha(X-\beta))\}, \quad (2)$$

Where:
α = the scale parameter (standard deviation of Gumbel distribution);
β = the location parameter (Model) of Gumbel distribution.

Parameter estimation

We obtained parameter estimation of Gumbel and GEV distributions by the method of moments and maximum likelihood, as described by Kite (1977). For the method of L-moments, we used the procedures described by Hosking (1994, 2005).

Adhesion tests

We applied adhesion tests to test the following null hypothesis (H_0): maximum daily rainfall data follow the distribution specified, against the alternative hypothesis H_1: maximum daily rainfall data do not follow the distribution specified. We used the adhesion tests of Kolmogorov–Smirnov, Anderson–Darling, and Filliben correlation (Rf), all at 5% significance level ($\alpha = 0.05$).

For the KS test (Abreu et al., 2018), we calculated D^+ and D^- differences given by Equations 3 and 4:

$$D^+ = \text{Max}|\text{Fn}(x) - F(x)|, \quad (3)$$

$$D^- = \text{Max}|F(x) - \text{Fn}(x)|. \quad (4)$$

The test statistic is given by the highest D^+ and D^- value, which was compared with the critical value (D_{crit}) at 5% significance level. Whenever D_{max} value exceeds the D_{crit} value, the distribution is rejected.

For the Anderson–Darling test (Abreu et al., 2018), we calculated the statistic by Equation 5:

$$A^2 = -N - \sum_{i=1}^{N} \frac{(2i-1)\{\ln F_X(x_{(i)}) + \ln[1 - F_X(x_{(N-i+1)})]\}}{N}. \quad (5)$$

For Gumbel distribution and GEV distribution, as recommended by Naghettini and Pinto (2007), we corrected the AD test statistic by Equation 6:

$$\text{ADc} = A^2(1+0.20/\sqrt{N}). \quad (6)$$

We compared the calculated values of ADc statistics with the critical value at 5% significance level ($AD_{crit} = 0.757$), recommended for Gumbel and GEV distributions (Naghettini and Pinto, 2007).

The Filliben adhesion test (1975) is based on the linear correlation coefficient Rf between observations ordered in increasing order and theoretical quantiles calculated by Equation 7:

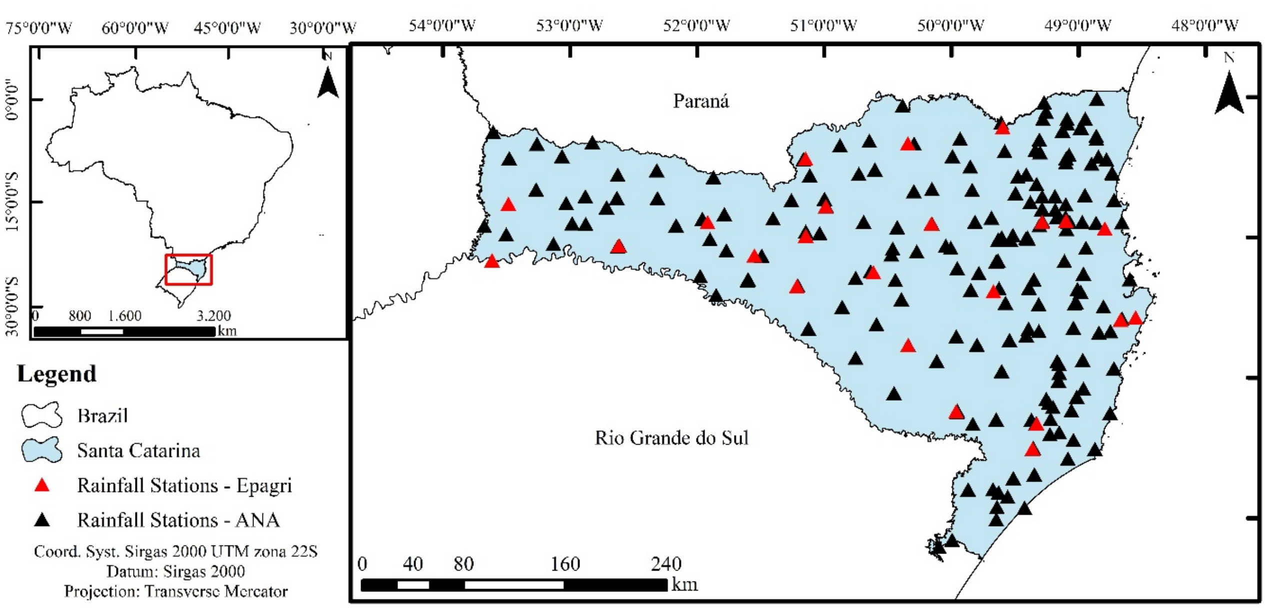

Figure 1 – Location of rainfall stations.

$$W_i = F_x^{-1}(1 - q_i), \quad (7)$$

Where:
q_i = the empirical probability corresponding to the order of classification given by Equation 8:

$$q_i = \frac{i\text{-}a}{N+1\text{-}2a}, \quad (8)$$

Where:
N = the series size;
a = 0.4, according to the formula suggested by Cunnane (1973).

The Filliben test statistic is expressed by Equations 9, 10 and 11 (Abreu et al., 2018):

$$\text{Rf} = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(w_i - \bar{w})}{\sqrt{\sum_{i=1}^{N}(x_i - \bar{x})^2 \sum_{i=1}^{N}(w_i - \bar{w})^2}}, \quad (9)$$

$$\text{where } \bar{x} = \frac{\sum_{i=1}^{N} x_{(i)}}{N} \quad (10)$$

$$\text{and } \bar{w} = \frac{\sum_{i=1}^{N} w_i}{N}. \quad (11)$$

The Rf value calculated is compared with the critical value (R_{crit}). The Filliben test has the disadvantage that critical values depend on sample size, distribution to be tested, and the expression used to calculate empirical probability. In this study, we calculated critical values according to the equations shown by Heo et al. (2008).

Distribution selection criteria

In order to select the best distribution, we calculated values of standard error of estimate (Se) and used the Akaike's criterion. In addition, we considered a global ranking based on the total score obtained in three adhesion tests along with the other selection criteria. Each test was assigned a value from 1 to 7, with the best distribution receiving the lowest value. Thus, the final score for each series tested ranges from 5 to 35, and the best distribution was given by the lowest overall score of each series.

For the standard error of an estimate, we used the expression suggested by Equation 12 (Kite, 1977):

$$\text{Se} = \sqrt{\frac{\sum_{i1}^{n}(X_i - Xe_i)^2}{n - k}}, \quad (12)$$

Where:
Se = the standard error for a given probability distribution;
X_i = the precipitation recorded of order i;
Xe_i = the precipitation estimated by the theoretical probability distribution;
n = the number of elements in the series of annual maximums;
k = the number of parameters estimated for probability distribution (k = 2 for Gumbel distribution and k = 3 for GEV distribution).

Akaike's information criterion was developed to test whether a given model is suitable, defining its criterion as Equation 13:

$$\text{AICc} = -2\text{LogLike} + 2k + \frac{2k(K+1)}{N-k-1}, \quad (13)$$

Where:
LogLike = the Log-likelihood function of the probability distribution;
k = the number of model parameters.

For Gumbel distribution, we calculate the Log-likelihood function by Equation 14:

$$\text{LogLike} = n ln(\alpha) - \alpha \sum_{i=1}^{n}(X_i - \mu) - \sum_{i=1}^{n} \exp(-\alpha(X_1 - \mu), \quad (14)$$

While for GEV distribution, the Log-likelihood function is by Equation 15:

$$\text{LogLike} = -n ln(\alpha) - \left(\frac{1+k}{k}\right)\sum_{i=1}^{n} ln\left[1 + k\left(\frac{X_i - \beta}{\alpha}\right)\right] - \sum_{i=1}^{n}\left[1 + k\left(\frac{X_i - \beta}{\alpha}\right)\right]^{-1/k}. \quad (15)$$

According to this criterion, the best model considered for problem construction is the one with the lowest Akaike's information criterion (AICc) value. This criterion penalizes the addition of parameters, that is, the selection of an extremely complex model with many parameters (Ramos and Moala, 2014).

Results and Discussion

Table 1 contains the summary of descriptive statistics of the series of annual maximums. In the 224 series studied, series size ranged from 12 to 90 years, with 25% of the series containing up to 29 years and 25% of the series containing more than 50 years of data. Series means ranged from 55.7 to 134.8 mm, although 50% of the series averaged in the 79.8–96.6 mm range. The variation coefficient ranged from 27.5 to 47.2%, with 50% of series between 27.2 and 31.9%. Regarding extremes, we found that the highest values in each series range from 95.5 to 367 mm, although 50% of the series had maximum values within the 138.3–196.2 mm range. The asymmetry coefficient ranged from -0.277 to 3.917, with only eight stations (3.6%) having negative asymmetry and 25% of the series with asymmetry below 0.50. In addition, 25% of series showed asymmetry above 1.22 and only 6.7% showed asymmetry above 2.0. Alam et al. (2018) stated that series with asymmetry coefficient above 1.0 can be considered highly asymmetric, while asymmetry from 0.5 to 1 is considered moderately asymmetric. Series with asymmetry from -0.5 to 0.5 can be considered approximately symmetric.

Table 2 shows rejection frequencies for the adhesion tests of distributions fitted to the series of annual maximums. The KS test only rejected four distributions (0.25%), one for the Gumbel–MM distribution, two for the Gumbel–Chow distribution, and one for GEV–LM. These series rejected by the KS test contained asymmetry coefficient above 2.8 with extreme values above 300 mm, which can be an outlier in the series. As the KS test is based only on the greatest difference between observed and estimated frequencies, an outlier can imply the rejection of the adhesion hypothesis. We obtained 142 rejections for the 1568 tested (224 series × 7 candidate distributions) with the Anderson–Darling test, equivalent to 9.06% rejection. The Rf test rejected the Gumbel distribution for 19 series analyzed (8.5%). The Gumbel distribution adjustment for the eight series with asymmetry coefficient above 2 was rejected by the Rf test. Among GEV distributions, the Rf test rejected 62 series, the majority being of GEV–MV distribution. Considering the total series, the Rf test rejected 8.8% of series.

Thus, we observed that the KS test is little rigorous in rejecting adhesion hypotheses to the series of annual maximums. Abreu et al. (2018) obtained similar results. One of the criticisms of KS test is that its application assumes that the distribution to be tested is previously known. However, in applications, we usually adjusted distribution parameters based on the series to be tested. Even with these limitations, the KS test is widely used often as the only adhesion test (Al-Suhili and Khanbilvardi, 2014; Pereira et al., 2017; Silva Neto et al., 2017; Ottero et al., 2018) and also commonly used as criterion for selecting the best distribution (Caldeira et al., 2015; Back and Cadorin, 2020). AD and Rf tests proved to be more rigorous and should be favored. Gumbel distribution was the most rejected as some series show negative asymmetry, and other series show asymmetries above 2.0. Gumbel distribution has a theoretical asymmetry coefficient of 1.1396. Thus, it is normal that series with asymmetry far from this value are considered inadequate. On the contrary, GEV distribution has the *k* parameter that allows better adjustment to the format of data distribution.

Beskow et al. (2015) obtained similar results, who analyzed data from 342 rainfall stations in the state of Rio Grande do Sul and found that the KS test did not reject any GEV distribution and rejected only 0.29% of Gumbel distributions. For the AD test, rejections were of 2.92% and 13.45% for GEV and Gumbel distribution, respectively. These rejections were of 2.05% and 8.19% by the Rf test, respectively. The authors concluded that the AD adhesion test was the most appropriate to evaluate the adequacy of probability models to the historical series analyzed, as being more restrictive than Rf and KS tests.

Marques et al. (2014) analyzed series of maximum rainfall in the state of Minas Gerais and analyzed the performance of GEV, Gumbel, and Gama probability distributions with two parameters, concluding that the Gumbel probability distribution performed better, adjusting to 87.5% of cases. Among probability distributions evaluated, GEV adjusted by ML method showed adhesion for all rainfall stations, being indicated for use. Mello and Silva (2005) also compared the adjustment of parameters by MM and ML using the chi-square adhesion test and concluded that the ML method performed better. Abreu et al. (2018) observed that adhesion tests can indicate different results regarding adequacy of probability distributions and concluded that the KS test was the least rigorous, admitting adhesion in all situations tested.

Table 3 shows frequencies in which different distributions were identified as the best according to different criteria. Using the criterion of lowest value of the KS statistic, Gumbel distribution was identified as the best in 83 series analyzed (11 MM, 23 ML, 13 LM, and 36 using the Gumbel–Chow method), and 141 series indicate GEV distribution as the best (37 MM, 43 ML, and 61 LM). By the Anderson–Darling

Table 2 – Frequency of rejection of the adhesion hypothesis.

Distribution tested	Adhesion test		
	Kolmogorov–Smirnov	Anderson–Darling	Filliben
Gumbel–MM	1	42	19
Gumbel–MV	0	25	19
Gumbel–LM	0	27	19
Gumbel–Chow	2	13	19
GEV–MM	0	21	7
GEV–MV	0	7	47
GEV–LM	1	7	8
Total	4	142	138

Table 1 – Summary of descriptive statistics of the series of annual maximums.

Statistics	Nr. of data	Mean (mm)	Coefficient of		Highest (mm)	Lowest (mm)
			Variation (%)	Asymmetry		
Maximum	90	134.8	47.2	3.917	367.0	85.2
Minimum	12	55.7	27.5	-0.277	95.5	15.3
Mean	40.3	89.4	30.8	0.910	169.7	47.9
1st Quartile	29	79.8	27.2	0.504	138.3	41.0
2nd Quartile	38	88.0	29.1	0.789	160.8	47.3
3rd Quartile	50	96.6	31.9	1.219	196.2	54.2
Quartile Range	21	16.8	54.5	0.715	57.9	13.2

test, Gumbel distribution was selected in 75 series, 57 of which use the Gumbel–Chow method. GEV distribution was selected in 149 series, 88 of which use the LM method. Similar results were obtained by Lima et al. (2021), who reported that the GEV distribution had the best performance in Anderson–Darling test and it was suitable to represent series with positive skewness with high values. Also Back and Cadorin (2020), comparing the Gumbel and GEV distribution in 11 pluviometric stations in the state of Acre, concluded that the GEV distribution with parameters estimated by the LM method was considered the best in 73% of the stations. Rf criterion indicated Gumbel distribution as the best in 24 series, indicating GEV distribution for the remaining 200 series. The Rf criterion does not distinguish between adjustment methods of Gumbel distribution. In the Akaike's criterion, Gumbel–ML distribution, with 172 series, and GEV–ML distribution, with 40 series, stood out. In Akaike's criterion, adjustment methods using maximum likelihood stand out for considering the Log-likelihood function in the calculation, which is minimized in the parameter adjustment process. Moretti and Mendes (2003) showed that small samples cause quality loss and less precision in parameter estimates using the method of maximum likelihood. Molina-Aguilar et al. (2019) highlighted that multiple methods for estimating the parameters of the Gumbel distribution function are reported in the literature, with the moments and ML methods being the best known and most used of them all.

In the criterion standard error of estimation, GEV distribution also prevailed with 192 series, of which GEV–MM is the most frequent. Adopting the ranking, GEV distribution is indicated in 164 series and Gumbel distribution is indicated in 60 series. González-Álvarez et al. (2019) reported similar results when investigating whether the Gumbel was most suitable, based on 318 rain gauges from the Caribbean region. They concluded that GEV was most suitable in 47.2% of the rain gauges, while Gumbel, in spite of being widely used in Colombia, was only suitable in 34.3% of the cases. Coronado-Hernández et al. (2020), with records from 362 stations distributed throughout Colombia, concluded that GEV distribution presents the best fit with an overall value of 52%.

Table 3 – Indication of the best probability distribution according to the selection criteria.

Probability distribution	Selection criteria					
	KS	AD	Rf	AK	Se	Ranking
Gumbel–MM	11	1	24*	0	2	10
Gumbel–ML	23	8	24*	172	1	20
Gumbel–LM	13	9	24*	6	25	23
Gumbel–Chow	36	57	24*	6	4	7
GEV–MM	37	17	73	0	93	49
GEV–ML	43	44	53	40	22	53
GEV–LM	61	88	74	0	77	62

*Non-differentiated between Gumbel distributions.

We observed that distribution selection varies according to the criterion used, and the lack of agreement between most of these criteria is evident. Table 4 shows the agreement matrix in the selection of distribution between criteria. The KS criterion showed 32.6% agreement with the AD criterion, that is, in 32.6% of series, the best distribution was selected equally by KS and AD criteria. Agreement of KS criteria with Rf and Akaike's criteria and standard error of estimate were 16.5, 13.8, and 13.8%, respectively. Regarding ranking criteria, agreement was 29.5%. We note that, even for completely random events, we expected 14% agreement. Thus, we state that there is no agreement between KS, Rf, and Se criteria. For the AD criterion, agreement with Rf, Akaike's, and Se criteria was 19.2, 12.1, and 17.9%, respectively, and agreement with the ranking was 36.2%. The Rf criterion had 73.7% agreement with the standard error of estimate. These were the indexes with the greatest agreement observed, reflecting increased compliance with the ranking. Abreu et al. (2018), who evaluated criteria for choosing probability distributions, also concluded that the Filliben test was the one with greatest convergence when considering the three best performances. Akaike's criterion showed the least agreement with other criteria, being only 5.4% with standard error and 17.4% with the sum of the ranking. These results show that different criteria used in the selection of distribution may indicate different probability distributions to be used. Akaike's criterion did not show significant agreement with any other criteria for privileging distributions estimated by the method of maximum likelihood. The greatest agreement, observed between Rf and Se methods (73.4%), can be explained as both consider differences between all precipitation values observed and estimated and distribution, while the KS criterion considers only the greatest difference.

As different criteria indicate different distributions, several authors (Mandal and Choudhury, 2015; Alam et al., 2018) have been making a ranking considering all indexes. In this case, agreement for KS criterion is 29.5 and 36.25% for AD, 47.8% for Rf, and 48.2% for Se. Akaike's criterion has only 17.4% agreement, practically not differentiating from the completely random value. This fact reinforces that although the Akaike criterion is an index used to select models in general, its application in the selection of probability distribution is not in line with the other criteria and contributes less to the general score.

Table 4 – Agreement matrix between adhesion criteria.

Criterion	Classification criteria					
	KS	AD	Rf	AK	Se	Ranking
KS	1.000	0.326	0.165	0.138	0.138	0.295
AD	0.326	1.000	0.192	0.121	0.179	0.362
Rf	0.165	0.192	1.000	0.129	0.737	0.478
AK	0.138	0.121	0.129	1.000	0.054	0.174
Se	0.138	0.179	0.737	0.054	1.000	0.482
Ranking	0.295	0.362	0.478	0.174	0.482	1.000

Some authors, besides using quantitative criteria, also adopted qualitative criteria, mainly with the evaluation of Q–Q plot or distribution curve graphs with confidence interval (Aiyelokun et al., 2017). Qualitative evaluation is feasible when evaluating some distributions for a data series. However, for studies evaluating hundreds of series and various distributions, graphical analysis is unfeasible.

Figure 2 shows percentage differences between distribution estimated by Gumbel and GEV best ranked with the distribution selected by the ranking criteria. We observe that quartiles of differences are within the range of -7.8 and +1.8% with Gumbel distribution for a return period of up to 50 years. This means that differences between rainfall estimated by these distributions are lower than 10% for more than 50% of the series studied. Differences are even lower for GEV distribution. This finding explains reduced agreement in the distribution selection criteria, as in most cases differences are insignificant, and more than one of distributions tested can be used to estimate maximum rainfall. Thus, distribution classified in the second or third place in the ranking can estimate rainfall with nonsignificant differences from the distribution in the first place.

On the contrary, we observe that some series show differences of more than 20% with Gumbel distribution estimates for a return period of above 20 years, reaching 84% with a return period of 1,000 years. For GEV distribution, differences above 20% were only observed with a return period of more than 100 years. These results are in consonance with Coelho et al. (2017), who reported differences greater than 18% in the maximum rainfall calculated with the GEV and Gumbel distributions with parameters estimated by the methods of moments and L-moments method. Back (2018), who analyzed maximum flow estimates with different probability distributions, observed that for the 10-year return period, differences were

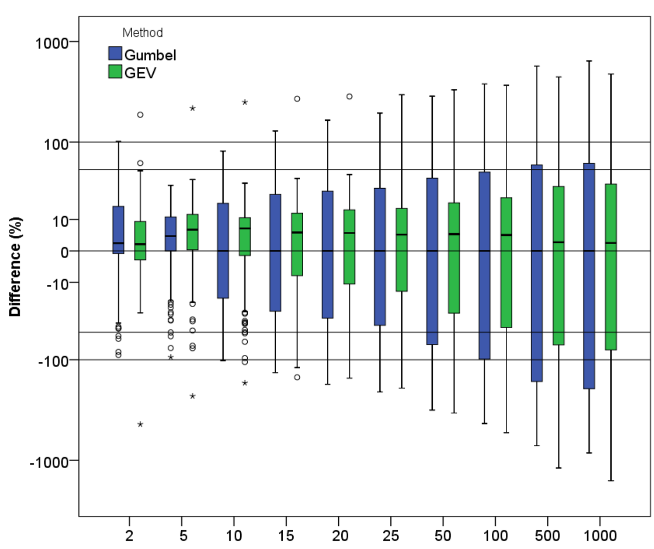

Figure 2 – Differences (%) between maximum rainfall estimated with the best-ranked Gumbel and GEV distributions and maximum rainfall estimated with the distribution selected using ranking criteria.

below 10%, while differences could be above 20% for the 100-year return period. Therefore, we highlight the importance of careful analysis of the probability distribution to be used in the estimation of extreme events with a return period of 100 years or more. In dam projects, the recommendation is to use a return period of up to 10,000 years. In these cases, we can obtain very different estimates for maximum rainfall according to the distribution selected, even if we perform adhesion test.

Esteves (2013) showed that extreme rainfall estimates for long return periods can differ by more than 40% depending on the distribution model used and question whether the level of protection they offer are appropriate in locations where data demonstrate clearly that alternative probability distributions may have a better fit to the local rainfall data. Adequate selection of the probability distribution is one of the more important issues in flood frequency analysis.

Fischer et al. (2012) claimed that extreme weather events regularly cause damages to ecosystems and affect the socioeconomic sphere. The population that is living in areas vulnerable to weather extremes such as floods, rain, storms, and droughts is increasing. Statistically, weather index insurance covers the extreme tail of the probability distribution of weather events for a specified region. The determination of the index depends on the probabilities associated with the given risk. An accurate estimation of return levels at given return periods is relevant for the determination of indices for weather index-based crop insurance and other adaptation measure.

Conclusions

The use of 224 series of maximum annual rainfall data ranging from 12 to 90 years, with asymmetry coefficient ranging from -0.277 to 3.917, allows important conclusions on parameter adjustment and selection of probability distributions to estimate maximum extreme rainfall.

The Kolmogorov–Smirnov test is little rigorous as adhesion test criterion to adjust probability distributions to maximum annual rainfall data. In addition, its use to indicate the best probability distribution does not demonstrate confidence. Anderson–Darling and Filliben tests were more rigorous, rejecting 9.06 and 8.5% of the distributions tested, respectively. Filliben test also showed that it can be used as a criterion to select the best distribution, showing 73.7% agreement with the criterion with the lowest standard error of estimate.

Akaike's criterion showed less agreement with the other criteria tested, and for considering the likelihood function in calculation, only indicated Gumbel and GEV distributions with parameters estimated by the method of maximum likelihood. The ranking consisting of several criteria can be an alternative to select the best probability distribution, although not superior to the use of standard error of estimate or Filliben test.

The GEV distribution was selected as the best distribution for most of the series used in all selection criteria. However, all distributions adjusted with the different parameter estimation methods showed rejections by Anderson–Darling and Filliben tests. This finding reinforc-

RBCIAMB | v.56 | n.4 | Dec 2021 | 654-664 - ISSN 2176-9478

es the need to look for the best distribution to fit the data observed, especially when the series is asymmetric or has the presence of extreme values. A single distribution cannot be indicated for all cases.

The selection of the probability distribution can affect the estimates of extreme events and thus impact the determination of maximum flows with consequences in the dimensioning of hydraulic works and definition of risk areas, and influence the cost of insurance against extreme events.

As the return periods gets longer, the differences between the rainfall estimates obtained with the different probability distributions are more accentuated. Therefore, we recommend careful analysis of adjustment to select the most adequate probability distribution to estimate extreme events with return periods of 100 years or more. Detailed analysis of the fit of probability distributions to the observed data series is a better alternative than assuming *a priori* that a given probability distribution is adequate.

Contribution of authors:

Back, Á.J.: Conceptualization, Methodology, Investigation, Writing — original draft; Bonfante, F.M.: Organization, Formal analysis, Writing — review and editing.

References

Abreu, M.C.; Cecílio, R.A.; Pruski, F.F.; Santos, G.R.; Almeida, L.T.; Zanettim, S.S., 2018. Critérios para escolha de distribuições de probabilidade em estudos de Eventos extemos de precipitação. Revista Brasileira de Meteorologia, v. 33, (4), 601-613. http://dx.doi.org/10.1590/0102-7786334004.

Affonso, V.; Faria, G.A.; Lopes, B.G.; Tsutsumoto, N.Y.; Fonseca, A.D.; Felizardo, L.M., 2020. Análise dos dados de precipitação máxima no noroeste paulista pela teoria dos valores extremos. Research, Society and Development, v. 9, (10), e9709109396. https://doi.org/10.33448/rsd-v9i10.9396.

Agência Nacional das Águas (ANA). Sistema de Informações Hidrológicas (Accessed October 8, 2020) at: http://hidroweb.ana.gov.br/.

Aiyelokun, O.; Ojelabi, A., Malomo, S.; Agbede, O., 2017. Efficient flood forecasting for the operation of hydraulic structures in a typical river basin. International Journal of Scientific & Engineering Research, v. 8, (11), 463-481.

Alam, M.A.; Emura, K.; Farnham, C.; Yuan, J., 2018. Best-Fit Probability Distributions and Return Periods for Maximum Monthly Rainfall in Bangladesh. Climate, v. 6, (1), 9. https://doi.org/10.3390/cli6010009.

Almeida, K.N., Reis, J.A.T.; Mendonça, A.S.F., 2015. Avaliação do desempenho dos métodos expeditos de determinação de equações de chuvas intensas. Brazilian Journal of Environmental Sciences, (35), 63-77 (Accessed December, 2020) at: http://www.rbciamb.com.br/index.php/Publicacoes_RBCIAMB/article/view/207

Al-Suhili, R.H.; Khanbilvardi, R., 2014. Frequency Analysis of the Monthly Rainfall Data at Sulaimania Region, Iraq. American Journal of Engineering Research, v. 3, (5), 212-222.

Back, Á.J., 2018. Análise de frequência de vazões máximas para projetos de drenagem. Revista Técnico-Científica de Engenharia Civil, v. 1, (2), 1-14. http://dx.doi.org/10.18616/civiltec.v1i2.5065.

Back, Á.J.; Cadorin, S.B., 2020. Extreme rainfall and intensity-duration-frequency equations for the state of Acre, Brazil. Brazilian Journal of Environmental Sciences, v. 55, (2), 159-170. https://doi.org/10.5327/Z2176-947820200597.

Bella, N.; Dridi, H.; Kalla, M., 2020. Statistical modeling of annual maximum precipitation in Oued El Gourzi Watershed, Algeria. Applied Water Science, v. 10, 94. https://doi.org/10.1007/s13201-020-1175-6.

Beskow, S.; Caldeira, T.L.; Mello, C.R.; Faria L.C.; Guedes, H.A.S., 2015. Multiparameter probability distributions for heavy rainfall modeling in extreme southern Brazil. Journal of Hydrology: Regional Studies, 4, (part B), 123-133. https://doi.org/10.1016/j.ejrh.2015.06.007.

Bork, C.K.; Castro, A.S.; Leandro, D.; Corrêa, L.B.; Siqueira, T.M., 2017. Índices de precipitação extrema para os períodos atual (1961-1990) e futuro (2011-2100) na bacia do rio Taquari-antas, RS. Brazilian Journal of Environmental Sciences, (46), 29-45. https://doi.org/10.5327/Z2176-947820170233.

Caldeira, T.L.; Beskow, S.; Mello, C.R.; Faria, L.C.; Souza, M.R.; Guedes, H.A.S., 2015. Modelagem probabilística de eventos de precipitação extrema no estado do Rio Grande do Sul. Revista Brasileira de Engenharia Agrícola e ambiental, v. 19, (3), 197-203. http://dx.doi.org/10.1590/1807-1929/agriambi.v19n3p197-203.

Chow, V.T., 1964. Handbook of applied hydrology. McGraw-Hill Co., New York, 42 pp.

Coelho Filho, J.A.P.; Melo, D.C.R.; Araújo, M.L.M., 2017. Estudo de chuvas intensas para a cidade de Goiânia/GO por meio da modelação de eventos máximos anuais pela aplicação das distribuições de Gumbel e generalizada de valores extremos. Ambiência, v. 13, (1), p. 75-88. http://dx.doi.org/10.5935/ambiencia.2017.01.05.

Coronado-Hernández, O.C.; Merlano-Sabalza, E.; Díaz-Vergara, Z.; Coronado-Hernández, J.R., 2020. Selection of Hydrological Probability Distributions for Extreme Rainfall Events in the Regions of Colombia. Water, v. 12, (5), 1397. http://dx.doi.org/10.3390/w12051397.

Costa, J.N.; Silva Júnior, J.B.; Araújo, S.M.S., 2018. Riscos e desastres relacionados a eventos extremos (climáticos e meteorológicos) no estado da Paraíba. Revista de Geociências do Nordeste, v. 4, 110-125.

Coulson, C.H., 1991. Manual of operational hydrology in B.C., 2ndedn B.C. Water Management Division, Hydrology Section, Ministry of Environment, Landsand Parks, BC, Canada.

Cremoneze, I.Z.; Peralta, D.; Mazucheli, J.; Emanuelli, I.P., 2017. Análise de frequências das precipitações máximas mensais observadas nos estados do Paraná e Rio Grande do Sul. Enciclopédia Biosfera, v. 14, (25), 48-57.

Cunnane, C., 1973. A particular comparison of annual maxima and partial duration series methods of flood frequency prediction. Journal of Hydrology, v. 18, (3-4), 257-271. https://doi.org/10.1016/0022-1694(73)90051-6.

Das, N.M.S.; Simonovic, S.P., 2011. The comparison of GEV, Log-Pearson type 3 and Gumbel distributions in the Upper Thames River Watershed under global climate models. Water Resources Research Report, London, 54 pp.

De Paola, F.; Giugni, M.; Pugliese, F.; Annis, A; Nardi, F., 2018. GEV parameter estimation and stationary vs. non-stationary analysis of extreme rainfall in African test cities. Hydrology, v. 5, (2), 28. https://doi.org/10.3390/hydrology5020028.

Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina (EPAGRI). 2020. Banco de dados de variáveis ambientais de Santa Catarina. Epagri, Florianópolis, 20 p. (Epagri, Documentos, 310).

Esteves, L., 2013. Consequences to flood management of using different probability distributions to estimate extreme rainfall. Journal of Environmental Management, v. 115, 98-105. https://doi.org/10.1016/j.jenvman.2012.11.013.

Fernandes, RA.; Valverde, M.C., 2017. Análise da resiliência aos extremos climáticos de chuva: estudo preliminar na região de Mauá no ABC Paulista – São Paulo. Brazilian Journal of Environmental Sciences, (44), 1-17. https://doi.org/10.5327/z2176-947820170183.

Feyissa, T.A.; Tukura, N.G., 2019. Evaluation of the best-fit probability of distribution and return periods of river discharge peaks. Case study: Awetu River, Jimma, Ethiopia. Journal of Sedimentary Environments, v. 4, (4), 360-368. https://doi.org/10.12957/jse.2019.46128.

Filliben, J.J., 1975. The probability plot correlation coefficient test for normality. Technometrics, v. 17, (1), 11-117. https://doi.org/10.2307/1268008.

Fischer, T.; Su, B.; Luo, Y.; Scholten, T., 2012. Probability Distribution of Precipitation Extremes for Weather Index–Based Insurance in the Zhujiang River Basin, South China. Journal of Hydrometeorology, v. 13, (3), 1023-1037. https://doi.org/10.1175/JHM-D-11-041.1.

González-Álvarez, Á.; Viloria-Marimón, O.M.; Coronado-Hernández, Ó.E.; Vélez-Pereira, A.M.; Tesfagiorgis, K.; Coronado-Hernández, J.R., 2019. Isohyetal maps of daily maximum rainfall for different return periods for the Colombian Caribbean Region. Water, v. 11, (2), 358. https://doi.org/10.3390/w11020358.

Heo, J.H.; Kho, Y.W.; Shin, H.; Kim, S.; Kim, T., 2008. Regression equations of probability plot correlation coefficient test statistics from several probability distributions. Journal of Hydrology, v. 355, (1-4), 1-15. https://doi.org/10.1016/j.jhydrol.2008.01.027.

Hosking, J.R.M., 1990. L-moments: analysis and estimation of distributions using linear combinations of order statistics. Journal of the Royal Statistical Society. Series B. Statistical Methodological, v. 52, (1), 105-124 (Accessed December, 2020) at: https://www.jstor.org/stable/2345653.

Hosking, J.R.M., 1994. The four-parameter Kappa distribution. IBM Journal of Research and Development, v. 38, (3), 251-258. https://doi.org/10.1147/rd.383.0251.

Hosking, J.R.M., 2005. FORTRAN routines for use with the method of L-moments. Version 3.04, Rep. No. RC 20525 (90933). IBM Research Division, T.J. Watson Research Center, Yorktown Heights, NY.

Kite, G.W., 1977. Frequency and risk analyses in hydrology. Water Resources Publications, Fort Collins, Colorado, 224 pp.

Leite, M.L.; Virgens Filho, J.S., 2011. Ajuste de modelos de distribuição de probabilidade a séries horárias de velocidade do vento para o município de Ponta Grossa, Estado do Paraná. Acta Scientiarum. Technology, v. 33, (4), 447-455. https://doi.org/10.4025/actascitechnol.v33i4.7072.

Lima, A.O.; Lyra, G.B.; Abreu, M.C.; Oliveira-Júnior, J.F.; Zeri, M.; Cunha-Zeri, G., 2021. Extreme rainfall events over Rio de Janeiro State, Brazil: Characterization using probability distribution functions and clustering analysis. Atmospheric Research, v. 247, 1052212. https://doi.org/10.1016/j.atmosres.2020.105221.

Mandal, S.; Choudhury, B.U., 2015. Estimation and prediction of maximum daily rainfall at Sagar Island using best fit probability models. Theoretical Appied Climatolology, v. 121, (1-2), 87-97. https://doi.org/10.1007/s00704-014-1212-1.

Marques, R.F.P.V.; Mello, C.R.; Silva, A.M.; Franco, C.S.; Oliveira, A.S., 2014. Desempenho de distribuições de probabilidades aplicadas a eventos extremos de precipitação diária. Ciência Agrotecnologia, v. 38, (4), 335-342. https://doi.org/10.1590/S1413-70542014000400003.

Marra, F.; Morin, E.; Peleg, N.; Mei, Y.; Anagnostou, E.N., 2017. Intensity–duration–frequency curves from remote sensing rainfall estimates: comparing satellite and weather radar over the eastern Mediterranean. Hydrology and Earth System Sciences, v. 21, (5), 2389-2404. https://doi.org/10.5194/hess-21-2389-2017.

Mello, C.R.; Silva, A.M., 2005. Métodos estimadores dos parâmetros da distribuição de Gumbel e sua influência em estudos hidrológicos de projeto. Irriga, v. 10, (4), 318-334. https://doi.org/10.15809/irriga.2005v10n4p334-350.

Mistry, P.B.; Suryanarayana, M.V., 2019. Estimation of annual one day maximum rainfall using probability distributions for Waghodia Taluka, Vadodara. Global Research and Development Journal for Engineering, 296-300 (Accessed November, 2020) at: https://www.grdjournals.com/uploads/conference/GRDCF/012/059/GRDCF012059.pdf

Molina-Aguilar, J.P.; Gutierrez-Lopez, A.; Raynal-Villaseñor, J.A.; Garcia-Valenzuela, L.G., 2019. Optimization of Parameters in the Generalized Extreme-Value Distribution Type 1 for Three Populations Using Harmonic Search. Atmosphere, v. 10, (5), 257. http://dx.doi.org/10.3390/atmos10050257.

Monteiro, J.B.; Zanella, M.E., 2017. A metodologia dos máximos de precipitação aplicada ao estudo de eventos extremos diários nos municípios de Crato, Fortaleza e Sobral-CE. GeoTextos, v. 13, (2), 135-159. http://dx.doi.org/10,977/194-5537geo.v13i2.24011.

Moretti, A.R.; Mendes, B.V.M., 2003. Sobre a precisão das estimativas de máxima verossimilhança nas distribuições bivariadas de valores extremos. Pesquisa Operacional, v. 23, (2), 301-324. https://doi.org/10.1590/S0101-74382003000200004.

Mouri, G.; Minoshima, D.; Golosov, V.; Chalov, S.; Seto, S.; Yoshimura, K.; Nakamura, S.; Oki, T., 2013. Probability assessment of flood and sediment disasters in Japan using the total runoff-integrating pathways model. International Journal of Disaster Risk Reduction, v. 3, 31-43. https://doi.org/10.1016/J.IJDRR.2012.11.003.

Naghettini, M.; Pinto, E.J.A., 2007. Hidrologia estatística. CPRM, Belo Horizonte (Accessed Mês xx, 20xx) at: http://rigeo.cprm.gov.br/jspui/handle/doc/454.

Namitha, M.R.; Vinothkumar, V., 2019. Development of empirical models from rainfall-intensity-duration-frequency curves for consecutive Days maximum rainfall using GEV distribution. Journal of Pharmacognosy and Phytochemistry, v. 8, (1), 2705-2709.

Nanvapisheh, A.A., 2021. The comparison between Gumbel and exponentiated Gumbel distributions and their applications in hydrological process. American Journal of Computer Science and Information Technology, v. 9, (3), 80.

Ottero, C.R.; Chargel, L.T.; Hora, M.A.G.M., 2018. Análise de frequência dos dados pluviométricos observados em 2011 a 2013 na região Serrana do Rio de Janeiro. Revista Brasileira de Meteorologia, v. 33, (1), 131-139. http://dx.doi.org/10.1590/0102-7786331007.

Pereira, D.C.; Duarte, L.R.; Sarmento, A.P., 2017. Intensity-duration-frequency curves determination of Ipameri – Goiás. Revista Eletrônica de Engenharia Civil, v. 13, (2), 233-246. http://dx.doi.org/10.5216/reec.V13i2.43330.

Pérez-Sánchez, J.; Senent-Aparicio, J., 2017. Intensity-duration-frequency curves of short-duration storms in the Segura River Basin, Spain. Agrociência, v. 51, (6), 607-616.

Ramos, P.L.; Moala, F.A., 2014. A aplicação da distribuição exponencial geométrica estendida para modelagem de dados pluviométricos. Revista Brasileira de Meteorologia, v. 29, (4), 613-620. https://doi.org/10.1590/0102-778620130612.

Rizwan, M.; Guo, S.; Xiong, F.; Yin, J., 2018. Evaluation of various probability distributions for deriving design flood featuring right-tail events in Pakistan. Water, v. 10, (11), 1603. https://doi.org/10.3390/w10111603.

Salinas, J.L.; Castellarin, A.; Kohnová, S.; Kjeldsen, T.R., 2014. Regional parent flood frequency distributions in Europe-Part 2: Climate and scale controls. Hydrology and Earth System Sciences, v. 18, (11), 4391-4401. https://doi.org/10.5194/hess-18-4391-2014.

Santos, G.G.; Griebeler, N.P.; Oliveira, L.F.C., 2010. Chuvas intensas relacionadas à erosão hídrica. Revista Brasileira de Engenharia Agrícola e Ambiental, v. 14, (2), 115-123. https://doi.org/10.1590/S1415-43662010000200001.

Selge, F.; Hagel, H.; Gunkel, G.; Doluschitz, R., 2015. Annual rainfall variability and economical dependency of smallholder agriculture in the Semi-Arid Northeastern region of Brazil. Brazilian Journal of Environmental Sciences, (36), 155-167. https://doi.org/10.5327/Z2176-947820151009.

Silva Neto, V.L.; Viola, M.R.; Silva, D.D.; Mello, C.R.; Pereira, S.B.; Giongo, M., 2017. Daily rainfall disaggregation for Tocantins State, Brazil. Ambiente & Água, v. 12, (4), 605-617. https://doi.org/10.4136/ambi-agua.2077.

Skees, J.R., 2010. State of Knowledge Report — data requirements for the design of weather index insurance. GlobalAgRisk, Inc., Broadway, 153 pp.

Souza, V.A.S.; Nunes, M.L.A.; Francener, S.F.; Rosa, A.L., 2014. Eventos de precipitações extremas na Amazônia Ocidental: Rondônia – Brasil. Revista Brasileira de Climatologia, v. 14, 295-315. http://dx.doi.org/10.5380/abclima.v14i1.36816.

U.S. Water Resources Council (USWRC). 1981. Guidelines for determining flood flow frequency. Bulletin 17A. Washington, D.C., U.S Geological Survey, 148 pp. https://doi.org/10.3133/tm4B5.

Vivekanandan, N., 2015a. Comparison of L-moments of probability distributions for extreme value analysis of rainfall for estimation of peak flood discharge for ungauged catchments. International Journal of Scientific Research in Science and Technologic, v. 1, (5), 2395-6011.

Vivekanandan, N., 2015b. Quantitative assessment on fitting of Gumbel and Frechet distributions for extreme value analysis of rainfall. International Journal of Scientific Research in Science and Technology, v. 1, (2), 68-73. https://doi.org/10.32628/IJSRST151224.

Vivekanandan, V.; Shukla, S, 2015. Flood frequency analysis using method of moments and L-moments of probability distributions. Cogent Engineering, v. 2, (1), 1018704. https://doi.org/10.1080/23311916.2015.1018704.

Yuan, J.; Emura, K.; Farnham, C.; Alam, M.A., 2018. Frequency analysis of annual maximum hourly precipitation and determination of best fit probability distribution for regions in Japan. Urban Climate, v. 24, 276-286. https://doi.org/10.1016/j.uclim.2017.07.008.

Zhang, W.B.; Xie, Y.; Liu, B.Y., 2002. Rainfall erosivity estimation using daily rainfall amounts. Scientia Geographica Sinica, v. 22, (6), 705-711. https://doi.org/10.13249/j.cnki.sgs.2002.06.705.

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Atlantic seabob shrimp as biomonitor of Cu and Zn near port activities: is it really a suitable choice?

Camarão sete-barbas como biomonitor de cobre e zinco no entorno de atividades portuárias: a escolha é realmente adequada?

Ana Paula Madeira Di Beneditto[1], *Keltony de Aquino Ferreira*[1], *Braulio Cherene Vaz de Oliveira*[1], *Carlos Eduardo de Rezende*[1], *Inácio Abreu Pestana*[1]

ABSTRACT

The trace elements concentration in the muscle of the Atlantic seabob shrimp (*Xiphopenaeus kroyeri*) caught in coastal fishing highlighted copper (Cu) and zinc (Zn), both related to antifouling systems, as the main elements related to the intensity of port activities of southeast Brazil (~20—to 22ºS). The aim of this study is to analyze if the behavior of Cu and Zn in the muscle of this shrimp species is constant among different sampling sites, verifying if the species is suitable as biomonitor for these elements. The shrimps came from fisheries done in 2017 in Vitória, Anchieta, and Farol de São Tomé, southeast Brazil. After sampling, each individual was categorized for gender and maturity stage, measured, and weighted. Bulk muscle samples were freeze-dried for determination of Cu, Zn, and ratios of stable isotopes of carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). The data analysis verified if the concentration of Cu and Zn in male and female shrimps vary among maturity stages and sampling sites, and how the concentration of Cu and Zn is related to shrimps foraging area and/or trophic position. Both bioaccumulation and growth dilution occurred, but not in the same way for genders and sampling sites, with Cu showing more variability. Relationships between elements and shrimps foraging area and trophic position did not show a clear trend among the sampling sites. Regression models indicated moderate relationships, explaining 51% (Cu) and 60% (Zn) of the association with the foraging area in Anchieta, but up to 8% in Vitória and Farol de São Thomé. For the trophic position, the models explained 33% (Cu) and 34% (Zn) in Anchieta and up to 14% in Vitória and Farol de São Thomé. The results showed that the

RESUMO

A concentração de elementos traço no músculo do camarão sete-barbas (*Xiphopenaeus kroyeri*) capturado na pesca costeira destacou cobre (Cu) e zinco (Zn), ambos relacionados com sistemas anti-incrustantes, como os principais elementos associados à intensidade das atividades portuárias do Sudeste do Brasil (~20–22ºS). O objetivo deste estudo foi analisar se o comportamento de Cu e Zn no músculo dessa espécie de camarão era constante entre os diferentes locais de amostragem, verificando se a espécie era adequada como biomonitor para esses elementos. Os camarões vieram de pescarias realizadas em 2017 em Vitória, Anchieta e Farol de São Thomé, Sudeste do Brasil. Após a amostragem, cada indivíduo foi categorizado quanto a sexo e estágio de maturidade, medido e pesado. Amostras compostas de músculo foram liofilizadas para a determinação de Cu, Zn e razões de isótopos estáveis de carbono ($\delta^{13}C$) e nitrogênio ($\delta^{15}N$). A análise dos dados verificou se a concentração de Cu e Zn em camarões machos e fêmeas variou entre os estágios de maturidade e locais de amostragem, e como a concentração de Cu e Zn estava relacionada à área de forrageamento e/ou posição trófica dos camarões. Tanto a bioacumulação quanto a diluição do crescimento ocorreram, mas não da mesma forma para os gêneros e locais de amostragem, com Cu apresentando maior variabilidade. As relações entre os elementos e a área de forrageamento e a posição trófica dos camarões não mostraram tendência clara entre os locais de amostragem. Modelos de regressão indicaram relações moderadas, explicando 51% (Cu) e 60% (Zn) da associação com a área de forrageamento em Anchieta, mas somente até 8% em Vitória e Farol de São Thomé. Para a posição trófica, os modelos explicaram 33% (Cu) e 34% (Zn) em Anchieta e até 14% em Vitória e Farol de São Thomé. Os resultados

[1]Universidade Estadual do Norte Fluminense Darcy Ribeiro – Campos dos Goytacazes (RJ), Brazil.

Correspondence address: Ana Paula Madeira Di Beneditto – Avenida Alberto Lamego, 2.000 – Parque Califórnia – CEP: 28013-602 – Campos dos Goytacazes (RJ), Brazil. E-mail: anapaula@uenf.br

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utilization of this shrimp species as biomonitor of marine coastal environments near port activities to monitoring the levels of Cu and Zn is not a suitable choice, at least in the spatial scale considered by this study.

Keywords: trace elements; stable isotopes; coastal shrimp; environmental monitoring; Western Atlantic.

mostraram que a utilização dessa espécie de camarão como biomonitor de ambientes costeiros marinhos próximos às atividades portuárias para monitoramento dos níveis de Cu e Zn não é uma escolha adequada, pelo menos na escala espacial considerada neste estudo.

Palavras-chave: elementos traço; isótopos estáveis; camarão costeiro; monitoramento ambiental; Atlântico Ocidental.

Introduction

The Atlantic seabob shrimp, *Xiphopenaeus kroyeri* (Heller 1862), is a penaeid from Western Atlantic Ocean (36°N to 30°S) widely caught in coastal commercial fisheries along its distribution range (FAO, 2018). The species is an omnivorous consumer that spends its entire life cycle in marine coastal waters feeding on a broad spectrum of food items, such as primary sources (phytoplankton and macroalgae) and small animals from both seabed and water column. In this species, males and females have similar diets, whereas juveniles feed on smaller prey when compared to adults, which are in a higher trophic position (Branco and Moritz-Júnior, 2001; Willems et al., 2016). Like other penaeid shrimps, the Atlantic seabob shrimp presents sexual dimorphism in body size, with females larger and heavier than males, and adult males comparable to juvenile females in size (Hartnoll, 1982).

In general, shrimps are recognized as biomonitors of trace elements contamination in coastal environments due to their abundance, easy sampling, and strong association with the benthic environment (Stentiford and Feist, 2005; Fry et al., 2016). Biomonitors are sentinel organisms that provide quantitative information on the environmental quality because they accumulate contaminants in their tissues, yielding a relative measure of the total amount of these contaminants in the environment (Hatje, 2016). Crustaceans accumulate trace elements from the environment, mainly from water and diet, whether they are essential or not to their body functions. The accumulation pathway in crustaceans may vary among species, gender, maturity stage, and organs (Rainbow, 2002; Pourang et al., 2004; Yilmaz and Yilmaz, 2007). In animal ecotoxicological studies, the relationships between the concentration of trace elements and the ratios of stable isotopes of carbon and nitrogen allow evaluating the assimilation of trace elements from a foraging area, measured by $\delta^{13}C$ values, and from a trophic position, estimated by $\delta^{15}N$ values (Asante et al., 2008; Liu et al., 2018; Liu et al., 2019). As a common sense, $\delta^{13}C$ values indicate the food source origin, being more depleted (more negatives values) in pelagic than benthic areas; and $\delta^{15}N$ values are usually more enriched at higher trophic levels (Fry, 2008).

The concentration of 12 trace elements in the muscle (edible portion) of the Atlantic seabob shrimp caught in coastal fishing highlighted copper (Cu) and zinc (Zn) as the main elements related to the intensity of port activities of southeast Brazil (~20–22ºS) (Di Beneditto et al., 2020). The tributyltin (TBT) antifouling systems used in ships and boats were worldwide banned in 2008, and they were replaced by antifouling products with Cu metal oxides in combination with other co-biocides, such as Zn pyrithione or the polymer zineb (Dafforn et al., 2011; Amara et al., 2018). These antifouling products increased levels of Cu and Zn in fishes, as demonstrated by Nikolaou et al. (2014) in aquaculture farms. Di Beneditto et al. (2020) considered the same explanation to Cu and Zn concentrations in shrimps caught near large port activities of southeast Brazil. It is noteworthy that both elements are essential in crustaceans' metabolism (and in most animals), as key components of many enzymes (Zn) and constituent of hemocyanin (Cu) (Rainbow, 2002; 2007). However, Cu and Zn can cause hazardous effects in animal species, including humans, at high concentrations (Ali and Khan, 2019).

Based on the previous results of Di Beneditto et al. (2020) and because shrimps are recognized as good biomonitors of trace element contamination in coastal environments (Stentiford and Feist, 2005; Fry et al., 2016), the aim of this study is to analyze if the behavior of Cu and Zn in the muscle of the Atlantic seabob shrimp (herein referred to as shrimp) is constant among different sampling sites, verifying if the species is suitable as biomonitor for these elements. The study raised two questions to understand the presence of Cu and Zn in the shrimps, considering its population structure and habitat: Does the concentration of Cu and Zn in male and female shrimps vary among maturity stages and sampling sites? and How is the concentration of Cu and Zn related to shrimps foraging area and/or trophic position? This study may contribute for future decisions on environmental quality monitoring near port activities, since the Atlantic seabob shrimp is widely distributed in marine coastal waters along the Western Atlantic Ocean, and both Cu and Zn are elements present in most antifouling systems applied in vessels and boats.

Material and Methods

Sampling

The shrimps analyzed in this study came from the same dataset considered in Di Beneditto et al. (2020). The samplings were done in June–July 2017, during landings from commercial fisheries in three fishing sites from southeast Brazil: Vitória (20º31´S; 40º30´W), near Vitória and Tubarão ports; Anchieta (20º48´S; 40º38´W), near Ponta de

Ubu maritime terminal; and Farol de São Thomé (22º02´S, 41º02´W), near Açu superport. The first two sites are located in the state of Espírito Santo (ES) and the last one in the state of Rio de Janeiro (RJ) (Figure 1). Details regarding cargo activities in Vitória and Tubarão ports (largest ports), Ponta de Ubu maritime terminal, and Açu superport are in Di Beneditto et al. (2020).

Each shrimp was categorized macroscopically for gender (male or female) and maturity stage (juvenile or adult), as described in Campos et al. (2009). Each individual was measured to carapace size with a caliper (± 0.1 mm) and weighted in a digital scale (± 0.1 g). Carapace, gills, hepatopancreas, gonads, and intestine were removed before analysis and only abdominal muscle was considered for the quantification of Cu, Zn, and stable isotopes. Muscle is a low metabolic tissue with low turnover rate (Madigan et al., 2012), being a good tissue to represent trace elements incorporation in the shrimps' body (Di Beneditto et al., 2020). Muscle samples were kept frozen (−20°C) in transparent and clean plastic bags prior to analysis.

The sample size and number of bulk samples from each sampling site were 115 individuals from Vitória with 49 bulk samples (12 juvenile males, 13 adult males, 10 juvenile females, and 14 adult females); 116 individuals from Anchieta with 49 bulk samples (11 juvenile males, 14 adult males, 9 juvenile females, and 15 adult females); and 119 individuals from Farol de São Tomé with 57 bulk samples (13 juvenile males, 14 adult males, 15 juvenile females, and 15 adult females). According to the end mass after freeze-dried, each bulk sample was composed by one to four individuals of similar size (carapace length and total weight), and same gender (male or female) and maturity stage (juvenile or adult).

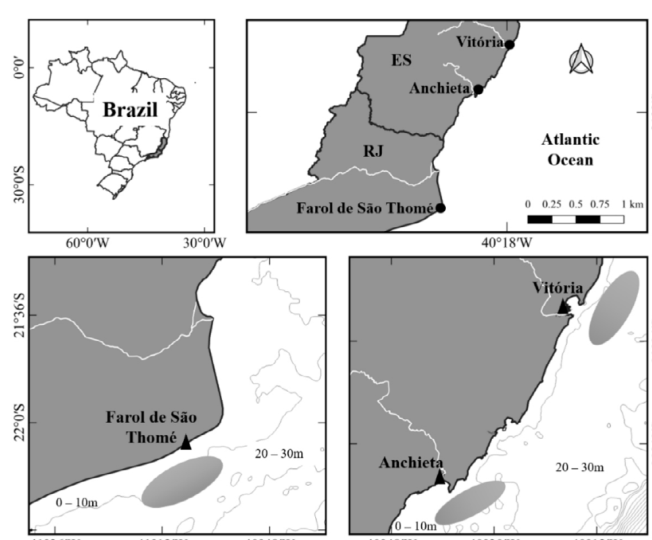

Figure 1 – Fishing areas of the Atlantic seabob shrimp (gray ellipses) and the fishing ports of Vitória and Anchieta, state of Espírito Santo (ES), and Farol de São Thomé, state of Rio de Janeiro (RJ).

Cu and Zn determination and stable isotope analysis

Muscle samples were freeze-dried and homogenized into a fine powder using a mortar and pestle. Each bulk sample (0.3 g dry weight) was analyzed for the concentration of Cu and Zn. For the determination of each element, dry samples were solubilized in 10 mL of 65% HNO_3, and then heated in a digestion block at 150°C until drying the extract. The samples were resuspended with 5 mL of 0.5 N HNO_3 at 60°C in a digestion block. Subsequently, the samples were filtered on filter paper (Whatman 40) and completed to 20 mL with 0.5 N HNO_3. Analytical blanks controls were prepared for each 20 samples to check for solution contamination. Certified reference material (Standard Reference Material DORM 4) was analyzed, with recovery of 110% and 70% for Cu and Zn, respectively, and coefficients of variation of triplicates < 10%. The certificate reference material recovery showed good results, and we assumed that the possible trace elements loss during the filtering processes did not significantly affect the results. No reference is available for shrimps; but there are references for fish tissues that show it (Maurya et al., 2019; Lacerda et al., 2020).

The trace elements were determined using an inductively coupled plasma-optical emission spectrometer (ICP-OES 720 ES, Varian). The operating conditions for ICP-OES were detailed in Di Beneditto et al. (2020). To avoid measurement errors, we performed the ICP-OES calibration every 30 samples and the quantification control with a calibration standard of 0.05 mg L^{-1} for 15 samples. Cupper and Zn concentrations were expressed in μg g^{-1} of dry weight. The limit of detection (LOD) and limit of quantification (LOQ) of ICP-OES followed the calculation presented in Skoog and Leary (1992): LOD = 3× standard deviation of blanks divided by the slope of the calibration curve. The LOQ were obtained by 3.3× LOD, coinciding with the first point of the calibration curve after the control blanks (Thomsen et al., 2003). The LOD (μg g^{-1}) and LOQ (μg g^{-1}) for each trace element are, respectively: Cu (< 0.27 and 0.88) and Zn (< 0.20 and 0.66). Determinations for all samples had results above the LOD and LOQ.

The ratios of stable isotopes ($\delta^{13}C$ and $\delta^{15}N$) were determined in 0.4 mg of each bulk sample using an organic elemental analyzer (Flash 2000, Thermo Scientific) coupled to a mass spectrometer (Delta V Advantage Isotope Ratio Mass Spectrometer, Thermo Scientific) through the ConFlo-VI interface (Model BR30140, Thermo Scientific). Reference values for C and N were Pee Dee Belemnite (PDB) and atmospheric nitrogen, respectively. Samples were analyzed using analytical blanks and urea analytical standards (IVA Analysentechnik-330802174). Analytical control and reproducibility were done for every 10 samples using a certified isotopic standard (Elemental Microanalysis Protein Standard OAS) and based on triplicates for every 10 samples (± 0.2‰ for $\delta^{13}C$; ± 0.3‰ for $\delta^{15}N$), respectively. There was no prior extraction of lipids from the muscle samples; however, the C/N ratios were lower than 3.5, indicating low lipid levels that do not compromise the interpretation of $\delta^{13}C$ values (Post et al., 2007). The isotopic results were presented as parts per thousand (‰). All analysis (trace elements and stable isotopes) were done at Laboratório de Ciências Ambientais from Universidade Estadual do Norte Fluminense Darcy Ribeiro (UENF).

Data analysis

All statistical analyses were done in the R program (R Core Team, 2020). The concentration of Cu and Zn was normalized by the shrimp carapace length to remove intraspecific bias in bioaccumulation or growth dilution. Karimi et al. (2007; 2010) defined somatic growth dilution (SGD) (or just growth dilution) as a reduction in the somatic concentration of an element during rapid growth that normally happens in aquatic invertebrates. In general, SGD of an ingested element occurs when total biomass gain outpaces element gain from food, thereby diluting mass-specific element concentration in the body.

The relationship between the square root of shrimp's total weight ($\sqrt{W}$) and carapace length (CL) was adjusted for all bulk samples (mean values): $\sqrt{W} = 0.142 \cdot CL - 0.466$ ($R^2 = 0.95$, $p < 0.000001$). Since these measures have a strong relationship with each other, as demonstrated by the R^2 value, both could be applied as a measure of shrimp size in data normalization. Then, we evaluated how gender, maturity stage, foraging area ($\delta^{13}C$) and/or trophic position ($\delta^{15}N$) might influence the elements concentration in the shrimp muscle.

To answer the first question (Does the concentration of Cu and Zn in male and female shrimps vary among maturity stages and sampling sites?), the concentration of each element was used to calculate the ratio between the normalized concentrations in adults per normalized concentration in juveniles, as indicated below. Thus, when $Ratio_{Adults,Juveniles}$ is > 1, there is trace element bioaccumulation between the maturity stages, whereas values < 1 indicate a growth dilution effect (Equation 1).

$$Ratio_{Adults,Juveniles} = \frac{\text{Normalized elements concentration by carapace size in adults}}{\text{Normalized elements concentration by carapace size in juveniles}} \quad (1)$$

All combinations of Cu and Zn concentration in adults and juveniles were calculated through empirical combinatorial analyses (Monte Carlo method; expand.grid function, BASE package, Khitalishvili, 2016; R Core Team, 2020). This method generates all possible scenarios among individuals sampled in each sampling site, and correctly propagates the error associated with the ratios of trace elements between maturity stages into the results. The number of combinations performed did not exceed X·Y, with X and Y being the count of values for adults and juveniles, respectively. Only unique combinations were used to prevent biased results.

A two-way analysis of variance (ANOVA) compared the $Ratio_{Adults,Juveniles}$, isolating the effects of each factor (gender and sampling site) separately, and measuring the interactions between them. Because the number of combinations generated by the Monte Carlo method were reasonably large (Anchieta = 289 combinations, Farol de São Thomé = 407 combinations, and Vitória = 296 combinations), the p values associated with ANOVA were all significant, even when corrected by the Bonferroni method (Signorell, 2020). Therefore, we report the effect size without p values to avoid redundancy.

To answer the second question (How is the concentration of Cu and Zn related to shrimps foraging area ($\delta^{13}C$) and/or trophic position ($\delta^{15}N$)?), a linear regression between each trace element (normalized concentrations) and stable isotopes values was done considering all shrimps sampled in a given sampling site (R^2 and p values are in Table 1). The slopes of regression equations from different sampling sites were compared by ANCOVA followed by Tukey multiple comparison test (Lenth, 2019).

When it was necessary, a maximum likelihood function (boxcox, MASS package; Venables and Ripley, 2002) was used for variable transformation to meet the parametric tests assumptions (linearity, normality, and homoscedasticity). Data transformations were done when necessary, as indicated in the figure and table legends. In addition, the type I *a priori* error was $\alpha = 0.05$ for all hypothesis tests.

The main steps described in Material and Methods section to reach the aim of this study are summarized in Figure 2.

Results

For Cu, both bioaccumulation and growth dilution were recorded in males and females, while for Zn only growth dilution was noted (Figure 3). The Cu behavior in the shrimp's muscle was variable among the sampling sites. In Vitória, males and females showed similar $Ratio_{Adults,Juveniles}$. In Anchieta, males had higher $Ratio_{Adults,Juveniles}$ than females, and in Farol de São Thomé females had higher $Ratio_{Adults,Juveniles}$ than males. For males, an increasing latitudinal gradient was noted for Cu $Ratio_{Adults,Juveniles}$: Vitória (0.59) < Anchieta (0.78) < Farol de São Thomé (0.95). For females, there were two groups: Vitória and Anchieta with Cu concentrations at least 40% higher in juveniles than adults, and Farol de São Thomé with an opposite trend (Figure 3).

Regarding Zn, males showed higher $Ratio_{Adults,Juveniles}$ than females in Vitória and Anchieta, but not in Farol de São Thomé. The $Ratio_{Adults,Juveniles}$ was similar for males among the sampling sites, and for females, there was an increasing latitudinal gradient: Vitória (0.46) < Anchieta (0.61) < Farol de São Thomé (0.95) (Figure 3).

The relationships of Cu and Zn with the shrimps foraging area (measured by $\delta^{13}C$ values) and trophic position (measured by $\delta^{15}N$ values) were stronger in Anchieta compared to the other sampling sites (Table 1). In Anchieta, the concentrations of Cu and Zn decreased with the enrichment of $\delta^{13}C$ and $\delta^{15}N$ (negative slope). The regression models indicated moderate relationships, explaining 51% (Cu) and 60% (Zn) of the relationship with the foraging area in Anchieta (Table 1). In Vitória and Farol de São Thomé, the models explained up to 8% (Table 1). A similar trend was noted for shrimp's trophic position. The mod-

Table 1 – Associations of Cu and Zn concentration normalized by shrimp carapace size (Cu_{Norm} and Zn_{Norm}) with foraging area ($\delta^{13}C$) and trophic position ($\delta^{15}N$) in the sampling sites*.

Elements	Sampling Sites	$\delta^{13}C$				
		Regression Models			Slope Comparisons	
		Equations	R^2	p-value	Slope (Confidence Interval)	Multiple comparisons (p-value)
Cu	Vitória	$Cu_{Norm} = -0.23 \cdot \delta^{13}C - 2.59$	0.07	0.05	-0.23 (-0.47, 0.008)	Anchieta–Farol de São Thomé = 0.01
	Anchieta	$Cu_{Norm} = -0.60 \cdot \delta^{13}C - 8.46$	0.51	< 0.0001	-0.60 (-0.77, -0.43)	Anchieta–Vitória = <0.0001
	Farol de São Thomé	$Cu_{Norm} = -0.03 \cdot \delta^{13}C - 0.10$	<0.0001	0.59	-0.03 (-0.15, 0.08)	Farol de São Thomé–Vitória = 0.57
Zn	Vitória	$Zn_{Norm} = -0.56 \cdot \delta^{13}C - 6.80$	0.07	0.05	-0.56 (-1.14, 0.002)	Anchieta–Farol de São Thomé = 0.62
	Anchieta	$Zn_{Norm} = -0.76 \cdot \delta^{13}C - 10.09$	0.60	< 0.0001	-0.76 (-0.94, -0.58)	Anchieta–Vitória = 0.69
	Farol de São Thomé	$Zn_{Norm} = -0.39 \cdot \delta^{13}C - 5.20$	0.08	0.02	0.39 (-0.73, -0.04)	Farol de São Thomé–Vitória = 0.90
Elements	**Fishing Areas**	$\delta^{15}N$				
		Regression Models			**Slope Comparisons**	
		Equations	R^2	**p-value**	**Slope (Confidence Interval)**	**Multiple Comparisons (p-value)**
Cu	Vitória	$Cu_{Norm} = -0.23 \cdot \delta^{15}N + 3.77$	0.08	0.04	-0.23 (-0.45, -0.01)	Anchieta–Farol de São Thomé = < 0.0001
	Anchieta	$Cu_{Norm} = -1.16 \cdot \delta^{15}N + 14.08$	0.33	< 0.0001	-1.16 (-1.65, -0.68)	Anchieta–Vitória = < 0.0001
	Farol de São Thomé	$Cu_{Norm} = 0.16 \cdot \delta^{15}N - 1.36$	0.14	0.004	0.16 (0.05, 0.26)	Farol de São Thomé–Vitória = 0.12
Zn	Vitória	$Zn_{Norm} = -0.49 \cdot \delta^{15}N + 8.02$	0.06	0.06	-0.49 (-1.03, 0.03)	Anchieta–Farol de São Thomé = 0.005
	Anchieta	$Zn_{Norm} = -1.39 \cdot \delta^{15}N + 17.63$	0.34	< 0.0001	-1.39 (-1.95, -0.83)	Anchieta–Vitória = 0.11
	Farol de São Thomé	$Zn_{Norm} = 0.33 \cdot \delta^{15}N - 2.47$	0.07	0.04	0.33 (0.007, 0.66)	Farol de São Thomé–Vitória = 0.09

*Regression models were fitted for each element and area. R^2, p values, and slope comparisons (Lenth, 2019) are shown.

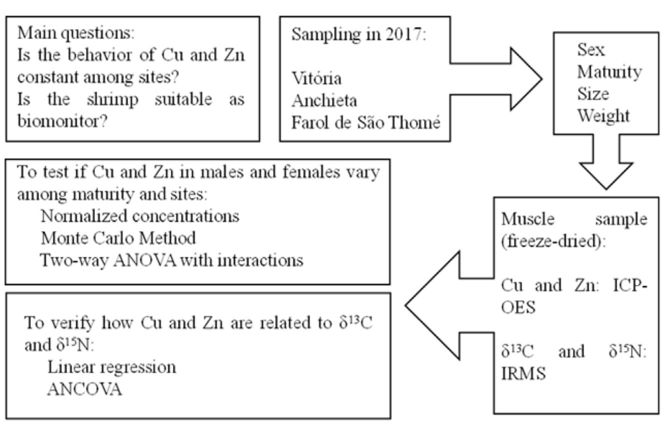

Figure 2 – Flowchart of the methodological steps of this study.

els explained 33% (Cu) and 34% (Zn) in Anchieta, and up to 14% in Vitória and Farol de São Thomé (Table 1).

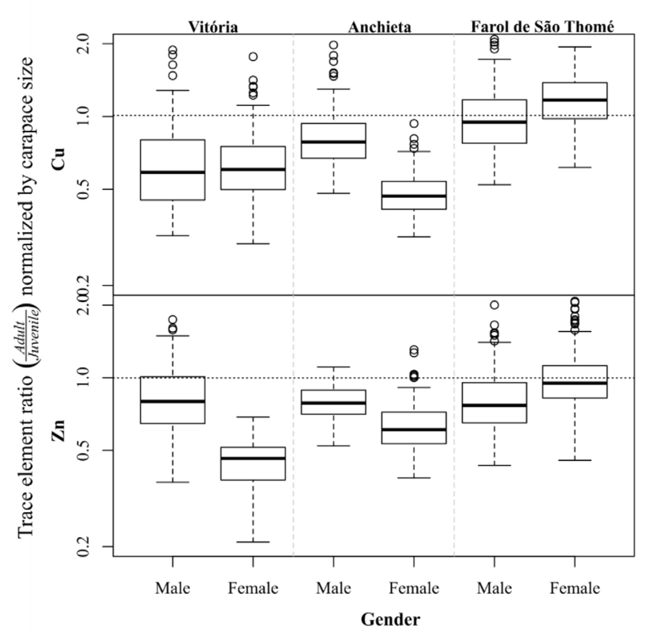

Figure 3 – Ratios of Cu and Zn concentration (adult/juvenile) normalized by shrimps' size among sampling sites and genders. Horizontal dashed lines indicate that trace elements concentration between maturity stages is the same ($Ratio_{Adults,Juveniles} = 1$). Values > 1.0: higher concentrations in adults (bioaccumulation) and values < 1.0: higher concentrations in juveniles (growth dilution). The distances between the y-axis values were log-transformed.

Discussion

The concentrations of Cu and Zn in the Atlantic seabob shrimp varied between genders and maturity stages among the sampling sites. Indeed, the trace elements pathway in crustaceans may vary between males and females and juveniles and adults, as demonstrated in the previous studies (Rainbow, 2002; Pourang et al., 2004; Yilmaz and Yilmaz, 2007); however, a constant behavior of both elements in the shrimp's muscle regardless of the sampling site would be expected. Both variables (gender and maturity stage) were poor predictors for elements concentrations among sampling sites, especially for Cu. For Cu, the comparisons within the same gender indicated both bioaccumulation ($Ratio_{Adults,Juveniles} > 1$) and growth dilution ($Ratio_{Adults,Juveniles} < 1$).

Asante et al. (2008) analyzed nine crustacean species and verified that Cu concentrations were lower in higher trophic levels. For the Atlantic seabob shrimp, adult individuals of both genders are in higher trophic position than juveniles, such as demonstrated by Branco and Moritz-Júnior (2001) in the state of Santa Catarina, southern Brazil, and Willems et al. (2016) in Suriname coastal waters. Then, it would be expected lower concentrations of Cu in adult shrimps of our sampling. This was true for Anchieta and Vitória shrimps, but not for Farol de São Thomé. Shrimps caught in Farol de São Thomé showed bioaccumulation of Cu; that is, concentration was higher in adult shrimps. The feeding habits of the Atlantic seabob shrimp stock from Farol de São Thomé could differ from the above pattern, in which adults are in higher trophic position than juveniles; however, there are no data on the species feeding habits in this sampling site for further discussion.

Crustaceans accumulate trace elements in proportion to their bioavailability in the environment, mainly from water (gills breathing) and diet (Rainbow, 2002). The stable isotopes applied in this study are chemical proxies that track trace elements uptake from diet (Fry, 2008; Fry et al., 2016). The relationships between Cu and Zn and shrimps foraging area ($\delta^{13}C$) and trophic position ($\delta^{15}N$) did not show the same trend among sampling sites. In Anchieta, the concentration of trace elements in the shrimp muscle was lower the stronger its association with foraging areas on the seabed ($\delta^{13}C$ more enriched) and the higher its trophic position ($\delta^{15}N$ more enriched). Since this shrimp species is an omnivorous consumer with high food plasticity (Willems et al., 2016), it is possible that the main food sources responsible for the transfer of Cu and Zn in Anchieta are pelagic, not benthic. In Vitória and Farol de São Thomé, in turn, both foraging area and trophic position had a negligible influence on the concentrations of these trace elements. The negligible influences indicate that both benthic and pelagic food sources contribute to the transfer of these trace elements to the consumer, and that the shrimp trophic position did not drive this transfer. Probably, the shrimps share the foraging area and trophic level in these sampling sites, regardless of their maturity stage.

The relationship between trace elements and stable isotopes to understand the elements trophic pathway is quite variable among marine organisms, often making data interpretation difficult. Asante et al. (2008), for instance, analyzed 22 elements in marine organisms (invertebrates to fish from shallow to deep waters) sampled in China Sea, including Cu and Zn. The relationships between them and $\delta^{15}N$ values were negative (Cu) and negligible (Zn), while between them and $\delta^{13}C$ values were positive (Cu) and negligible (Zn). Liu et al. (2019) investigated the relationship between eight trace elements, including Cu and Zn, and carbon and nitrogen stable isotopes in crustaceans, shellfish and fish from Chinese coastal waters, and did not record any significant relationship among them.

Metabolic processes in crustaceans (and other animals) that vary among species, gender, maturity stage, and organs, together with spatial-temporal variations in trace elements availability, influence the elements accumulation (Rainbow, 2002; Pourang et al., 2004). The longevity of the Atlantic seabob shrimp varies from 2 to 3 years (Jardim et al., 2011) and the muscle represents food assimilation (and trace elements accumulation) over the last months, being more consistent than internal organs, such as gills, gonads, and hepatopancreas, to represent the feeding site and elements pathway in a medium-long term (Di Beneditto et al., 2020; Ferreira et al., 2021). The trace elements behavior in the trophic pathway, measured through $\delta^{13}C$ and $\delta^{15}N$, can vary among elements and sampling sites, as recorded here. For the Atlantic seabob shrimp, this behavior was intra-specifically variable within same gender and maturity stage, which was an unexpected finding.

The Atlantic seabob shrimp has features of a putatively good biomonitor of trace elements pollution in coastal waters, as reported for other shrimp species in Stentiford and Feist (2005) and Fry et al. (2016). The species is widely and continuously distributed along Western Atlantic Ocean (36°N to 30°S) (FAO, 2018), allowing spatial comparisons in large scale. The species has site-fidelity (Bissaro et al., 2013; Boos et al., 2016), allowing long-term monitoring in the same environment. This shrimp is easy to sample because it lives in coastal waters, and it is found in high abundance because it is a commercial species targeted by fisheries (FAO, 2018). Like all penaeid shrimps, the species has a strong association with the seabed (Boos et al., 2016), which is the marine compartment with the highest accumulation capacity for trace elements (Di Leonardo et al., 2017).

Fry et al. (2016) showed how marine shrimps over a broad range of sampling sites along coastlines of Asia-Pacific countries could serve as biomonitors of emerging anthropogenic pollution trends. Rainbow (2002) highlighted that any meaningful comparison on the concentration of trace elements in aquatic invertebrates should only be done intra-specifically to reach reliable results in monitoring programs. Our comparisons were done within the same species and caught in the same time interval (June–July 2017) in the three sampling sites. Meanwhile, our results showed that during the shrimp development (juvenile vs. adult) both bioaccumulation and growth dilution were recorded, but not in the same way between genders and sampling sites. Variations in trace elements concentration between genders and maturity stages are expected; however, for environmental quality monitoring, the biomonitor or sentinel species should follow the same trend among the sampling sites.

Conclusions

The results showed that the behavior of Cu and Zn in the muscle of the Atlantic seabob shrimp was not constant among Vitória, Anchieta, and Farol de São Thomé, which are fishing sites near port activities in southeast Brazil. Therefore, the utilization of this shrimp species as biomonitor of marine coastal environment near port activities to monitoring the levels of Cu and Zn, elements related to antifouling systems applied in vessels and boats, is not a suitable choice, at least in the spatial scale considered by this study.

The study raised two questions to understand the presence of Cu and Zn in the shrimps (Does the concentration of Cu and Zn in male and female shrimps vary among maturity stages and sampling sites? How is the concentration of Cu and Zn related to shrimps foraging area and/or trophic position?). The answers to both questions did not reveal clear trends about the presence of Cu and Zn in the shrimp's muscle. In the first question, the results showed variations among genders, maturity stages, and sampling sites. Even removing intraspecific bias in bioaccumulation or growth dilution and selecting only individuals from the same gender and maturity stage (e.g., adult males), the comparisons among the sampling sites did not show a clear trend, especially for Cu. Regarding the second question, the results demonstrated that both benthic and pelagic food sources contribute to the transfer of Cu and Zn to the shrimp, and shrimp's trophic position did not drive the transfer of these elements to the individuals.

This study may contribute for future decisions on environmental quality monitoring near port activities. The Atlantic seabob shrimp is an easy sampling species widely distributed in marine coastal waters along the Western Atlantic Ocean and might be one of the first choices for biomonitoring purposes along this area. Meanwhile, the limitations raised in this study must be considered for decisions, since the results showed that the choice is not suitable at all.

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Contribution of authors:

Di Beneditto, A.P.M.: Project administration, Funding acquisition, Conceptualization, Investigation, Writing – original draft, Writing – review and editing; Ferreira, K.A.: Methodology; Oliveira, B.C.V.: Methodology; Rezende, C.E.: Funding acquisition, Writing – review and editing; Pestana, I.A.: Formal analysis, Writing – review and editing.

References

Ali, H.; Khan, E., 2019. Trophic transfer, bioaccumulation, and biomagnification of non-essential hazardous heavy metals and metalloids in food chains/webs – Concepts and implications for wildlife and human health. Human Ecology and Risk Assessment, v. 25, (6), 1353-1376. https://doi.org/10.1080/10807039.2018.1469398.

Amara, I.; Miled, W.; Slama, R.B.; Ladhari, N., 2018. Antifouling processes and toxicity effects of antifouling paints on marine environment. A review. Environmental Toxicology and Pharmacology, v. 57, 115-130. https://doi.org/10.1016/j.etap.2017.12.001.

Asante, K.A.; Agusa, T.; Mochizuki, H.; Ramu, K.; Inoue, S.; Kubodera, T.; Takahashi, S.; Subramanian, A.; Tanabe, S., 2008. Trace elements and stable isotopes (d13C and d15N) in shallow and deep-water organisms from the East China Sea. Environmental Pollution, v. 156, (3), 862-873. https://doi.org/10.1016/j.envpol.2008.05.020.

Bissaro, F.G.; Gomes Jr., J.L.; Di Beneditto, A.P.M., 2013. Morphometric variation in the shape of the cephalothorax of shrimp *Xiphopenaeus kroyeri* on the east coast of Brazil. Journal of the Marine Biological Association of the United Kingdom, v. 93, (3), 683-691. https://doi.org/10.1017/s0025315412000409.

Boos, H.; Costa, R.C.; Santos, R.A.F.; Dias-Neto, J.; Severino-Rodrigues, E.; Rodrigues, L.F.; D'Incao, F.; Ivo, C.T.C.; Coelho, P.A., 2016. Avaliação dos camarões peneídeos (Decapoda: Penaeidae). In: Pinheiro, M.; Boos, H. (Eds.), Livro vermelho dos crustáceos do Brasil: avaliação 2010-2014. Sociedade Brasileira de Carcinologia, Porto Alegre, pp. 300-317.

Branco, J.O.; Moritz-Júnior, H.C., 2001. Alimentação natural do camarão sete-barbas (*Xiphopenaeus kroyeri*), na Armação do Itapocoroy, Penha, SC. Revista Brasileira de Zoologia, v. 18, (1), 53-61. https://doi.org/10.1590/S0101-81752001000100004.

Campos, B.R.; Dumont, F.C.; D'Incao F.; Branco, J.O., 2009. Ovarian development and length at first maturity of the sea-bob-shrimp *Xiphopenaeus kroyeri* (Heller) based on histological analysis. Nauplius, v. 17, (1), 9-12.

Dafforn, K.A.; Lewis, J.A.; Johnston, E.L., 2011. Antifouling strategies: History and regulation, ecological impacts and mitigation. Marine Pollution Bulletin, v. 62, (3), 453-465. http://doi.org/10.1016/j.marpolbul.2011.01.012.

Di Beneditto, A.P.M.; Ferreira, K.A.; Oliveira, B.C.V.; Rezende, C.E., 2020. Trace elements in commercial shrimps caught near port activities in SW Atlantic Ocean and human health risk assessment on consumption. Reginal Studies in Marine Science, v. 39, 101449. https://doi.org/10.1016/j.rsma.2020.101449.

Di Leonardo, R.; Mazzola, A.; Cundy, A.B.; Tramati, C.D.; Vizzini, S., 2017. Trace element storage capacity of sediments in dead *Posidonia oceanica* mat from a chronically contaminated marine ecosystem. Environmental Toxicology and Chemistry, v. 36, (1), 49-58. https://doi.org/10.1002/etc.3539.

Ferreira, K.A.; Braga, A.A.; Di Beneditto, A.P.M., 2021. Can stable isotopes be applied to determine shrimp stocks origin in SE Brazil? An approach for utilization in fishery management. Ocean & Coastal Management, v. 205, 105500. https://doi.org/10.1016/j.ocecoaman.2020.105500.

Food and Agriculture Organization – FAO. 2018. The state of world fisheries and aquaculture 2018 - Meeting the sustainable development goals. License: CC BY-NC-SA 3.0 IGO. FAO, Rome (Accessed January, 2021) at: http://www.fao.org/3/i9540en/i9540en.pdf.

Fry, B., 2008. Stable Isotope Ecology. Springer-Verlag, New York, 308 pp.

Fry, B.; Carter, J.F.; Tinggi, U.; Arman, A.; Kamal, M.; Metian, M.; Waduge, V.A.; Yaccup, R.B., 2016. Prawn biomonitors of nutrient and trace metal pollution along Asia-Pacific coastlines. Isotopes in Environmental and Health Studies, v. 52, (6), 619-632. https://doi.org/10.1080/10256016.2016.1149481.

Hartnoll, R.G., 1982. Growth. In: Bliss, D. (Ed.), The Biology of Crustacea, 2. Academic Press, New York, pp. 111-185.

Hatje, V., 2016. Biomonitors. In: Kennish, M.J. (Ed.), Encyclopedia of Estuaries. Encyclopedia of Earth Sciences Series. Springer, Dordrecht. pp. 83-84. https://doi.org/10.1007/978-94-017-8801-4_140.

Jardim, L.P.; Fernandes, L.P.; Di Beneditto, A.P.M.; Silva, A.C.; Keunecke, K.A., 2011. Growth and recruitment of the Atlantic seabob shrimp, *Xiphopenaeus kroyeri* (Heller, 1862) (Decapoda, Penaeidae), on the coast of Rio de Janeiro, southeastern Brazil. Crustaceana, v. 84, 12-13, 1465-1480. https://doi.org/10.1163/156854011X605765.

Karimi, R.; Chen, C.Y.; Pickhardt, P.C.; Fisher, N.S.; Folt, C.L., 2007. Stoichiometric controls of mercury dilution by growth. Proceedings of the National Academy of Sciences of the United States of America, v. 104, 18, 7477-7482. https://doi.org/10.1073/pnas.0611261104.

Karimi, R.; Fisher, N.S.; Folt, C.L., 2010. Multielement Stoichiometry in aquatic invertebrates: When growth dilution matters. American Naturalist, v. 176, (6), 699-709. https://doi.org/10.1086/657046.

Khitalishvili, K., 2016. Monte Carlo Simulation in R: Basic Example (Accessed January, 2021) at: https://rpubs.com/Koba/Monte-Carlo-Basic-Example.

Lacerda, D.; Vergílio, C.S.; Silva Souza, T.; Viana Costa, L.H.; Rangel, T.P.; Vaz de Oliveira, B.C.; Ribeiro de Almeida, D.Q.; Pestana, I.A.; Almeida, M.G.; Rezende, C.E., 2020. Comparative metal accumulation and toxicogenetic damage induction in three neotropical fish species with distinct foraging habits and feeding preferences. Ecotoxicoly and Environmental Safety, v. 195, 110449. https://doi.org/10.1016/j.ecoenv.2020.110449.

Lenth, R., 2019. emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.4.3.01 (Accessed January, 2021) at: https://CRAN.R-project.org/package=emmeans.

Liu, H.; Liu, G.; Yuan, Z.; Ge, M.; Wang, S.; Liu, Y.; Da, C., 2019. Occurrence, potential health risk of heavy metals in aquatic organisms from Laizhou Bay, China. Marine Pollution Bulletin, v. 140, 388-394. https://doi.org/10.1016/j.marpolbul.2019.01.067.

Liu, Y.; Liu, G.; Yuan, Z.; Liu, H.; Lam, P.K.S., 2018. Heavy metals (As, Hg and V) and stable isotope ratios (δ13C and δ15N) in fish from Yellow River Estuary, China. Science of the Total Environment, v. 613-614, 462-471. http://dx.doi.org/10.1016/j.scitotenv.2017.09.088.

Madigan, D.J.; Litvin, S.Y.; Popp, B.N.; Carlisle, A.B.; Farwell, C.J.; Block, B.A., 2012. Tissue turnover rates and isotopic trophic discrimination factors in the endothermic teleost, Pacific bluefin (*Thunnus orientalis*). PLoS One, v. 7, 11, e49220. http://dx.doi.org/10.1371/journal.pone.0049220.

Maurya, P.K.; Malik, D.S.; Yadav, K.K.; Kumar, A.; Kumar, S.; Kamyab, H., 2019. Bioaccumulation and potential sources of heavy metal contamination in fish species in River Ganga basin: Possible human health risks evaluation. Toxicololy Reports, v. 6, 472-481. https://doi.org/10.1016/j.toxrep.2019.05.012.

Nikolaou, M.; Neofitou, N.; Skordas, K.; Castritsi-Catharios, I.; Tziantziou, L., 2014. Fish farming and anti-fouling paints: a potential source of Cu and Zn in farmed fish. Aquaculture Environmental Interactions, v. 5, 163-171. http://dx.doi.org/10.3354/aei00101.

Post, D.M.; Layman, C.A.; Arrington, D.A.; Takimoto, G.; Quattrochi, J.; Montaña, C.G. 2007. Getting to the fat of the matter: models, methods and assumptions for dealing with lipids in stable isotope analyses. Oecologia, v. 152, 179-189. http://dx.doi.org/10.1007/s00442-006-0630-x.

Pourang, N.; Dennis, J.H.; Ghourchian, H., 2004. Tissue distribution and redistribution of trace elements in shrimp species with the emphasis on the roles of metallothionein. Ecotoxicology, v. 13, 519-533. https://doi.org/10.1023/B:ECTX.0000037189.80775.9c.

Rainbow, P.S., 2002. Trace metal concentrations in aquatic invertebrates: why and so what? Environmental Pollution, v. 120, (3), 497-507. https://doi.org/10.1016/S0269-7491(02)00238-5.

R Core Team. 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria (Accessed January, 2021) at: https://www.R-project.org/

Signorell, A., 2020. DescTools: Tools for descriptive statistics. R package version 0.99.34 (Accessed January, 2021) at: https://cran.r-project.org/package=DescTools.

Skoog, D.A.; Leary, J.L., 1992. Principles of instrumental analysis. Harcourt Brace College Publishers, Orlando, 220 pp.

Stentiford, G.D.; Feist, S.W., 2005. A histopathological survey of shore crab (*Carcinus maenas*) and brown shrimp (*Crangon crangon*) from six estuaries in the United Kingdom. Journal of Invertebrates Pathology, v. 88, 2, 136-146. http://doi.org/10.1016/j.jip.2005.01.006.

Thomsen, V.; Schatzlein, D.; Mercuro, D., 2003. Limits of detection in spectroscopy. Spectroscopy, v. 18, 12, 112-114.

Venables, W.N.; Ripley, B.D., 2002. Modern Applied Statistics with S. Springer-Verlag, New York, 495 pp.

Willems, T.; De Backer, A.; Kerkhove, T.; Dakriet, N. N.; De Troch M.; Vincx, M.; Hostens, K., 2016. Trophic ecology of Atlantic sea-bob shrimp *Xiphopenaeus kroyeri*: Intertidal benthic microalgae support the subtidal food web off Suriname. Estuarine Coastal and Shelf Science, v. 182, part A, 146-157. http://dx.doi.org/10.1016/j.ecss.2016.09.015.

Yilmaz, A.B.; Yilmaz, L., 2007. Influences of sex and seasons on levels of heavy metals in tissues of green tiger shrimp (*Penaeus semisulcatus* de Hann, 1844). Food Chemistry, v. 101, (4), 1664-1669. http://dx.doi.org/10.1016/j.foodchem.2006.04.025.

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Soil-cement blocks: a sustainable alternative for the reuse of industrial solid waste

Blocos de solo-cimento: uma alternativa sustentável para o reaproveitamento de resíduos sólidos industriais

Tulane Rodrigues da Silva[1,2], *Daiane Cecchin*[2], *Afonso Rangel Garcez de Azevedo*[1], *Jonas Alexandre*[1], *Izabella Christynne Ribeiro Pinto Valadão*[2], *Nivam Alves Bernardino*[2], *Dirlane de Fátima do Carmo*[2], *Patrícia Ferreira Ponciano Ferraz*[3]

ABSTRACT

This study aimed to analyze potential industrial solid waste that can be added to soil-cement blocks. A narrative literature review was conducted in the Scopus academic database, using as the search criteria keywords related to the topic, such as soil-cement, building materials, soil-cement blocks, soil-cement bricks, physical and mechanical properties, solid waste, life cycle analysis, and civil construction. A variety of industrial solid waste that can be incorporated into soil-cement blocks was observed, such as waste rock, sludge from water treatment plants, wood sawdust, polyethylene terephthalate fibers (PET), vegetable fibers from loofah, hemp fibers, rice husks, brachiaria grass, poultry eggshells, sugar cane bagasse, wheat and barley straw, welding slag, foundry sand, waste from quartzite mining, construction, and demolition, mechanical turning, pulp industry grains, and steel mill co-products. Among the investigated wastes, those that improved the physical and mechanical properties of the soil-cement blocks were grains from the cellulose industry, rice husks, *Brachiaria* grass, steel by-products with granulated soil-cement blocks and blast furnace slag. The waste that produced no satisfactory results was sludge from a water treatment plant, sugarcane bagasse, and vegetable loofah. Through this research, it was possible to verify that the behavior of soil-cement blocks is influenced by several factors in their manufacture, mainly regarding the type and percentage of incorporated waste. However, it is important to be concerned with its application in waste blocks so as not to increase the environmental impacts in the long term.

Keywords: building materials; sustainability; waste management.

RESUMO

Objetivou-se, com o presente estudo, analisar potenciais resíduos sólidos industriais que possam ser adicionados a blocos de solo-cimento. Foi realizada uma revisão bibliográfica narrativa por meio da base acadêmica *Scopus*, utilizando-se como critérios de busca palavras-chave ligadas ao tema, como: solo-cimento, materiais de construção, blocos de solo-cimento, tijolos solo-cimento, propriedades físicas e mecânicas, resíduos sólidos, análise de ciclo de vida e construção civil. Observou-se a versatilidade de resíduos sólidos industriais que podem ser incorporados em blocos de solo-cimento, como resíduos de rochas ornamentais, lodo de estações de tratamento de água, serragem de madeira, fibras de politereftalato de etileno, fibras vegetais de bucha, fibras de cânhamo, cascas de arroz, capim braquiária, cascas de ovos aviários, bagaço de cana-de-açúcar, palha de trigo e cevada, escória de soldagem, areia de fundição, rejeitos de mineração de quartzito, de construção e demolição, tornearia mecânica, grãos de indústria de celulose e coprodutos siderúrgicos. Entre os resíduos incorporados que contribuíram para a melhoria nas propriedades físicas e mecânicas dos blocos de solo-cimento estiveram: grãos da indústria de celulose, casca de arroz, capim braquiária, subprodutos siderúrgicos com blocos de solo-cimento granulado e escória de alto forno. Os resíduos sem resultados satisfatórios foram lodo de estação de tratamento de água, bagaço de cana-de-açúcar e bucha vegetal. Por meio desta pesquisa foi possível verificar que o comportamento dos blocos de solo-cimento é influenciado por diversos fatores em sua fabricação, principalmente no que diz respeito ao tipo e ao percentual de resíduos incorporados. Entretanto, é importante a preocupação com a sua aplicação de modo a não potencializar os impactos ambientais em longo prazo.

Palavras-chave: materiais de construção; sustentabilidade; gestão de resíduos.

[1]Universidade Estadual do Norte Fluminense – Campos dos Goytacazes (RJ), Brazil.

[2]Universidade Federal Fluminense – Niterói (RJ), Brazil.

[3]Universidade Federal de Lavras – Lavras (MG), Brazil.

Correspondence address: Tulane Rodrigues da Silva – Universidade Estadual do Norte Fluminense – Avenida Alberto Lamego, 2000 – Parque Califórnia – CEP: 28013-602 – Campos dos Goytacazes (RJ), Brazil. E-mail: tulanerodrigues@gmail.com

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Introduction

According to Nascimento (2012), the idea of sustainability started in the 1950s and was related to development due to the expanding production and consumption pattern along with the perception of an environmental crisis in the world. For Romeiro (2012), sustainability is a systemic concept, which proposes complexity, because the social, environmental and economic pillars must be completely interconnected. According to the United Nations (2020) in 1972 at the Stockholm Conference, the existing environmental guidelines began to be discussed through a more holistic perception of sustainability. Since then, the topic has been gaining a lot of space in society, with the union of social, economic, and environmental guidelines becoming increasingly important.

Bricks have played a significant role in construction for thousands of years, because of their outstanding properties such as durability, high strength, and low production costs (Campbell and Pryce, 2003; Zhang et al., 2018). Brick was a fundamental building material in the Mesopotamian, Egyptian, and Roman periods (Fernandes et al., 2010). Increasing sustainability is one of the greatest challenges facing the construction industry and, in this regard, alternative building materials are being developed to mitigate environmental impacts and meet sustainable development, production, and consumption standards (Silva et al., 2009; Araújo et al., 2019; Balaguera et al., 2018; Murmu and Patel, 2018). According to Bruna and Vizioli (2006), sustainability promotes joint action in the construction industry — multiple and interdisciplinary — to meet the needs of humans, including the need for housing, and to organize quality environments for society.

With the intensification of environmental problems arising from the action of humans during the industrial revolution and the growth of consumer goods production, the crisis also reached the construction and architecture models. As a result, construction made with dirt was emphasized as a sustainable alternative to mitigate these impacts. In the 1930s, soil stabilization with binders opened new possibilities for building construction, including masonry components such as soil-cement blocks, known as CEB (Compressed Earth Blocks). Soil-cement was then considered an evolution in construction materials, compared with mud and adobe brick. This was justified by the possibility of industrialization of construction at that time, that is, soil-cement blocks emerged as a component of masonry whose manufacturing process allows the application of an effective quality control system, in addition to ensuring that the blocks have uniform dimensions (Neves and Faria, 2011).

Clay brick masonry is one of the oldest and most durable construction techniques used by mankind. Over the years, as the brick industry has evolved, technological advances in processing (with the development of machines such as excavation equipment and tunnel kilns, among others) has significantly stimulated the production capacity of this type of material (Kadir and Mohajerani, 2011; Zhang, 2013; Zhang et al., 2018). However, Al-Fakih et al. (2019) and Venkatarama Reddy and Jagadish (2003) claim that this advance provoked an increase in the depletion of resources, in addition to greater energy consumption, corresponding to around 30% more energy than that required to produce concrete blocks and blocks of soil-cement, due to the need to use burning for its manufacture, resulting in a greater carbon footprint, even though concrete and soil-cement blocks use cement in their production process.

According to Kadir and Mohajerani (2012), the masonry block is one of the most complete building material components, due to its physical and mechanical properties, in addition to the innovation of incorporating various wastes in its production. According to Zhang et al. (2018), despite the good workability and accessibility, it is known that the production of sintered masonry blocks has always been a very intensive process in terms of energy and resources, in addition to the large quantities of carbon it consumes. According to Buyle et al. (2013), reducing energy consumption is a major focus of civil construction.

The global urbanization process is one of the main factors responsible for the substantial growth in the generation of solid waste. Developing countries favor irregular disposal in landfills and open landfills (Cardoso et al., 2014; Rodseth et al., 2020). As a result, for example, Kadir and Mohajerani (2011) state that recycling wastes by incorporating them into building materials is an alternative to these issues regarding the disposal of solid waste and mitigation of environmental impacts. Kurmus and Mohajerani (2020) found in their studies that the incorporation of 1% of cigarette butts in sintered clay bricks can save approximately 10.2% of burning energy in the manufacturing process.

The natural resource scarcity and the generation of solid waste without proper disposal is a worldwide concern, and this enables ecological viability for construction systems, which encourage sustainable development and process optimization (Araújo et al., 2019; Krishna et al., 2020). According to Ashour et al. (2015), the current global concerns arose from extensive environmental problems, together with the accelerated pace of technological advancement in the industry, especially in construction, and, with that, the interest in the development of alternative building materials gained space, especially materials made of earth. According to Zakham et al. (2018), stabilized soil blocks help improve the construction energy efficiency, mainly because they have low thermal conductivity. In this way, it is possible to use them to improve the thermal and acoustic insulation in buildings.

The construction and demolition industry is responsible for 40% of the energy consumed worldwide and for a third of greenhouse gas emissions (Silva et al., 2010; Muñoz et al., 2016). According to De Lassio et al. (2016), with the growth of the demand for building materials, there was an increase in the consumption of raw materials and energy that stands out mainly during the extraction, processing, and material transport phases. The current global amount of solid waste generation is approximately 2.01 billion tons per year, and it is expected to increase to approximately 3.40 billion tons per year by 2050 (Slipa Kasa et al., 2018). The use of solid industrial waste in construction activities as alternative stabilizers has proven to be a viable solution for reducing environmental impact, in addition to the social and economic benefits (Arrigoni et al., 2017; Sekhar and Nayak, 2018).

According to Smol et al (2015) and Murmu and Patel (2018), the growing demand for ecological and sustainable products has encouraged studies of alternative methods and materials to produce building bricks. According to Raut and Gomez (2017), the raw materials consumed by the construction industry represent approximately 24% of the global raw material supply. Thus, to achieve the goal of sustainable development, the selection of a construction material plays a very significant role. Soil-cement blocks pose a solution to these issues, because they are easily manufactured by a process that does not require burning, decreases the amount of cement used, and still allows the incorporation of waste materials in their composition. In addition, the use of cement blocks reduces costs by up to 40% compared with traditional masonry, especially in popular housing. In this way, cement blocks can be considered eco-friendly relative to traditional masonry blocks (Bruna and Vizioli, 2006; Sena et al., 2017).

This study aimed to conduct a narrative literature review about different types of industrial solid waste evaluated for the possibility of addition to soil-cement blocks and bricks. Searches were conducted in the *Scopus* bibliographic database. This database was selected for the relevance of the indexed papers focusing on the area and topic addressed. At the end of the database search, duplicate references were excluded. The searches were made between November 12 and November 30, 2020, using the keywords: soil-cement, building materials, soil-cement blocks, soil-cement bricks, physical and mechanical properties, solid waste, life cycle analysis, and civil construction. The keywords were combined by means of the operators "and", "or", and "not", which were related to the diversity of waste limited to soil-cement blocks and bricks, as well as combined for the association of these materials with their life cycle in the construction industry. In addition, truncation was used to gain more control over search variations. The inclusion criteria were original articles and literature reviews indexed within a 17-year time frame (articles published between 2003 and 2020), articles written in Portuguese and English, and articles that addressed the main properties evaluated for this type of material, such as physical and mechanical properties, as well as literature that evaluated different types of incorporated waste. The exclusion criteria were articles that addressed other types of materials made with soil-cement, as well as articles that did not report on the addition of waste to construction materials.

For data analysis, a qualitative content analysis protocol was adopted, following the methodology proposed by Bardin (1977), and divided into pre-analysis, analysis, and data interpretation steps. For the pre-analysis, the first stage was a floating analysis, consisting of a survey of bibliographic references to the theme studied; in the second stage, the choice of literature that comprised the body of the analysis was made; and the third stage was the formulation of the choice of information for each content. In the analysis (exploration of the material), the information gathered in the pre-analysis stage was compiled in spreadsheets, and the informational content was categorized. Finally, in the data interpretation stage, this categorization of information was considered so that the discussion was related to the main topics that make up the sections discussed in this paper: Soil-cement; Industrial solid waste in soil-cement blocks; Life Cycle Analysis (LCA) in construction: An alternative to evaluate soil-cement blocks with industrial solid waste.

Soil-cement

Soil-cement is the product resulting from the mixture of soil, cement, and water compacted at the optimum humidity to provide maximum density. To verify the suitability of a soil for stabilization with cement, it is necessary to perform granulometric analysis and determine consistency limits (Ferreira et al., 2018). Once the soil is chosen, soil and soil-cement compaction tests must be carried out to quantify compaction control values. The molding process of the soil-cement brick consists of compaction by means of a manual or hydraulic press, which reduces its porosity through a compressive force and preserves the dimensional symmetry of the interlocking bricks' faces (ABCP, 2000; Ferreira et al., 2018). The addition of cement to the soil increases the optimum humidity value of the mixture compared with that of natural soil (Ferreira et al., 2018).

Soil-cement blocks with a cement content greater than 10% may not be considered advantageous in terms of cost, but a cement content of less than 5% may affect the technological properties of the material. Soils with a plasticity index (PI) between 15 and 25 are the most suitable for soil-cement blocks, because a greater plasticity or clay could cause a bigger interference in the connection between cement and fine aggregates and, consequently, in water absorption due to the occurrence of retractions in the drying process and an increase in the appearance of cracks.

The main properties analyzed in this type of block are compressive strength and water absorption according to Brazilian Technical Standards ABNT NBR 8491 and ABNT NBR 8492. For compressive strength, the blocks must reach a minimum value of 2.0 MPa (average), and for water absorption, less than or equal to 20% (average) (ABNT, 2012a, 2012b; Ferreira et al., 2018; Murmu and Patel, 2018). The amount of water has a dominant effect on the mechanical performance of clay bricks and sintered masonry. Each component of the block, including pores of water and air, plays a role and interacts with others in the mix, contributing to the overall strength of the system (Li Piani et al., 2020). The proportion of water in the mixture is between 5 and 20%, and the optimum humidity is defined as the value of humidity corresponding to the value of the maximum dry density, that is, the ideal amount of water required to obtain stable compaction (Campos et al., 2019).

According to Al-Jabri et al. (2017), soils with a higher clay content are more compressible than those with a lower one. The increase in clay content, cement, and density in the soil-cement block directly influences the increase in the thermal conductivity of the material (Balaji et al., 2017; Saidi et al., 2018). According to McGregor et al. (2014) and Rempel and Rempel (2016), unburned masonry has a high potential to regulate its internal humidity, and hygroscopic earth buildings are characterized by the maintenance of comfortable internal temperatures.

Soil-cement blocks are a more sustainable alternative to traditional masonry blocks. Despite the use of cement, the process of manufacturing soil-cement blocks does not involve burning, which minimizes greenhouse gas emissions (Paschoalin Filho et al., 2016; Azevedo et al., 2019). Segantini and Wada (2011) and Azevedo et al. (2019) emphasize that this constructive method streamlines the construction process, reduces the amount of waste generated, and reduces the consumption of mortar. This type of block is superimposed on the settlement, forming ducts through which hydraulic wires and pipes can be passed, besides offering thermal and acoustic comfort (Weber et al., 2017), as can be seen in Figure 1.

Industrial solid waste in soil-cement blocks

According to Huarachi et al. (2020), it is necessary to quantify the real impact of alternative blocks through different waste addition scenarios. Zhang (2013) adds that it is important to ensure adequate treatment for the waste that contains contaminants to produce materials. Literature (Table 1) shows the versatility of industrial solid waste incorporated in the production of soil-cement blocks.

According to Anjum et al. (2017), the addition of sludge from wastewater treatment plants directly affects the increase in water absorption in the block, as it is a plastic solid waste. Because of that, it also affects the cement hydration reactions next to the organic matter present in the sludge and the type of soil used, since the sludge traps large amounts of water; therefore, it lacks an adequate amount of water to complete these reactions.

Rodrigues and Holanda (2015) also analyzed the addition of waste from a water treatment plant to soil-cement blocks and observed that the amount of soil used was replaced by up to 1.25% of this waste, although the main limitation was associated with the increase in water absorption due to waste plasticity. Having an adequate amount of water helps in the homogenization, hydration, and crystallization process of the cement, that is, it provides fluidity, plasticity, and workability to the material. In addition, the water/cement factor must always be as low as possible, within the required characteristics of the block and the quality of the materials available for its composition. The higher the water content in the mixture, the greater the tendency for exudation to occur, which causes the water to reach the surface of the block, creating a greater number of voids inside and, consequently, reducing the resistance, increasing the permeability, and impairing the block's durability (Castro and Pandolfelli, 2009).

According to Barros et al. (2020), soil-cement blocks with the use of ornamental stone wastes and polyester resin using methyl ethyl ketone peroxide as a catalyst showed superior results for compressive strength. The result for water absorption was lower than that of conventional

(A) (B)

Figure 1 – Soil-cement blocks. (A) Holes in soil-cement blocks. (B) Ducts in soil-cement blocks.
Source: Eco Máquinas.

Table 1 – Studies on the incorporation of different industrial solid wastes in soil-cement blocks.

Title	Journal	Authors	Waste used
Production of soil-cement bricks using sludge as a partial substitute	*Earth Science Malaysia*	Anjum et al. (2017)	Sludge from a water treatment plant
Ecological bricks from dimension stone waste and polyester resin	*Construction and Building Materials*	Barros et al. (2020)	Ornamental stone waste and polyester resin
Assessment of Mechanical Properties and the Influence of the Addition of Sawdust in Soil–Cement Bricks Using the Technique of Ultrasonic Anisotropic Inspection	*Journal of materials in civil engineering*	Carrasco et al. (2014)	Wood sawdust (*Eucalyptus Grandis* and *Eucalyptus Cloeziana*)
Evaluation of compressive strength and water absorption of soil-cement bricks manufactured with addition of pet wastes	*Acta Scientiarum*	Paschoalin Filho et al. (2016)	Polyethylene terephthalate fibers (PET bottles)
Brick solo cement with vegetable fiber addition: an alternative in civil construction	*Research, Society and Development*	Cristina et al. (2018)	Loofah vegetable fiber (*Luffa Cylindrica*)
Quality evaluation of soil-cement-plant waste bricks by the combination of destructive and non-destructive tests	*Revista Brasileira de Engenharia Agrícola e Ambiental*	Ferreira and Cunha (2017)	Rice husk and Brachiaria grass (*Brachiaria brizantha cv. Marandu*)
Manufacture of soil-cement bricks with the addition of sugarcane bagasse ash	*Engenharia Agrícola*	Jordan et al. (2019)	Sugar cane bagasse
Characterization of soil-cement bricks with incorporation of used foundry sand	*Cerâmica*	Leonel et al. (2017)	Discarded foundry sand
Incorporation of solid residues from mechanical turning in soil-cement bricks manufacturing	*Nativa*	Oliveira et al. (2014)	Mechanical turning
Recycling of Water Treatment Plant Waste for Production of Soil-Cement Bricks	*Procedia Materials Science*	Rodrigues and Holanda (2015)	Sludge from a water treatment plant
Physical-mechanical properties of soil-cement bricks with the addition of the fine fraction from the quartzite mining tailings (State of Minas Gerais – Brazil)	*Bulletin of Engineering Geology and the Environment*	Reis et al. (2020)	Quartzite mining waste
Effect of incorporation of grits waste on the densification behavior of soil cement bricks	*Cerâmica*	Siqueira and Holanda (2015)	Grains from the pulp industry
Influence of industrial solid waste addition on properties of soil-cement bricks	*Cerâmica*	Siqueira et al. (2016)	Poultry eggshells and welding slag
Thermal conductivity of unfired earth bricks reinforced by agricultural wastes with cement and gypsum	*Energy and Buildings*	Ashour et al. (2015)	Wheat and barley straw
Sorption characteristics of stabilised soil blocks embedded with waste plastic fibres	*Construction and Building Materials*	Subramaniaprasad et al. (2014)	Plastic fibers (PET bottles and bags)
Evaluation of physical and mechanical properties of soil-cement bricks formulated with steel co-products	*Matéria*	Castro et al. (2016)	Steel co-products: Balloon blast furnace dust powder, dedusting powder, electric arc furnace slag, and defective granulated soil-cement blocks
Utilization of granulated blast furnace slag and cement in the manufacture of compressed stabilized earth blocks	*Construction and Building Materials*	Sekhar and Nayak (2018)	Granulated blast furnace slag
Thermal performance of fired and unfired earth bricks walls	*Journal of Building Engineering*	Bruno et al. (2020)	Hemp fibers
Sustainable unfired bricks manufacturing from construction and demolition wastes	*Construction and Building Materials*	Seco et al. (2018)	Construction and demolition waste (concrete and ceramics)
Ecological brick made with non-cash banknotes	*Semioses Inovação, desenvolvimento e sustentabilidade*	Valadão et al. (2017)	Worthless cash bills

sintered block. The soil-cement blocks analyzed showed good thermal stability and fire strength using 90% of limestone wastes.

Carrasco et al. (2014) observed in soil-cement blocks with the addition of wood sawdust and with different block shapes that the mechanical characteristics of soil-cement blocks depend not only on the type of soil used, but also on the form and configuration of blocks and prisms. The authors also pointed out that the incorporation of wood sawdust into sandy soil increased its compressive capacity, strength, modulus of elasticity, and ductility. In clayey soils, it caused a decrease in compressive strength, but an increase in elasticity and ductility modulus. The authors also demonstrated the results obtained through non-destructive tests by ultrasonic waves that allowed estimation of the values of compressive strength and elasticity modulus of samples, blocks, and prisms, relating the variation of soil, cement, and wastes, in addition to allowing the analysis of the structural characteristics of the aggregate.

Paschoalin Filho et al. (2016) demonstrated positive results regarding the reduction of (polyethylene terephthalate) PET waste for the environment with the manufacture of soil-cement blocks. The authors evaluated blocks with waste added at proportions of 20, 15 and 10%, and cement at proportions of 15, 20, and 25%, and found that, with the addition of 10% PET, it was possible to reuse approximately 300 g of PET in each block. Although the results showed low values of compressive strength, they still proved to be an alternative solution for masonry works that are not subjected to heavy loads or structural functions.

Cristina et al. (2018) showed that soil-cement blocks with added loofah vegetable fiber presented low compressive strength under conditions of 5% and 10% fiber variation and molded with a water content of 17.5% and a cement content of 5%. The authors found that, with the increase in waste, there was low adherence of the vegetable fiber to the cement with the amount of water used.

Bruno et al. (2020) demonstrated the incorporation of 1.5% of the hemp fibers mass in soil-cement blocks with a water content of 5.4% to facilitate mixing and hypercompaction of the material. The authors found that the insulating fibers provided better thermal performance due to their low density, low porosity, and low thermal conductivity.

Ferreira et al. (2008) evaluated soil-cement blocks with the addition of rice husks and *Brachiaria* grass with different proportions of cement (60, 70, 80, and 90%) and waste (10, 20, 30, and 40%). The authors stated that the best results, in terms of compressive strength and water absorption, were obtained by incorporating the wastes as 10% of the cement content. Ferreira and Cunha (2017) also used the addition of rice husks and *Brachiaria* in their studies of soil-cement blocks and pointed out that, to achieve the maximum apparent specific weight of the molding blocks, the optimum moisture values of the soil at the compaction tests should be used. The authors performed an anisotropic strength measurement, a non-destructive test using ultrasonic waves, to characterize the technical quality of the blocks in physical-mechanical, and elastic-acoustic terms.

Sekhar and Nayak (2018) evaluated compressed blocks with the addition of granulated blast furnace slag (BFS) and observed that it was possible to substitute 25 and 20%, respectively, for two types of soil used (lithogenic and lateritic), an improvement of 53 and 40%, respectively, in the compressive strength. The authors calculated the levels of addition of each component mixture and observed that the cement content, in 10% in the mass mixture, directly interfered in the compression force with the lithogenic soil, with an improvement of up to 390%. With the lateritic soil, a cement content of 6% showed that there was an improvement of 209%.

Jordan et al. (2019) studied soil-cement blocks with and without the addition of sugarcane bagasse and observed that the lack of pre-treatment of the waste interfered with the physical and mechanical results of the block due to the presence of impurities and granulometric variables, which contributed to a decrease in the quality of the mixtures.

Leonel et al. (2017), when evaluating a mixture composed of 10% cement, 0–25% commercial sand, 0–65% foundry sand, 25–65% clay, and 15–30% gravel powder, observed a reduction in water absorption with the addition of discarded foundry sand combined with crushed stone, although the mechanical strength remained stable.

Oliveira et al. (2014) evaluated soil-cement blocks with the addition of mechanical turning waste with 0, 10, and 15% waste variation, and 10% cement content in the mixture. The results showed improvement in the mechanical properties with 15% addition of waste in relation to the block without waste; however, they did not reach the values established by the norm.

Seco et al. (2018) evaluated the incorporation of construction and demolition waste. The authors obtained different percentage results for maximum addition of each residue due to the workability of each mixture, with 50% of maximum addition for concrete and 30% for ceramic residue.

Reis et al. (2020) analyzed the physical-mechanical aspects of soil-cement blocks with the addition of tailings from quartzite mining and found that the incorporation of the waste reduced the limits of liquidity and plasticity due to the decrease in the percentage of the clay fraction of the soil, since clays, unlike sands, have a plastic behavior and a high agglutination capacity.

Siqueira and Holanda (2015) manufactured soil-cement blocks with the addition of grains from the cellulose industry and analyzed the incorporation of up to 20% by weight of cement in the manufacture of soil-cement blocks with a water content of 16% in relation to the total block weight. The authors varied the waste by 10, 20, and 30%, and observed that the compressive strength increased by 15% in relation to the reference line, without adding any waste. For additions of waste above 20%, the grain filling effect was lower, and water absorption increased. As for durability, for additions of up to 20% of grains, the loss of mass of the blocks decreased, and for additions greater than 20% of grains, it increased.

Siqueira et al. (2016) evaluated the addition of poultry eggshell and welding slag wastes for the manufacture of soil-cement blocks and found that up to 15% welding slag waste could be incorporated into the block as a substitute for soil and that the wastes of poultry eggshells could replace up to 30% in the cement composition.

Subramaniaprasad et al. (2014) analyzed the incorporation of plastic fibers in compressed blocks and observed that the plastic fiber forms interconnected channels and helps to increase water absorption when the samples are completely submerged in water. When the blocks with added fiber underwent greater molding pressure, water absorption decreased due to greater soil compaction and the considerable reduction of empty spaces between the waste and the high-pressure soil. Subramaniaprasad et al. (2015) used evaluation parameters with a variation of 7.5, 10, and 15% of cement, types of fiber (water bottles and transportation bags), fiber length (1 and 2 cm) and fiber percentage (0.1 and 0.2%). With that, the authors were able to find a 4.5-fold increase in the block's tensile strength.

Ben Mansour et al. (2017) showed in their study on acoustics that pressed blocks with a high apparent density are characterized by high airflow resistivity due to their low porosity and high sinuosity. When there is a decrease in the compaction pressure, there is an increase in porosity and a reduction in the airflow resistivity of the material; therefore, it is more efficient in relation to sound absorption at a low density, i.e., it is a better sound absorber, than at a higher density.

Ashour et al. (2015) studied the incorporation of wheat and barley straw into soil-cement blocks. The authors observed the density and thermal conductivity of the blocks with a variation in the percentage of wheat straw and barley from 0 to 3%. They concluded that there was a decrease in the thermal conductivity of the blocks by up to 54.4% (wheat) and 53% (barley straw), respectively, in relation to the blocks without residue. As for the density of the blocks, there was a decrease of about 9.8 to 22% in relation to the blocks without residue incorporation.

According to Castro et al. (2016), it is possible to incorporate steel by-products, such as balloon blast furnace dust powder, electric furnace dust, and granulated blast furnace slag. The authors point out that the wastes used are composed of granulometries corresponding to the typical range of fine and medium sand, except for balloon blast furnace dust powder, which is finer. Another aspect they mention is alteration of the cement mix as an alternative to increase granule cohesion and reach higher strength values, together with the adequate dosage of added wastes.

Valadão et al. (2017) analyzed the incorporation of worthless cash banknotes into soil-cement blocks in proportions of 10, 15, 20, and 25% of the waste and observed an increase in the compressive strength with the addition of the waste, considering that waste pre-treatment provided greater compaction of the block.

A study by Sekhar and Nayak (2018) evaluated compressed blocks with granulated blast furnace slag added to different types of soil (lithomargic soil and lateritic soil) and waste added in different proportions. The authors observed that a cement content of 10% in the mass mixture directly interfered in the compression force with the lithogenic soil, with an improvement of up to 390%. With the lateritic soil, a 6% cement content showed an improvement of 209%. Siqueira and Holanda (2015) manufactured soil-cement blocks by adding grains from the cellulose industry. The authors observed that the compressive strength increased by 15% in relation to the reference line, without adding waste.

Subramaniaprasad et al. (2015) analyzed the incorporation of plastic fibers in pressed blocks and found a 4.5-fold increase in the block's tensile strength. Ashour et al. (2015) studied the relationship between the incorporation of wheat straw and barley into soil-cement blocks and found a reduction in the thermal conductivity of the block by up to 54.4%, compared with the block without straws. With the increase in barley straw, the thermal conductivity decreased by up to 53% in relation to the block without waste, and the density decreased about 9.8%, to 22%.

According to the related literature in this study, the behavior of soil-cement blocks is influenced by several factors, including the type of soil used, the cement content, the percentage of incorporation and replacement of residue, and the type of waste incorporated (shown in Table 1). In addition, the tests of physical-chemical properties must be in accordance with the current standards for validating the material performance, including quality and accuracy in the manufacturing steps, mainly regarding the mixture homogenization, moisture content and compaction energy of the material (Murmu and Patel, 2018).

In general, there are difficulties in quantifying a complete comparison of the data present in the different authors listed in this review. In this context, a comparative synthesis was established for some of the advances obtained by each study (Tables 2 and 3):

There is a concern that the incorporation of wastes implies changes in the physical and mechanical properties of soil-cement bricks, impairing their performance. It is also necessary to pay attention to possible contamination problems that this incorporated waste may inflict on the environment with the effects of waste over time. Santos et al. (2013) studied the addition of leather waste to soil-cement bricks in different proportions (10, 15, 20, and 30%) and observed that only the sample relative to the addition of 10% showed results for chromium below the maximum limit allowed per liter of leachate, thus being considered non-hazardous by NBR 10004 (ABNT, 2004a). In contrast, other percentages of addition analyzed presented chromium content above the limit set by the standard, thus being considered hazardous (ABNT, 2004a). Despite the study showing satisfactory results in relation to water strength and absorption, the impossibility of retaining chromium in bricks has become a limiting factor in its use and must be considered.

A study by Pinheiro et al. (2013) evaluated the effects of incorporating grits waste into soil-cement bricks. The authors found that the soil-cement brick with grits added was characterized as non-hazardous by NBR 10004 (ABNT, 2004a), which can be used without restriction.

Table 2 – Summary of the bibliographic review regarding the factors that influence the behavior of the soil-cement block with the incorporation of industrial solid waste.

Authors	Soil type	Mixture	Waste (%)	Waste particle type and/or size	Pressing type	Waste content
Anjum et al. (2017)	Sandy	4:1 (soil:cement)	0-2.5-5-7.5-10	Solid – 1 to 500 µm	Uniaxial	Sludge from a water treatment plant
Barros et al. (2020)	Unidentified	Unidentified	2.33-4-5.66-9	Solid and liquid	Hydraulic	Ornamental stone waste and polyester resin
Carrasco et al. (2014)	Clay and sandy	8:1 (soil:cement)	0-0.5-1-2-3	Solid – 2.0 and 4.8 mm (length) 0.3mm (thickness)	Hydraulic	Wood sawdust (*Eucalyptus Grandis* and *Eucalyptus Cloeziana*)
Paschoalin Filho et al. (2016)	Red Latosol (Oxisol)	Cement 15, 20, 25%	20-15-10	Solid	Unidentified	Polyethylene terephthalate fibers (PET bottles)
Cristina et al. (2018)	Unidentified	Cement 5%	0-5-10	Solid	Hydraulic	Loofah vegetable fiber (*Luffa Cylindrica*)
Ferreira and Cunha (2017)	Clayish	Cement 60,70,80,90%	0-10-20-30-40	Solid – 1.19 to 0.42 mm and 2.00 to 0.105 mm	Manual	Rice husk and Brachiaria grass (*Brachiaria brizantha cv. Marandu*)
Jordan et al. (2019)	Sandy and clayey	6: 1, 7: 1, 10: 1 (soil-cement)	0-30-40	Solid	Manual	Sugar cane bagasse
Leonel et al. (2017)	Clayey and sandy	Cement 10%	0-25-30-35-45-65	Solid	Manual	Discarded foundry sand
Oliveira et al. (2014)	Silty	10:1 (soil:cement)	0-10-15	Pasty	Manual	Mechanical turning
Rodrigues and Holanda (2015)	Commercial soil (sandy)	10:1 (soil:cement)	0-1.25-2.50-5	Pasty – 1 to 600 µm	Uniaxial	Sludge from water treatment plant
Reis et al. (2020)	Red-Yellow Latosol	6:1, 8:1, 10:1 (soil:cement)	0-15-30	Solid	Hydraulic	Quartzite mining waste
Siqueira and Holanda (2015)	Weak clayey	9: 1, 9: 0.9, 9: 0.8, 9: 0.7 (soil:cement)	0-10-20-30	Solid	Not informed	Grains from the pulp industry
Siqueira et al. (2016)	Sandy	9:1 (soil:cement)	0-10-20-30	Solid – 150 µm	Unidentified	Poultry eggshells and welding slag
Ashour et al. (2015)	Silty	Cement 5%, 10%	0-1-3	Solid – 4cm	Mechanical pressing	Wheat and barley straw
Subramaniaprasad et al. (2014)	Sandy	Cement 5%, 10%,15%	0.1-0.2	Solid – 1 cm and 2 cm	Unidentified	Plastic fibers (PET bottles and bags)
Castro et al. (2016)	Kaolinitic	6:1 (soil:cement)	0-2.5-5-7.5-10-15-20	Solid	Hydraulic	Steel co-products: Balloon blast furnace dust powder, dedusting powder, electric arc furnace slag and defective granulated soil-cement blocks
Sekhar and Nayak (2018)	Lateritic and clayey	Cement 2%, 4%, 6%, 8%, 10%, 12%	0-20-25	Solid - soil size used	Hydraulic	Granulated blast furnace slag
Bruno et al. (2020)	Ilítico	3:1 (soil:cement)	0-1,5	Solid	Unidentified	Hemp fibers
Seco et al. (2018)	Clayey	Cement 10%	0-30-50	Solid – 4mm	Hydraulic	Construction and demolition waste (concrete and ceramics)
Valadão et al. (2017)	Sandy	8:1 (soil:cement)	0-10-15-20-25	Solid – 2mm	Hydraulic	Worthless cash bills

Table 3 – Synthesis of the main tests and results of the literature review on soil-cement blocks with industrial solid waste.

Authors	Tests with the waste	Tests with the blocks	Main results
Anjum et al. (2017)	Chemical analysis by X-ray spectrometry	Simple compressive strength, water absorption, and bulk density	Reduced density and compressive strength and increased water absorption
Barros et al. (2020)	Fourier Transform-Infrared Spectroscopy (FTIR) thermogravimetry (TG), X-ray diffraction (XRD), X-ray fluorescence spectrometry (XRF), Scanning electron microscopy (SEM)	Compressive strength, water absorption, TG/DTG, and flammability	Increase in compressive strength and fire strength and decreased water absorption
Carrasco et al. (2014)	Particle Size Distribution (PSD)	Proctor compaction, prism test, ultrasonic compressive strength, tensile strength	Reduced compressive and tensile strengths, increased ductility for clayey soil and increased compressive and tensile strengths and ductility for sandy soil
Paschoalin Filho et al. (2016)	Particle Size Distribution (PSD)	Particle size distribution, compaction test, simple compressive strength and water absorption	Reduced compressive strength and water absorption
Cristina et al. (2018)	Unidentified	Particle size distribution, simple compressive strength and water absorption	Reduced compressive strength, high porosity and high water absorption
Ferreira and Cunha (2017)	Particle size distribution and apparent density, pre-treatment in a hydrated lime solution and drying	Proctor compaction, prism test, ultrasonic compressive strength, tensile strength	Increase in compressive strength (rice husk), reduction in specific weight and anisotropic strength (*Branchiaria* grass)
Jordan et al. (2019)	Drying and screening	Particle size distribution, simple compressive strength and water absorption	Low compressive strength, increased porosity and water absorption
Leonel et al. (2017)	X-ray diffraction (XRD) X-ray fluorescence (XRF)	Isothermal colorimetric test, compressive strength, tensile strength, durability and water absorption	The replacement of the block sand by waste caused a reduction in the compressive strength
Oliveira et al. (2014)	Drying and screening	Particle size distribution, simple compressive strength, prism test, and water absorption	Increase in compressive strength and low water absorption with increased waste
Rodrigues and Holanda (2015)	Sedimentation, drying and screening, X-ray diffraction (XRD), particle size distribution	Simple compressive strength, bulk density water absorption	Reduced mechanical strength and increased water absorption due to the plasticity of the waste
Reis et al. (2020)	Particle size distribution	Particle size distribution, simple compressive strength and water absorption	Compressive strength and stable water absorption with added waste
Siqueira and Holanda (2015)	X-ray diffraction (XRD)	Particle size distribution, X-ray diffraction (XRD), simple compressive strength, water absorption and durability, Scanning Electron Microscopy (SEM)	Reduction in porosity, good durability, strength and stable absorption (up to 20% of waste)
Siqueira et al. (2016)	Drying and screening	Volumetric shrinkage, X-ray diffraction (XRD), water absorption, bulk density, compressive strength, and durability	Low volumetric shrinkage, decreased porosity and water absorption, increased durability and reduced compressive strength with 30% waste
Ashour et al. (2015)	Drying	Thermal conductivity	Decrease in density and thermal conductivity
Subramaniaprasad et al. (2014)	Unidentified	Water absorption	Increase in water absorption with added residue

Continue...

Table 3 – Continuation.

Authors	Tests with the waste	Tests with the blocks	Main results
Castro et al. (2016)	Mineralogical composition with X-ray fluorescence (XRF), X-ray diffraction (XRD), particle size distribution and sieving	Particle size distribution, simple compressive strength and water absorption	Compressive strength and absorption suitable for 20% balloon blast furnace dust powder + 10% granulated soil-cement block; 10% slag or 20% steel slag + 10% granulated soil-cement block; 2.5% dedusting powder + 20% granulated soil-cement block
Sekhar and Nayak (2018)	Particle size distribution and chemical analysis	Particle size distribution, simple compressive strength and water absorption	Compressive strength and adequate absorption, mainly for lateritic soil with addition of residue
Bruno et al. (2020)	Unidentified	Thermal conductivity and apparent density	Unburned blocks showed better thermal conductivity with addition of residue
Seco et al. (2018)	Screening	X-ray diffraction (XRD) X-ray fluorescence (XRF), unconfined compressive strength, water absorption, freeze-thaw test, and environmental impact assessment	Decrease in compressive strength with the addition of concrete waste in relation to ceramic waste and increase in strength to freezing and thawing with concrete residue
Valadão et al. (2017)	Waste fragmentation	Particle size distribution, simple compressive strength	Increase in simple compressive strength

However, as for solubilization, the soil-cement brick with added grits presented constituents that are solubilized in concentrations higher than those allowed by NBR 10005 (ABNT, 2004b) in relation to the water potability pattern, realizing that this would impede the molding of soil-cement bricks.

Leonel et al. (2017) evaluated the incorporation of foundry sand into soil-cement bricks and found leaching values that did not exceed the limit established by NBR 10004 (ABNT, 2004a); therefore, the materials could be classified as non-hazardous. However, a solubilization test indicated that the phenol did not incorporate wastes; therefore, it is not an adequate component for the brick molding process. Cement and soil were classified as non-inert non-hazardous wastes, but in relation to cement, the parameters that exceeded the limits were chromium, phenol, sodium, and sulfate, and, for the soil, aluminum and iron.

Life cycle analysis (lca) in civil construction: an alternative to evaluate soil-cement blocks with industrial solid waste

Life Cycle Assessment (LCA) is an increasingly efficient and recognized tool, as it enables the assessment of the impacts of raw material extraction up to the final disposal of the products, providing knowledge about its different process phases (De Lassio et al., 2016). Several studies highlight LCA as an important tool for the civil construction sector in terms of sustainability in civil construction. (Galan-Marin et al., 2016; Marcelino-Sadaba et al., 2017; Peng and Wu, 2017; Joglekar et al., 2018; Lozano-Miralles et al., 2018; Mohajerani et al., 2018; Sandanayake et al., 2018; Seco et al., 2018; Yuan et al., 2018).

Yuan et al. (2018) compared permeable blocks and traditional concrete blocks and used LCA to analyze and compare the environmental and economic impacts, in addition to identifying the main processes and materials that make them beneficial for achieving a cleaner and more economical production. Seco et al. (2018) analyzed the incorporation of construction and demolition waste in non-sintered blocks and identified, through LCA, the environmental impact caused by these materials. Galan-Marin et al. (2016) conducted environmental impact studies in different construction systems, highlighting the masonry walls of sintered clay bricks, concrete block masonry, and masonry walls of soil blocks stabilized with natural fibers through LCA. Mohajerani et al. (2018) performed a comparative LCA to assess the environmental impacts of sintered blocks incorporating biosolids. Joglekar et al. (2018) evaluated different masonry alternatives in low-cost housing units, in order to define the material that represents the greatest sustainability.

Studies by Lozano-Miralles et al. (2018) evaluated the LCA of sintered blocks with organic waste and stated that using LCA can be a promising alternative approach regarding sustainability. Peng and Wu (2017) demonstrated, through modeling methodologies and ecological indicators, an LCA of carbon emissions from a modeled building and emphasized that this type of resource can be very useful in reducing efforts to estimate data, as it provides much-needed information and tools to perform this type of analysis. Thus, it alleviates part of the difficulty when executing the structuring of an LCA, since this study requires a vast database, and most of the time the obstacle is information acquisition.

According to Marcelino-Sadaba et al. (2017), the variability in the components of a product, the lack of data for each aspect of manufacturing and the processes involved create great challenges. As a result, through the incorporation of recycled waste and by-products, the quantification of data becomes more complex. For the authors, the incorporation of these materials creates problems in terms of data and means of conducting a robust and individualized analysis. Sandanayake et al. (2018) justify that a typical construction project involves several activities that cause particular environmental impacts and that, from this, a broader view of studies with a global perspective is necessary.

Through this approach, it is possible to verify the feasibility of applying LCA in new studies on the production of soil-cement blocks, as it allows a deeper analysis of the process and the material in question. In this sense, the quantification of data by using this methodology can enhance future studies, although Seco et al. (2018) emphasize that LCA also has the limitations of not fully considering the additional environmental benefits of replacing a non-renewable resource, such as natural soil, with recycled waste. Thus, it is still necessary to have broader and standardized details for future analysis of soil-cement blocks containing solid industrial waste.

Final considerations

Considering the general aspects of the discussion of literature in this study, the wastes that contributed to the improvement of soil-cement blocks properties were cellulose industry grains, rice husks, *Brachiaria* grass, steel by-products with soil blocks, granular cement, and blast furnace slag. The wastes that did not obtain satisfactory results were sludge from a water treatment plant, sugarcane bagasse, and vegetable loofah.

Through this article, it was possible to verify that the behavior of soil-cement blocks is influenced by several factors in their manufacture, mainly regarding the type and percentage of incorporated waste. Many wastes prove to be viable for use in this type of block in certain proportions, which is thus a sustainable alternative to their inadequate disposal in landfills and the environment. However, it is important to be concerned about the application of blocks with such wastes, requiring more environmental analyses linked to these types of studies so that the intention of these surveys is truly sustainable and does not enhance environmental impacts.

Contribution of authors:

Silva, T.R.: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Software, Writing — original draft. Cecchin, D.: Methodology, Validation, Resources, Supervision, Project administration. Azevedo, A.R.G.: Methodology, Validation, Resources, Supervision, Project administration. Alexandre, J.: Formal analysis, Software, Resources. Valadão, I.C.R.P.: Formal analysis, Visualization. Bernardido, N.A.: Formal analysis, Visualization. Do Carmo, D. F.: Methodology, Validation, Visualization. Ferraz, P. F. P.: Validation, Visualization.

References

Al-Fakih, A.; Mohammed, B.; Liew, M.S.; Nikbakht, E., 2019. Incorporation of waste materials in the manufacture of masonry bricks: an update review. Journal of Building Engineering, v. 21, 37-54. https://doi.org/10.1016/j.jobe.2018.09.023.

Al-Jabri, K.S.; Hago, A.W.; Sthapit, G., 2017. Properties of soil-cement blocks manufactured using produced water from oil fields: a preliminary investigation. International Journal of Geomate, v. 13, (35), 66-72. http://dx.doi.org/10.21660/2017.35.6671.

Anjum, T.; Khan, H.I.; Shauket, I., 2017. Production of soil-cement bricks using sludge as a partial substitute. Earth Science Malaysia, v. 1, (2), 10-12. http://dx.doi.org/10.26480/esmy.02.2017.10.12.

Araújo, C.; Salvador, R.; Piekarski, C.; Sokulski, C.; Francisco, A.; Camargo, S., 2019. Circular economy practices on wood panels: a bibliographic analysis. Sustainability, v. 11, (4), 1057. https://doi.org/10.3390/su11041057

Arrigoni, A.; Grillet, A.-C.; Pelosato, R.; Dotelli, G.; Beckett, C.T.S.; Woloszyn, M.; Ciancio, D., 2017. Reduction of rammed earth's hygroscopic performance under stabilization: an experimental investigation. Building and Environment, v. 115, 358-367. https://doi.org/10.1016/j.buildenv.2017.01.034.

Ashour, T.; Korjenic, A.; Korjenic, S.; Wu, W., 2015. Thermal conductivity of unfired earth bricks reinforced by agricultural wastes with cement and gypsum. Energy and Buildings, v. 104, 139-146. https://doi.org/10.1016/j.enbuild.2015.07.016.

Associação Brasileira de Cimento Portland – ABCP. 2000. Fabricação de tijolos de solo-cimento com a utilização de prensas manuais. 3ª ed. ABCP, São Paulo, 16 pp.

Associação Brasileira de Normas Técnicas – ABNT. 2004a. NBR 10004: Classificação de Resíduos Sólidos. ABNT, Rio de Janeiro, 71 pp.

Associação Brasileira de Normas Técnicas – ABNT. 2004b. NBR 10005: Procedimento para obtenção de extrato lixiviado de resíduos sólido. ABNT, Rio de Janeiro, 16 pp.

Associação Brasileira de Normas Técnicas – ABNT. 2012a. NBR 8491: Tijolo de solo-cimento — Requisitos. ABNT, Rio de Janeiro, 5 pp.

Associação Brasileira de Normas Técnicas – ABNT. 2012b. NBR 8492: Tijolo de solo-cimento — Análise dimensional, determinação da resistência à compressão e da absorção de água — Método de ensaio. ABNT, Rio de Janeiro, 4 pp.

Azevedo, A.R.G.; Marvila, T.M.; Júnior Fernandes, W.; Alexandre, J.; Xavier, G.C.; Zanelato, E.B.; Cerqueira, N.A.; Pedroti, L.G.; Mendes, B.C., 2019. Assessing the potential of sludge generated by the pulp and paper industry in assembling locking blocks. *Journal of Building Engineering*, v. 23, 334-340. https://doi.org/10.1016/j.jobe.2019.02.012.

Balaguera, A.; Carvajal, G.I.; Albertí, J.; Fullana-I-Palmer, P., 2018. Life cycle assessment of road construction alternative materials: a literature review. Resources, Conservation and Recycling, v. 132, 37-48. https://doi.org/10.1016/j.resconrec.2018.01.003.

Balaji, N.C.; Mani, M.; Venkatarama Reddy, B.V., 2017. Thermal conductivity studies on cement-stabilised soil blocks. Proceedings of Institution of Civil Engineers: Construction Materials, v. 170, (1), 40-54. https://doi.org/10.1680/jcoma.15.00032.

Bardin, L., 1977. Análise de conteúdo. 70, Persona, Lisboa, 224 pp.

Barros, M.M.; Oliveira, M.F.L.; Ribeiro, R.C.C.; Bastos, D.C.; Oliveira, M.G., 2020. Ecological bricks from dimension stone waste and polyester resin. Construction and Building Materials, v. 232, 117252. https://doi.org/10.1016/j.conbuildmat.2019.117252.

Ben Mansour, M.; Ogam, E.; Jelidi, A.; Cherif, A.S.; Jabrallah, S.B., 2017. Influence of compaction pressure on the mechanical and acoustic properties of compacted earth blocks: An inverse multi-parameter acoustic problem. Applied Acoustics, v. 125, 128-135. https://doi.org/10.1016/j.apacoust.2017.04.017.

Bruna, G.C.; Vizioli, S.H.T., 2006. Social housing with soil-cement brick as a structuring element for the sustainable development of João Dourado (BA). Brazilian Journal of Environmental Sciences (Online), (4), 43-49.

Bruno, A.; Gallipoli, D.; Perlot, C.; Kallel, H., 2020. Thermal performance of fired and unfired earth bricks walls. Journal of Building Engineering, v. 28, 101017. https://doi.org/10.1016/j.jobe.2019.101017.

Buyle, M.; Braet, J.; Audenaert, A., 2013. Life cycle assessment in the construction sector: A review. Renewable and Sustainable Energy Reviews, v. 26, 379-388. https://doi.org/10.1016/j.rser.2013.05.001.

Campbell, J.W.; Pryce, W. 2003. Brick a world history. Thames & Hudson, London, 320 pp.

Campos, A.; Nascimento Junior, J.B.; Brito, L.T., 2019. Structural behavior of soil-cement bricks using different sources of water and healing methods. Interações, v. 20, (1), 283-296. https://doi.org/10.20435/inter.v0i0.1565.

Cardoso, A.; Gallato, S.; Guadagnin, M., 2014. Estimated generation of construction waste and feasibility study for a sorting and recycling plant. Brazilian Journal of Environmental Sciences (Online), (31), 1-10.

Carrasco, E.V.M.; Silva, S.R.; Mantilla, J.N.R., 2014. Assessment of mechanical properties and the influence of the addition of sawdust in soil-cement bricks using the technique of ultrasonic anisotropic inspection. Journal of Materials in Civil Engineering, v. 26, (2), 219-225. https://doi.org/10.1061/(ASCE)MT.1943-5533.0000723.

Castro, A.L.; Pandolfelli, V.C., 2009. Review: concepts of particle dispersion and packing for special concretes production. Cerâmica, v. 55, (333), 18-32. https://doi.org/10.1590/S0366-69132009000100003.

Castro, M.A.M.; Costa, F.G.; Borba, S.C.; Fagury Neto, E.; Rabelo, A.A., 2016. Avaliação das propriedades físicas e mecânicas de blocos de solo-cimento formulados com coprodutos siderúrgicos. Revista Matéria, v. 21, (3), 666-676. https://doi.org/10.1590/S1517-707620160003.0064.

Cristina, P.; Salomão, P.E.A.; Cangussú, L.; Carvalho, P.H.V., 2018. Brick solo cement with vegetable fiber addition: an alternative in civil construction. Research, Society and Development, v. 7, (9), e779439. https://doi.org/10.17648/rsd-v7i9.439.

De Lassio, J.; França, J.; Santo, K.E.; Haddad, A., 2016. Case study: LCA methodology applied to materials management in a Brazilian residential construction site. Journal of Engineering, v. 2016, 8513293. https://doi.org/10.1155/2016/8513293.

Fernandes, F.M.; Lourenço, P.B.; Castro, F., 2010. Ancient clay bricks: manufacture and properties. In: Dan M.B., Přikryl R., Török Á. (Eds.), Materials, technologies and practice in historic heritage structures. Springer, Dordrecht, pp. 29-48.

Ferreira, D.; Luso, E.; Cruz, M., 2018. Blocos ecológicos de solo-cimento com incorporação de resíduos. Construction Pathology, Rehabilitation Technology and Heritage Management, v. 2018, 1368-1376.

Ferreira, R.; Gobo, J.; Cunha, A., 2008. Incorporação de casca de arroz e de braquiária e seus efeitos nas propriedades físicas e mecânicas de tijolos de solo-cimento. Engenharia Agrícola, v. 28, (1), 1-11. https://doi.org/10.1590/S0100-69162008000100001

Ferreira, R.C.; Cunha, A.H.N., 2017. Quality evaluation of soil-cement-plant waste bricks by the combination of destructive and non-destructive tests. Revista Brasileira de Engenharia Agrícola e Ambiental, v. 21, (8), 543-549. https://doi.org/10.1590/1807-1929/agriambi.v21n8p543-549.

Galan-Marin, C.; Rivera-Gomez, C.; Garcia-Martinez, A., 2016. Use of natural-fiber bio-composites in construction versus traditional solutions: operational and embodied energy assessment. Materials, v. 9, (6), p. 465. https://doi.org/10.3390/ma9060465.

Huarachi, D.A.; Gonçalves, G.; Francisco, A.C.; Canteri, M.H.G.; Piekarski, C.M., 2020. Life cycle assessment of traditional and alternative bricks: a review. Environmental Impact Assessment Review, v. 80, 106335. https://doi.org/10.1016/j.eiar.2019.106335.

Joglekar, S.N.; Kharkar, R.A.; Mandavgane, S.A.; Kulkarni, B.D., 2018. Sustainability assessment of brick work for low-cost housing: A comparison between waste-based bricks and burnt clay bricks. Sustainable Cities and Society, v. 37, 396-406. https://doi.org/10.1016/j.scs.2017.11.025.

Jordan, R.A.; Costa, M.V.; Martins, E.A.S.; Rosa, M.A.; Petrauski, A., 2019. Manufacture of soil-cement bricks with the addition of sugarcane bagasse ash. Engenharia Agrícola, v. 39, (1), 26-31. https://doi.org/10.1590/1809-4430-Eng.Agric.v39n1p26-31/2019.

Kadir, A.A.; Mohajerani, A., 2011. Bricks: an excellent building material for recycling wastes - a review. IASTED International Conference on Environmental Management and Engineering, v. 2, 108-115.

Kadir, A.A.; Mohajerani, A., 2012. Properties improvement of fired clay bricks incorporating with cigarette butts. Advanced Materials Research, v. 535-537, 1723-1730. https://doi.org/10.4028/www.scientific.net/AMR.535-537.1723.

Krishna, R.S.; Mishra, J.; Meher, S.; Das, S.K.; Mustakim, S.M.; Singh, S.K., 2020. Industrial solid waste management through sustainable green technology: Case study insights from steel and mining industry in Keonjhar, India. Materials Today: Proceedings, v. 33, (part 8), 5243-5249. https://doi.org/10.1016/j.matpr.2020.02.949.

Kurmus, H.; Mohajerani, A., 2020. Recycling of cigarette butts in fired clay bricks: a new laboratory investigation. Materials, v. 13, (3), 790. https://doi.org/10.3390/ma13030790.

Leonel, R.F.; Folgueras, M.V.; Dalla Valentina, L.V.O.; Prim, S.R.; Prates, G.A.; Caraschi, J.C., 2017. Characterization of soil-cement bricks with incorporation of used foundry sand. Cerâmica, v. 63, (367), 329-335. https://doi.org/10.1590/0366-69132017633672131.

Li Piani, T.; Weerheijm, J.; Peroni, M.; Koene, L.; Krabbenborg, D.; Solomos, G.; Sluys, L.J., 2020. Dynamic behaviour of adobe bricks in compression: The role of fibres and water content at various loading rates. Construction and Building Materials, v. 230, 117038. https://doi.org/10.1016/j.conbuildmat.2019.117038.

Lozano-Miralles, J.A.; Hermoso-Orzáez, M.J.; Martínez-García, C.; Rojas-Sola, J.I., 2018. Comparative study on the environmental impact of traditional clay bricks mixed with organic waste using life cycle analysis. Sustainability, v. 10, (8), 2917. https://doi.org/10.3390/su10082917.

Marcelino-Sadaba, S.; Kinuthia, J.; OTI, J.; Meneses, A.S., 2017. Challenges in life cycle assessment (LCA) of stabilized clay-based construction materials. Applied Clay Science, v. 144, 121-130. https://doi.org/10.1016/j.clay.2017.05.012.

McGregor, F.; Heath, A.; Fodde, E.; Shea, A., 2014. Conditions affecting the moisture buffering measurement performed on compressed earth blocks. Building and Environment, v. 75, 11-18. https://doi.org/10.1016/j.buildenv.2014.01.009.

Mohajerani, A.; Ukwatta, A.; Setunge, S., 2018. Fired-clay bricks incorporating biosolids: Comparative life-cycle assessment. Journal of Materials in Civil Engineering, v. 30, (7), 1-12. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002308.

Muñoz, P.; Morales, M.P.; Letelier, V.; Mendívil, M.A., 2016. Fired clay bricks made by adding wastes: Assessment of the impact on physical, mechanical and thermal properties. Construction and Building Materials, v. 125, 241-252. https://doi.org/10.1016/j.conbuildmat.2016.08.024.

Murmu, A.L.; Patel, A., 2018. Towards sustainable bricks production: an overview. Construction and Building Materials, v. 165, 112-125. https://doi.org/10.1016/j.conbuildmat.2018.01.038.

Nascimento, E.P., 2012. Trajetória da sustentabilidade: do ambiental ao social, do social ao econômico. Estudos Avançados, v. 26, (74), 51-64. https://doi.org/10.1590/S0103-40142012000100005.

Neves, C.; Faria, O.B., 2011. Técnicas de construção com terra. FEB-UNESP/PROTERRA, Bauru, 79 p (Accessed November 19, 2020) at: http://www.redproterra.org

Oliveira, J.R.; Garcia do Amaral, A.; Schneider, R.M., 2014. Incorporação de resíduos sólidos de tornearias mecânicas na fabricação de tijolos solo-cimento. Nativa, v. 2, (1), 53-57. https://doi.org/10.31413/nativa.v2i1.1370.

Paschoalin Filho, J.A.; Storopoli, J.H.; Dias, A.J.G., 2016. Avaliação da resistência à compressão e da absorção de água de tijolos de solo cimento manufaturados com adição de resíduos de pet (politereftalato de etileno). Acta Scientiarum – Technology, v. 38, (2), 163-171. https://doi.org/10.4025/actascitechnol.v28i2.28458.

Peng, C.; Wu, X., 2017. Retracted: case study of carbon emissions from a building's life cycle based on BIM and Ecotect. Advances in Materials Science and Engineering, v. 2017, 2193505. https://doi.org/10.1155/2017/2193505.

Pinheiro, M.L.; Alvarenga, R.C.S.S.; Ribeiro, B.C.; Silva Júnior, P.R.; Sarmet, P.S.; Fassoni, D., 2013. Experimental evaluation of pressed blocks of soil-cement with grits addition. Ambiente Construído, v. 13, (2), 29-46. https://doi.org/10.1590/S1678-86212013000200004.

Raut, A.N.; Gomez, C.P., 2017. Development of thermally efficient fibre-based eco-friendly brick reusing locally available waste materials. Construction and Building Materials, v. 133, 275-284. https://doi.org/10.1016/j.conbuildmat.2016.12.055.

Reis, F.M.D.; Ribeiro, R.P.; Reis, M.J., 2020. Physical-mechanical properties of soil-cement bricks with the addition of the fine fraction from the quartzite mining tailings (State of Minas Gerais – Brazil). Bulletin of Engineering Geology and the Environment, v. 79, 3741-3750. https://doi.org/10.1007/s10064-020-01765-3.

Rempel, A.R.; Rempel, A., 2016. W. Intrinsic evaporative cooling by hygroscopic earth materials. Geosciences, v. 6, (3), 38. https://doi.org/10.3390/geosciences6030038.

Rodrigues, L.P.; Holanda, J.N.F., 2015. Recycling of water treatment plant waste for production of soil-cement bricks. Procedia Materials Science, v. 8, 197-202. https://doi.org/10.1016/j.mspro.2015.04.064.

Rodseth, C.; Notten, P.; Von Blottnitz, H.A., 2020. A revised approach for estimating informally disposed domestic waste in rural versus urban South Africa and implications for waste management. South African Journal of Science, v. 116, (1-2), 1-6. https://doi.org/10.17159/sajs.2020/5635.

Romeiro, A.R., 2012. Desenvolvimento sustentável: uma perspectiva econômica ecológica. Estudos Avançados, v. 26, (74), 65-92. https://doi.org/10.1590/S0103-40142012000100006.

Saidi, M.; Cherif, A.S.; Zeghmati, B.; Sediki, E., 2018. Stabilization effects on the thermal conductivity and sorption behavior of earth bricks. Construction and Building Materials, v. 167, 566-577. https://doi.org/10.1016/j.conbuildmat.2018.02.063.

Sandanayake, M.; Zhang, G.; Setunge, S.A., 2018. Comparative method of air emission impact assessment for building construction activities. Environmental Impact Assessment Review, v. 68, 1-9. https://doi.org/10.1016/j.eiar.2017.09.003.

Santos, C.F.R.; Alvarenga, R.C.S.S.; Ribeiro, B.C., 2013. Tijolos de solo-cimento-couro: caracterização física e mecânica de teores de misturas. Elecs, 1-13. http://dx.doi.org/10.12702/978-85-89478-40-3-a049.

Seco, A.; Omer, J.; Marcelino, S.; Espuelas, S.; Prieto, E., 2018. Sustainable unfired bricks manufacturing from construction and demolition wastes. Construction and Building Materials, v. 167, 154-165. https://doi.org/10.1016/j.conbuildmat.2018.02.026.

Segantini, A.A.S.; Wada, P.H., 2011. Estudo de dosagem de tijolos de solo-cimento com adição de resíduos de construção e demolição. Acta Scientiarum - Technology, v. 33, (2), 179-183. http://dx.doi.org/10.4025/actascitechnol.v33i2.9377.

Sekhar, C.D.; Nayak, S., 2018. Utilization of granulated blast furnace slag and cement in the manufacture of compressed stabilized earth blocks. Construction and Building Materials, v. 166, 531-536. https://doi.org/10.1016/j.conbuildmat.2018.01.125.

Sena, R.J.; Laursen, A.; Silva, J., 2017. Avaliação mecânica de tijolo maciço solo-cimento contendo resíduo de pet. Veredas, v. 10, (1), 69-83.

Silva, W.M.; Ferreira, R.C.; Souza, L.O.; Silva, A.M., 2009. Effect of the incorporation of agro-industrial residues on the mechanical and thermophysical characteristics of soil-cement modular bricks. Brazilian Journal of Environmental Sciences (Online), (14), 9-14.

Silva, W.M.; Ferreira, R.C.; Souza, L.O.; Silva, A.M., 2010. Management of construction and demolition waste and its use as a base, sub-base and bituminous mixture in urban pavement in Goiânia - GO. Brazilian Journal of Environmental Sciences (Online), (15), 1-9.

Siqueira, F.B.; Amaral, M.C.; Bou-Issa, R.A.; Holanda, J.N.F., 2016. Influence of industrial solid waste addition on properties of soil-cement bricks. Cerâmica, v. 62, (363), 237-241. https://doi.org/10.1590/0366-69132016623631969.

Siqueira, F.B.; Holanda, J.N.F., 2015. Effect of incorporation of grits waste on the densification behavior of soil-cement bricks. Cerâmica, v. 61, (360), 414-419. https://doi.org/10.1590/0366-69132015613601917.

Slipa Kasa, S.; Yao, L.; Perinaz, B.T.; Woerden, F.V. 2018. What a Waste 2.0 - A global snapshot of solid waste management to 2050. World Bank, Washington, D.C., 271 p.

Smol, M.; Kulczycka, J.; Henclik, A.; Gorazda, K.; Wzorek, Z., 2015. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. Journal of Cleaner Production, v. 95, 45-54. https://doi.org/10.1016/j.jclepro.2015.02.051.

Subramaniaprasad, C. K.; Abraham, B.M.; Nambiar, E.K.K., 2014. Sorption characteristics of stabilised soil blocks embedded with waste plastic fibres. Construction and Building Materials, v. 63, 25-32. https://doi.org/10.1016/j.conbuildmat.2014.03.042.

Subramaniaprasad, C.K.; Abraham, B.M.; Nambiar, E.K.K., 2015. Influence of embedded waste-plastic fibers on the improvement of the tensile strength of stabilized mud masonry blocks. Journal of Materials in Civil Engineering, v. 27, (7), 1-7. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001165.

United Nations. 2020. A ONU e o meio ambiente. (Acessed November 2020) at: https://nacoesunidas.org/acao/meio-ambiente/.

Valadão, I.; Domingos, F.; Queiroz, I.; Silva, K.; Leal, L., 2017. Tijolo ecológico confeccionado com cédulas de dinheiro sem valor. Semioses, v. 11, (4). http://dx.doi.org/10.15202/1981996X.2017v11n4p64.

Venkatarama Reddy, B.V.; Jagadish, K.S., 2003. Embodied energy of common and alternative building materials and technologies. Energy and Buildings, v. 35, (2), 129-137. https://doi.org/10.1016/S0378-7788(01)00141-4.

Weber, E.; Campos, R.; Borga, T., 2017. Analysis of the efficiency of ecological brick solo-cement in civil construction. Ignis, v. 6, (2), 18-34.

Yuan, X.; Tang, Y.; Li, Y.; Wang, O.; Zuo, J.; Song, Z., 2018. Environmental and economic impacts assessment of concrete pavement brick and permeable brick production process - A case study in China. Journal of Cleaner Production, v. 171, 198-208. http://dx.doi.org/10.1016/j.jclepro.2017.10.037.

Zakham, N.; El Rhaffari, Y.; Ammari, A.; Cherraj, M.; Bouabid, H.; Gueraoui, K.; Samaouali, A.; Mzerd, A., 2018. Influence of cement content on the thermal properties of compressed earth blocks (CEB) in the dry state. MATEC, v. 149, 1-5. https://doi.org/10.1051/matecconf/201814901059.

Zhang, L., 2013. Production of bricks from waste materials - A review. Construction and Building Materials, v. 47, 643-655. https://doi.org/10.1016/j.conbuildmat.2013.05.043.

Zhang, Z.; Wong, Y.C.; Arulrajah, A.; Horpibulsuk, S., 2018. A review of studies on bricks using alternative materials and approaches. Construction and Building Materials, v. 188, 1101-1118. https://doi.org/10.1016/j.conbuildmat.2018.08.152.

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Survey of wildlife rescued and treated from 2014 to 2016 in Joinville (SC), Brazil

Levantamento dos animais silvestres resgatados e atendidos de 2014 a 2016 em Joinville (SC), Brasil

Carolina Konkel Barbosa[1], José Eduardo Basilio de Oliveira Gneiding[2], Túlio Tácito Ribeiro[3], Edevaldo Antonio Iachinski[1], Igor Christian Magno Gonçalves[4], Cláudia Turra Pimpão[1]

ABSTRACT

Natural ecosystems are in constant conflict with the growing and disordered urban expansion, arising from the mismanagement of human developments and infrastructure, facing an accelerated rate of deforestation and defaunation. The intense pressure on natural environments impacts the local fauna through various incidents, generating high mortality, such as hit-and-run, window-crashing, attacks by domestic animals, dissemination of diseases and electrocution. The purpose of this study was to carry out a retrospective survey of the wild fauna rescued and treated at a clinic associated with the environmental police in the region of Joinville - SC. A total of 379 wild animals were treated at the clinic from 2014 to 2016. Of these, 262 (69.13%) were birds, 107 (28.23%) mammals, 9 (2.37%) reptiles and 1 (0.26%) amphibian. The main causes of referral for clinical care were due to trauma (50.66%), seizures (1.32%) and other causes (48.02%), such as home invasion and orphaned puppies. Among the reasons for traumas, pedestrian accidents were the most prevalent, representing 39.58% of the cases treated, followed by animals found to be debilitated without a defined cause (31.77%), attack by domestic animals (14.58%) and window-crashing (9.89%). The data obtained in this study show a rich diversity of species in Joinville. These species are exposed to several anthropogenic challenges and barriers derived mainly from intense displacement and human invasion, causing many animals to move in order to adapt to urban areas.

Keywords: fauna; hit-and-run; atlantic forest; infrastructure; urbanization.

RESUMO

Os ecossistemas naturais estão em constante conflito com a crescente e desordenada expansão urbana, oriunda da má gestão de empreendimentos e infraestruturas humanas, enfrentando uma acelerada taxa de desmatamento e defaunação. A intensa pressão sobre os ambientes naturais impacta a fauna local através de incidentes variados gerando alta mortalidade, como atropelamentos, colisão em vidraças, ataques por animais domésticos, disseminação de doenças e eletrocussão em redes elétricas. O objetivo deste estudo foi realizar um levantamento retrospectivo da fauna silvestre resgatada e atendida em uma clínica conveniada à polícia ambiental na região de Joinville – SC. Um total de 379 animais silvestres foram atendidos na clínica no período de 2014 a 2016. Destes, 262 (69,13%) eram aves, 107 (28,23%) mamíferos, 9 (2,37%) répteis e 1 (0,26%) anfíbio. As principais causas de encaminhamento para atendimento clínico foram devido a traumas (50,66%), apreensões (1,32%) e outras causas (48,02%) como a invasão de residências e filhotes órfãos. Dentre os motivos de traumas, os atropelamentos foram os mais prevalentes, representando 39,58% dos casos atendidos, seguido por animal encontrado debilitado sem causa definida (31,77%), ataque por animal doméstico (14,58%) e colisão com vidraças (9,89%). Os dados obtidos neste estudo mostram uma rica diversidade de espécies em Joinville. Essas espécies são expostas a diversos desafios e barreiras antropogênicas derivadas principalmente do intenso deslocamento e à invasão humana, fazendo com que muitos animais tenham que se deslocar para se adaptar a viver em áreas urbanas.

Palavras-chave: fauna; atropelamento; mata atlântica; infraestrutura; urbanização.

[1]School of Life Sciences, Pontifícia Universidade Católica do Paraná – Curitiba (PR), Brazil.

[2]Centro Universitário, Sociedade Educacional de Santa Catarina – Blumenau (SC), Brazil.

[3]Faculdade Cesumar – Curitiba (PR), Brazil.

[4]Clínica Dr. Selvagem Medicina de Animais Silvestres e Exóticos – Joinville (SC), Brazil.

Correspondence address: Carolina Konkel Barbosa – Rua Imaculada Conceição, 1.155 – Prado Velho – CEP: 80215-901 – Curitiba (PR), Brazil. E-mail: carolinakonkel@gmail.com

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Introduction

Tropical ecosystems are facing an accelerating rate of deforestation and defaunation. Consequently, anthropogenic alteration of natural environments triggered the sixth largest extinction event in history, causing widespread changes in the global distribution of fauna and flora (Chapin et al., 2000). Landscape modification and habitat fragmentation are the main drivers of this widespread species loss as a result of the interaction of exogenous and endogenous threats, including habitat loss, degradation and isolation, changes in biology, behavior and species interactions, as well as threatening additional factors, such as logging and farming, fires, hunting, illegal trade, introduction of exotic species, edge effects and urbanization (Fischer and Lindenmayer, 2007; Symes et al., 2018).

Maintaining biodiversity in these landscapes is complex and faces a multitude of challenges. Their response to habitat disturbance differs between species and ecological groups, between landscapes and regions, depending on landscape heterogeneity (Ewers and Didham, 2006; Arroyo-Rodríguez et al., 2013). Furthermore, the negative effects of habitat modification and wildlife exploitation have ripple and cumulative effects that affect not only the target species, but also the structure, function and resilience of the forest due to the loss of critical animals for maintenance. environmental, which leads to changes in plant composition, animal communities and ecosystem dynamics that, associated with the development of anthropogenic infrastructures facilitating human access to wildlife habitats, aggravates the effects of deforestation (Ward et al., 2015; Sobral-Souza et al., 2017; Symes et al., 2018).

The Brazilian Atlantic Forest has high species richness and a long history of human disturbance. It is made up of a great diversity of ecosystems, being considered one of the five most important hotspots of global biodiversity, housing about 261 species of mammals (55 endemic), 1020 of birds (188 endemic), 340 of amphibians (90 endemic), 197 of reptiles (60 endemic) and 350 of fish (133 endemic), in addition to containing most of the Brazilian species threatened with extinction (Myers et al., 2000; Arruda and Sá, 2004; Fundação SOS Mata Atlântica and INPE, 2020).

However, the rate of destruction of the Atlantic Forest has increased in recent decades due to the occupation and exploitation of its resources, resulting in severe changes in this ecosystem, caused by the high fragmentation of habitats and the loss of biodiversity. The current result is the almost total loss of the original intact forests and the continuous devastation of the existing forest remnants, making this biome one of the most endangered ecosystems in the world (Brasil, 2010).

The State of Santa Catarina is inserted within this biome in all its extension, and is the third state with the largest area of remnants of the Atlantic Forest in the country, currently possessing about 17.46% of the original biome preserved (Reserva da Biosfera Mata Atlântica, 2008). Due to intense displacement and human invasion, long peri-urban areas are being incorporated into cities, leading to environmental imbalance and great destruction of natural habitats, causing many animals to move in order to adapt to urban areas.

In addition, the intense pressure on the areas still forested results in several encounters between the population and the fauna, with various incidents generating high mortality of the surrounding wild fauna, such as hit-and-run, window-crashing, attacks by domestic animals, disease dissemination and electrocution. A small part of these animals is found still alive, and is sent to the Wild Animal Screening Centers (CETAS), responsible for receiving, sorting, recovering, rehabilitating and disposing of wild animals (IBAMA, 2018).

Considering that most CETAS are located in a single city in the state, some clinics may have a contract with the Brazilian Institute for the Environment and Renewable Natural Resources - IBAMA or Environmental Institutes in the state, to provide emergency care to these animals before they are sent there. Considering this scenario, the purpose of this study was to carry out a survey and diagnosis of the fauna rescued alive in a clinic associated with the Environmental Police of Itajaí, aiming to identify critical points in the survival and conservation of wild species in anthropomorphized areas in the region of Joinville, Santa Catarina - Brazil.

Material and Methods

Description of the study area

The data were obtained from the clinic Dr. Selvagem – Wild and Exotic Animal Medicine, located in the city of Joinville – State of Santa Catarina, Brazil. The clinic provides specialized care for birds, reptiles, mammals, amphibians and privately owned fish that are legalized as required by IBAMA. Since 2006, it has been providing emergency care for free-living wild animals rescued by the environmental police, victims of trafficking, abuse, car crashes and electrical wiring, or at risk, which, after being discharged, are sent to the wild animal rehabilitation center (CETAS) or Fauna Keepers registered by IBAMA for rehabilitation and release.

Design and data analysis

A retrospective observational study was carried out by surveying the clinical care records of free-living wild animals rescued by the environmental police from April 2014 to July 2016, later tabulated in Microsoft Excel 2016 software, according to the date of entry, class, order, family, common name, scientific name, age group, type of rescue, reason for rescue and destination registered in the veterinary records. Data were descriptively analyzed and shown in percentages.

Results

A total of 379 animals were rescued by the environmental institute of Santa Catarina State in charge in the region of Joinville, and sent to a clinic specializing in wild animal care, from April 2014 to July 2016. Of these, 262 (69.13%) were birds, 107 (28.23%) were mammals, 9 (2.37%)

were reptiles and 1 (0.26%) was amphibian. The distribution of visits to birds and mammals according to month and year during this period is shown in Figures 1 and 2. According to Figure 1, it can be seen that there was no homogeneous distribution over the months.

The number of clinical consultations performed in birds during 2014 increased in November, concentrated in October and December 2015 and in January 2016. The registered occurrences of mammals showed dispersion according to the relevant year, and from July to September 2014 they had a larger sample of clinical care. In 2015 the records were mainly concentrated in January, March and June, and in 2016 until July, January and May there was a greater number of records. As for the occurrence of reptiles, clinical consultations were carried out only in 2015, with the majority of records in January (6/9).

The main causes of referral for clinical care due to trauma were 50.7% (n = 192) and other causes amounted to 48% (n = 182), such as home invasion and orphaned puppies, and 1.3% had been seized (n = 5). The trauma category included accidents involving hit-and-run, attack by domestic animals, window-crashing, entanglement in nets and fences, projectiles and animals found weakened without a defined cause. Tables 1, 2 and 3 list the order and animal species with the type of occurrence and conservation status according to the Endangered Species List – MMA (Brasil, 2018a, 2018b, 2018c, 2018d). Several groups of species treated at the clinic had more than one type of occurrence, indicating that the effects of anthropomorphized areas can be cumulative.

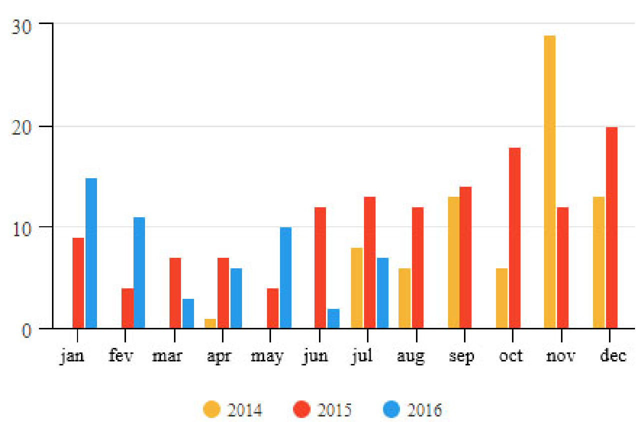

Figure 1 – Distribution of records of free-living birds rescued by the environmental police from April 2014 to July 2016 and treated at the clinic.

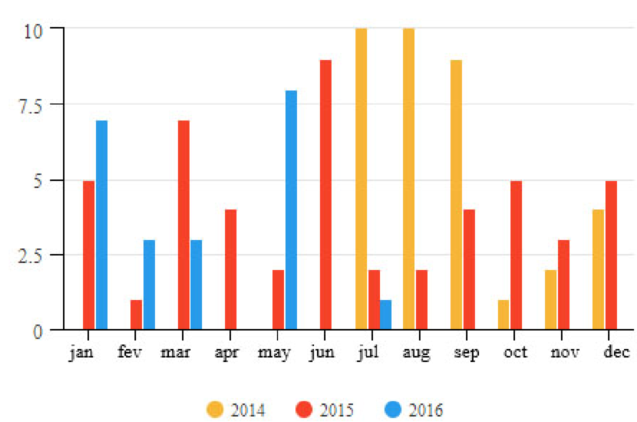

Figure 2 – Distribution of records of free-living mammals rescued by the environmental police from April 2014 to July 2016 and treated at the clinic.

In all, 94 different species of mammals, birds, reptiles and amphibians rescued by the Environmental Police were recorded and received emergency clinical care at Clínica Dr. Selvagem, highlighting the high species richness and a long history of anthropogenic disturbances experienced by the Atlantic Forest biome. As for the conservation status, almost threatened species (NT) were registered: magellanic penguin (*Spheniscus magellanicus*), with 1.06% (n = 4), saffron toucanet (*Pteroglossus bailloni*) (0.26%, n = 1) and the azure jay (*Cyanocorax caeruleus*) (0.26%, n = 1); vulnerable to extinction (VU): white-necked hawk (*Buteogallus lacernulatus*) (0.26%, n = 1), howler monkey (*Alouatta guariba*) (0.26%, n = 1) and northern tiger cat. (*Leopardus tigrinus*) (0.53%, n = 2) and endangered (EN): vinaceous-breasted Parrot (*Amazona vinacea*) (0.26%, n = 1) and Jaguarundi (*Puma yagouaroundi*) (0.26%, n = 1).

Among the reasons for trauma, hit-and-run was the most prevalent, representing 39.6% (n = 76) of the cases treated, followed by animals found debilitated without a defined cause (31.8%, n = 48), attack by domestic animals (14.6%, n = 28), birds in window-crashing accidents (9.9%, n = 19) and other reasons (Figure 3).

The other occurrences not related to trauma represented 48.02% (182/379) of the visits, with the main reason for rescue being related to orphan puppies (36.3%, n = 66), invasion of residence (31%, n = 56), causes not reported (27.5%, n = 50) and falls from the nest (5.5%, n = 10). Of the total number of occurrences recorded in the survey period, most of the animals treated (44.6%, n = 169) were, after stabilization in the clinic, sent to CETAS-SC. In 32.5% (n = 123) the type of destination was not entered in the clinical records, 17.7% (n = 67) of the animals died, 4.7% (n = 18) were destined for release.

Among the animals sent to the clinic due to hit-and-run, 41.7% (31/76) died, 30.2% (23/76) were sent to CETAS-SC, which was not informed in the clinical records (27.6%, 21/76) and only 1 (1/76) was discharged and sent for release. Considering the classes involved in accidents with vehicle collisions, mammals had the highest number of occurrences (60.5%, n = 46), followed by birds (38.2%, n = 29), and only one (1.3 %) species of reptile was registered. Within the Mammalia class, the order Didelphimorphia (43.5%, n = 20) was the most abundant. Additional orders also sampled were Rodentia (15.2%, n = 7), Pilosa (13%, n = 6), Carnivora and Primate (10.9%, n = 6), Cingulata (4.3%, n = 2) and Artiodactyla (2.2%, n = 1).

In birds, individuals of the order Strigiformes were the most recorded group (31%, n = 9), followed by Galiformes (20.7%, n = 6), Gruiformes (13.8%, n = 4), Accipitriforms (10.3%, n = 3) and others. Only one black-and-white Tegu (*Salvator merianae*) belonging to the reptile class was treated at the clinic due to a vehicle collision.

Table 1 – Type of occurrence of mammals rescued by the Environmental Police and sent to Clínica Dr. Selvagem, from 2014 to 2016.

Species	Type of occurrence	Conservation Status	Total
Didelphimorphia			67
Didelphis albiventris	A, B, D	LC	9
Didelphis aurita	A, B, C, D	LC	58
Artiodactyla			1
Not identified	A	-	1
Carnivora			7
Cerdocyon thous	A, C	LC	2
Leopardus tigrinus	A	VU	2
Procyon cancrivorus	A, E	LC	2
Puma yagouaroundi	A	EN	1
Chiroptera			1
Nyctinomops aurispinosus	D	LC	1
Cingulata			3
Dasypus novemcinctus	A, B	LC	3
Pilosa			9
Tamandua tetradactyla	A, D, E	LC	9
Primata			9
Alouatta guariba	E	VU	1
Callithrix penicillata	A, C, D	LC	6
Sapajus apella	A	LC	2
Rodentia			10
Cavia aperea	A, B	LC	2
Coendou prehensilis	A	LC	1
Dasyprocta aguti	A, C, E	LC	3
Hydrochoerus hydrochaeris	A, B	LC	4
Total			107

A: Vehicle collision; B: Domestic Animal Attack; C: Found Debilitated; D: Home Invasion; E: Orphan; LC: Out of danger; VU: Vulnerable; EN: In danger; CR: Critically Endangered.

Table 2 – Type of occurrence of birds rescued by the Environmental Police and sent to Clínica Dr. Selvagem, from 2014 to 2016.

Species	Type of occurrence	Conservation Status	Total
Galliformes			10
Ortalis guttata	A, H, K	LC	8
Penelope obscura	A, E	LC	2
Accipitriformes			13
Buteo brachyurus	E	LC	1
Buteogallus lacernulatus	A	VU	1
Not identified	A, C, E, G, K	-	7
Parabuteo unicinctus	A	LC	1
Rupornis magnirostris	E, G	LC	3
Anseriformes			2
Cairina moschata	A	LC	1
Dendrocygna bicolor	G	LC	1
Apodiformes			3
Not identified	C	-	3
Caprimulgiformes			1
Hydropsalis parvula	B	LC	1
Charadriiformes			13
Larus dominicanus	C, K	LC	2
Larus sp.	K	-	3
Thalasseus maximus	F	LC	1
Vanellus chilensis	A, E, G, H, K	LC	7
Columbiformes			18
Columba livia	G	LC	2
Columbina sp.	B, C, G, H, K	-	14
Geotrygon violacea	B	LC	1
Patagioenas picazuro	H, J	LC	1
Coraciiformes			1
Chloroceryle americana	B	LC	1
Cuculiformes			1
Piaya cayana	E	LC	1
Falconiformes			7
Caracara plancus	A, H, J, K	LC	4
Falco femoralis	G	LC	1

Continue...

Table 2 – Continuation.

Species	Type of occurrence	Conservation Status	Total
Milvago chimachima	A, C	LC	2
Gruiformes			10
Aramides saracura	A, H, K	LC	8
Gallinula galeata	A	LC	1
Porphyrio martinicus	G	LC	1
Nyctibiiformes			2
Nyctibius sp.	G, K	-	2
Passeriformes			67
Cacicus haemorrhous	C	LC	1
Coereba flaveola	B	LC	1
Cyanocorax caeruleus	E	NT	1
Furnarius rufus	C, G	LC	2
Molothrus bonariensis	D, E	LC	3
Myiodynastes maculatus	K	LC	1
Not identified	B, C, H, I, K	-	12
Passer domesticus	B	LC	2
Pitangus sulphuratus	B, C, H, E, I	LC	14
Sicalis flaveola	G	LC	1
Tachyphonus coronatus	E	LC	1
Tangara sp.	E, K	-	4
Thraupis sayaca	K	LC	1
Turdus albicollis	K	LC	1
Turdus amaurochalinus	G, K	LC	4
Turdus flavipes	A, B, K	LC	3
Turdus leucomelas	E	LC	1
Turdus rufiventris	D, E, G, H, I, K	LC	11
Tyrannus melancholicus	C, E, H	LC	3
Pelecaniformes			9
Ardea alba	C, E	LC	3
Nycticorax nycticorax	H, K	LC	2
Phimosus infuscatus	A, G	LC	3
Tigrisoma lineatum	K	LC	1
Piciformes			19
Colaptes campestris	G	LC	1

Continue...

Table 2 – Continuation.

Species	Type of occurrence	Conservation Status	Total
Not identified	I	-	1
Pteroglossus bailloni	K	NT	1
Ramphastos dicolorus	B, E, G, K	LC	10
Ramphastos vitellinus	E, G, H, K	VU	5
Selenidera maculirostris	K	LC	1
Procellariiformes			1
Diomedea sp.	E	-	1
Psittaciformes			16
Amazona vinacea	E	EN	1
Brotogeris tirica	C, E, K	LC	5
Forpus sp.	E	-	2
Pionus maximiliani	B, E, H, K	LC	7
Pyrrhura frontalis	K	LC	1
Sphenisciformes			4
Spheniscus magellanicus	E	NT	4
Strigiformes			57
Asio clamator	A, E, G, H, K	LC	7
Asio stygius	A, C, F, G	LC	8
Athene cunicularia	A, E, F, G	LC	5
Megascops choliba	E	LC	1
Megascops sanctaecatarinae	A, I	LC	3
Not identified	A, C, E, G, H, K	-	17
Pulsatrix koeniswaldiana	E, F	LC	2
Pulsatrix perspicillata	E, G	LC	3
Strix virgata	C	LC	1
Tyto furcata	A, E, G, H, K	LC	10
Sulidae			2
Sula leucogaster	E	LC	2
Suliformes			5
Fregata magnificens	E	LC	2
Phalacrocorax brasilianus	E, K	LC	3
Total			262

A: Vehicle collision; B: Domestic Animal Attack; C: Window-crashing; D: Seizures; E: Found Debilitated; F: Entanglement; G: Home Invasion; H: Orphan; I: Fall from the Nest; J: Firearm; K: Not Informed; LC: Least Concern; NT: Nearly Threatened; VU: Vulnerable; EN: In danger; CR. Critically Endangered.

Table 3 – Type of occurrence of reptiles and amphibians rescued by the Environmental Police and sent to Clínica Dr. Selvagem, from 2014 to 2016.

Species	Type of occurrence	Conservation Status	Total
Testudinata			
Hydromedusa tectifera	D	LC	1
Trachemys dorbigni	B, C	LC	3
Squamata			
Anguis fragilis	D	LC	1
Boa constrictor	D	LC	1
Micrurus corallinus	D	LC	1
Salvator merianae	A, C	LC	2
Anura			
Rhinella marina	D	LC	1
Total			10

A: Vehicle collision; B: Seizure; C: Found Debilitated; D: Home Invasion; LC: Out of danger; VU: Vulnerable; EN: In danger; CR: Critically Endangered.

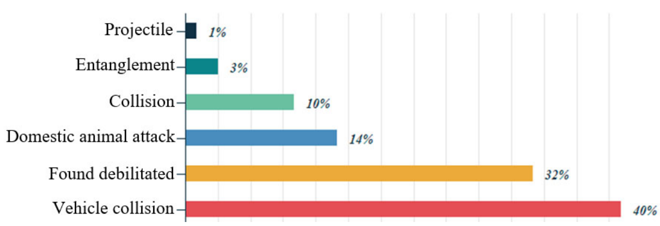

Figure 3 – Type of occurrence of trauma in birds, mammals and reptiles treated at Clínica Dr. Selvagem from April 2014 to July 2016.

Discussion

The type of interaction is directly related to the ecology and behavioral biology of each animal species. Mammals had a higher hit-and-run rate, while birds were concentrated in attacks by domestic animals, collisions with windows, hunting and seizures. Several groups of species treated at the clinic had more than one type of occurrence, indicating that the effects of anthropomorphization in the areas are overlapping and cumulative.

For example, the Mammalia class is the most sensitive and vulnerable group to the rapid development of road infrastructure, due to the specific characteristics of its life history. Many studies have shown that roadside mortality can reduce survival and population densities, and that vehicle collisions are a major source of mortality for many species (Forman and Alexander, 1998; Forman et al., 2003; Fahrig and Rytwinski, 2009; Grilo et al., 2009).

Impacts generated by road development range from direct mortality due to vehicle collisions to secondary effects, such as modification of animal behavior, alteration of the physical and chemical environment, dissemination of exotic species or the disruption of links between populations (Trombulak and Frissell, 2000; Ward et al., 2015). Among the main influences that lead to pedestrian accidents, vehicle speed and traffic volume, food abundance along the roads and the behavior of the species stand out (Forman et al., 2003). This interaction is, in most cases, fatal, decimating several animals daily (Rosa and Bager, 2012).

The effects of road mortality are not evenly distributed in time and space, and it is necessary to assess hotspots, propose mitigation periods and locations (Gunson et al., 2011). Only a small portion of these individuals is found alive, requiring emergency care for these species in specialized clinics associated with the Environmental Police. This study represents only a small portion of the animals that are found trampled alive, making the prognosis of threatened species difficult from an ecological point of view.

This translocation of wildlife to urban environments is probably linked to the suppression of natural resources caused by habitat fragmentation. Thus, with the distribution of habitats in highly fragmented landscapes, it is randomly dispersed, so animals are forced to overcome this great diversity of barriers in search of resources for their survival, and end up invading homes, coming into conflict with human beings (Cervinka et al., 2015).

Another important factor is the seasonality of these events. According to Ferreguetti et al. (2020), temporal variations are directly related to the behavior and period of activity of mammals, and in this study, carried out in a fragment of BR-262 immersed in the Atlantic Forest in the State of Espírito Santo, the months with the highest rates of roadkill were December, January and February, and those with the lowest rates were April, August and September, being significantly higher during the rainy season than during the dry season. These data do not corroborate those found in the present study, where there was no concentration of the number of fixed cases in a certain period. The explanation for this may be due to the high mortality rate, as these animals may die even before receiving any kind of clinical care.

According to a survey of human-fauna impact events conducted by the non-governmental organization Associação Mata Ciliar carried out by Hilário et al. (2021), mortality was not homogeneous along the roads, being determined with data from animals that were taken to non-governmental organizations after getting involved in these events, influenced by the detection of the relationship between the length of roads and the number of animals run over, which corroborates our survey.

Despite the high number of deaths recorded, in developing countries, efforts to reduce wildlife mortality on the roads are still an obstacle, mainly due to the lack of research, which can be extremely costly due to the high sampling effort required, but also due to other priorities generally dictated by the country's socioeconomic situation (Collinson et al., 2015; Williams et al., 2019). However, to preserve the animal habits and needs, structures that allow their safe passage on highways have been used (Gaisler et al., 2009; Freitas, 2010), particularly galleries, dry boxes, overpasses wildlife corridor and fauna viaducts.

One of the great building challenges is the diverse number of species that would depend on these passages and their particular habits, which must be taken into account in planning and construction. In addition, collisions with wild animals can generate several impacts, both for economy and human safety (Ascensão et al., 2021), which makes efforts to elucidate the interaction of linear constructions with these animals fundamental to the reduction of accidents that may promote human and animal mortality.

The introduction of faunal passages of different types and sizes is an important factor in increasing their use by wild animals (Huijser et al., 2007). Some species have a predilection for large and open passages, while others for smaller and confined areas. The study and knowledge of the local fauna is extremely important for the successful implementation of these structures (Clevenger and Waltho, 2005; Huijser et al., 2007). Studies carried out in Canada have shown falls of 80% or more in collisions between large species and vehicles, when structures such as underpasses or wildlife viaducts associated with conduction fences are used (Clevenger et al., 2001; Huijser et al., 2007).

However, due to financial constraints and lack of knowledge about the material costs caused by collisions in most regions, it is rarely realistic to fence off an entire road network simultaneously, and thus mitigating specific road sections can be more cost-effective than fencing all roads (Ascensão et al., 2013; Spanowicz et al., 2020).

Due to the wide diversity of environments and behaviors and, consequently, greater exposure to negative effects associated with habitat transformation, such as mortality from window collisions, exposure to new diseases and predators, birds have been used to study the effects of urbanization on the diversity of species (Carvajal-Castro et al., 2019).

For birds, the greatest risks that cause fatalities directly in anthropogenic landscapes include predation by domestic animals and collision with man-made structures and vehicles (Parkins et al., 2015). The animals sent to the clinic due to attacks by domestic animals and collisions on mirrored surfaces and windows represented 6.33% (24/379) and 5.01% (19/379) of the records, and all species registered were birds.

Collisions with man-made structures such as windowpanes or moving vehicles like automobiles and planes pose threats to birds. According to Riding et al. (2021), the seasonal peaks of collision rates occur in late spring and early autumn with increasing latitude, corroborating what was evidenced in this study. Furthermore, Loss et al. (2019), showed variation in collision correlates between spring and autumn migration and among bird species, whose factors influencing collision fatalities also influence the number of colliding species, and the proportion, and potentially the area, of glass illuminated at night are associated with collisions (Loss et al., 2019).

Study carried out by Klem et al. 2009, determined the fatality of bird crashes on windows in New York, with 475 and 74 crashes in 2006 fall and 2007 spring being recorded. 82% and 85%, respectively, were fatal, partially corroborating the present study, where this event was concentrated in the spring months (September to December). Thus, factors related to the reproductive phenology of birds may have contributed to the observed monthly and seasonal collision patterns.

Among birds, the most affected species in collisions with vehicles were of the family of Strigiformes [*Asio clamator* (1), *Asio stygius* (2), *Athene cunicularia* (1), *Megascops sanctaecatarinae* (2)], Galliformes [*Ortalis guttata* (5), *Penelope obscura* 1], Gruiformes [*Aramides saracura* (3), *Gallinula galeata* (1)] and Accipitriformes [*Buteogallus lacernulatus* (1), *Parabuteo unicinctus* (1)].

The main species of birds affected were of the order of passerines and columbiformes. These species have synanthropic habits and, therefore, live in urban areas, making their nests in homes, being more susceptible to predation by domestic animals and collisions with urban structures. However, some registered species, such as Amazona vinacea, are on the red list of threatened species, and it is extremely important to record and survey these interactions to understand the impact generated and assess the degree of susceptibility of the species.

The number of bird colliding with glass structures is underestimated, receiving greater scientific interest for conservation and political attention recently due to high mortality. In the US alone, bird mortality from this type of structure has been estimated at between 365 and 988 million per year, requiring the adoption of mitigation measures to avoid major losses of bird biodiversity (Barton et al., 2017).

The negative impacts generated by domestic animals represent specific conservation issues, as they are closely linked to the economic, social and political values of local populations and, therefore, require interdisciplinary cooperation to assess the effects of predation, competition, disturbance, hybridization and transmission of diseases from domestic animals under wild populations (Young et al., 2011).

As the human population spread, so did the intentional and accidental introduction of many species into a variety of habitats and ecosystems. An example of this is the transmission of diseases such as rabies and canine distemper virus, which can seriously affect wild species. Randall et al. (2006) observed a 75% reduction in the Ethiopian wolf population (*Canis simensis*) in the last 20 years due to the incidence of rabies transmitted by domestic dogs.

With regard to hunting and seizure among all the animals involved, birds are the class with the highest number of seizures. Trafficking of wild animals is the third largest illegal activity in the world and the second largest in Brazil (Dias Junior et al., 2013). Estimates point to the removal of more than 400 bird species, which represents 23% of the native bird species in Brazil (Alves et al., 2013). In our study, the main species involved in seizures were the Shiny Cowbird (*Molothrus bonariensis*), Rufous-bellied Thrush (*Turdus rufiventris*) and D'Orbigny's slider (*Trachemys dorbigni*), which were strongly linked to animal trafficking. We have also obtained records of gunshot traumas in two specimens of Southern Caracara (*Caracara plancus*) and a Picazuro Pigeon (Patagioenas picazuro).

A useful way to understand the potentially negative effects of landscape modification on native animals is to consider the range of processes that can threaten a particular individual species (Fischer and Lindenmayer, 2007). For example, the orders Rodentia and Didelphimorphia are groups of small mammals, composed of small rodents and marsupials, highly specialized in the maintenance of neotropical ecosystems, with a relevant role in seed dispersal and consequently in the recovery and reforestation process of impacted areas (Grazzini et al., 2015). Many species of these two orders are threatened by habitat loss and fragmentation, which have led to a pronounced decline in their richness and abundance (Grazzini et al., 2015).

The Big-eared Opossum (*Didelphis aurita*) and the White-eared opossum (*D. albiventris*), are didelphid marsupials that, despite not being threated of extinction, are opportunistic and tolerant to altered environments, being found in highly fragmented landscapes, such as urban centers (Abreu et al., 2011). This approximation may justify the greater number of calls registered among the species sampled in our study.

The Rodentia order occupied the second group of mammals with the highest incidence of roadkill in the present study. The families Caviidae, Hydrochaeridae, Dasyproctidae and Erethizontidae were observed, represented respectively by the Brazilian Guinea Pig (*Cavia aperea*), capybaras (*Hydrochaeris hydrochaeris*), Azara's Agouti (*Dasyprocta azarae*) and Orange-spined Hairy Dwarf Porcupine (*Sphiggurus villosus*).

Capybaras (*Hydrochaeris hydrochaeris*) were the rodents with the highest incidence of rescues and visits at Clínica Dr. Selvagem. They are widely distributed in Central and South America, inhabiting different environments, from riparian forests to seasonally flooded savannas, up to 500 m away from the water (Bonvicino et al., 2008). It can compete with cattle for pasture and invade crops, especially in the dry season, being often attracted to urban areas.

Carnivores (Mammalia: Carnivora) are the most sensitive and vulnerable group to accidents due to the rapid development of road infrastructure due to the specific characteristics of their life history, such as low population density and large living areas. Since animals with large ranges of motion typically have low reproduction rates (e.g., large carnivores), they cannot quickly compensate for higher mortality through increased reproduction, so mortality leads to population decline (Spellerberg, 1998).

In this study, two individuals of *Leopardus tigrinus* (northern tiger cat) and one *Puma yagouaroundi* (Jaguarundi) were registered. Felids are species that have relatively low population densities, but inhabit large territorial zones (Cardillo et al., 2004). However, their populations are severely fragmented, being severely reduced by the conversion of their natural habitat into plantations and pastures (Payan and Oliveira, 2016), increasing the need to understand their response to human pressures on large scales (Boyd et al., 2008). Furthermore, local populations tend to decline where roadkill rates exceed those of reproduction and migration (Forman and Alexander, 1998). There was also an occurrence of the white-necked hawk (*Buteogallus lacernulatus*), categorized as vulnerable (VU) by the C2a(i) criteria, in view of the decline due to the loss of area and habitat quality and the removal of individuals from the wild.

In general, most species that feed near roads are more vulnerable to being run over, which includes many predators, scavengers and grass-eating herbivores (Coffin, 2007; Laurance and Useche, 2009). Mammals are victims of roadkill when they travel along highways crossing their area of residence or when they are attracted by available resources in the surrounding area (Laurance and Useche, 2009). Birds are attracted to roads by the availability of perches around the roads, the abundance of small mammals that serve them as food, the grain that falls from vehicles and the carcasses of animals (Grilo et al., 2010). The main risks of reptiles being run over are associated with slow movements and the behavior of heating up on roads as a means of thermoregulation (Laurance and Useche, 2009; Grilo et al., 2010).

Conclusion

The data obtained in this study point to a rich diversity of species in the Joinville region. These species are exposed to several anthropogenic challenges and barriers mainly derived from intense displacement and human invasion, with the incorporation of long peri-urban areas to cities, drastically modifying the landscape and its natural resources, causing many animals to have to move in order to adapt to life in urban areas.

However, only animals rescued still alive and taken to emergency care were measured. Despite this, part of the individuals died, mainly as a result of being run over. Hit-and-run was the main reasons for trauma seen at the clinic during the survey period. However, no data, such as the exact location of each event, or temporal data, such as climate, rainfall, local characteristics of roads were obtained, which could allow exploring the effects of other variables or even identifying hotspots of different species for planning and implementation of urban mitigation measures, such as fauna passages, to reduce the impact generated on local biodiversity. In addition, another variable that can also influence the reported sample is related to the characteristics of the animals, such as size, charisma or whether the animal represents any danger to people.

Thus, the region of Joinville is constituted as a territory covered by native vegetation in constant conflict with anthropogenic activities, leading to dualism in the occupation of environments between wildlife and human population, with the occurrence of accidents on highways, in homes through attacks by domestic animals or collisions on windows, requiring further studies covering different field measurement techniques and data on the care of these animals.

Contribution of authors:

Barbosa, C.K.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing — original draft, Writing — review and editing. Gneiding, J.E.B.O.: Data curation, Formal analysis, Investigation, Methodology, Writing — original draft, Writing — review and editing. Ribeiro, T. T.: Data curation, Investigation, Methodology. Iachinski, E.A.: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources. Gonçalves, I.C.M.: Authorization, Supervision, Visualization, Writing — review and editing. Pimpão, C.T.: Conceptualization, Guidance, Formal analysis, Project administration, Supervision, Visualization, Writing — review and editing.

References

Abreu, M.S.L.; Christoff, A.U.; Vieira, E.M., 2011. Identificação de marsupiais do Rio Grande do Sul através da microestrutura dos pelos-guarda. Biota Neotrop (Online), v. 11, (3), 391-400. http://dx.doi.org/10.1590/S1676-06032011000300031.

Alves, R.R.N.; Lima, J.R.F.; Araujo, H.F.P., 2013. The live bird trade in Brazil and its conservation implications: an overview. Bird Conservation International (Online), v. 23, (1), 53-65. http://dx.doi.org/10.1017/S095927091200010X.

Arroyo-Rodríguez, V.; Ros, M.; Escobar, F.; Melo, F.P.L.; Santos, B.A.; Tabarelli, M.; Chazdon, R, 2013. Plant b-diversity in fragmented rain forests: testing floristic homogenization and differentiation hypotheses. Journal of Ecology (Online), v. 101, (6), 1449-1458. https://doi.org/10.1111/1365-2745.12153.

Arruda, M.B.; Sá, L.F.S.N., 2004. Corredores ecológicos: uma abordagem integradora de ecossistemas no Brasil. Edições IBAMA, Brasília, 203 pp.

Ascensão, F.; Clevenger, A.; Santos-Reis, M.; Urbano, P.; Jackson, N. 2013. Wildlife–vehicle collision mitigation: Is partial fencing the answer? An agent-based model approach. Ecological Modelling, v. 257, 36-43, https://doi.org/10.1016/j.ecolmodel.2013.02.026.

Ascensão, F.; Yogui, D.R.; Alves, M.H.; Alves, A.C.; Abra, F.; Desbiez, A.L.J., 2021. Preventing wildlife roadkill can offset mitigation investments in short-medium term. Biological Conservation, v. 253, 108902. https://doi.org/10.1016/j.biocon.2020.108902.

Barton, C.M.; Riding, C.S.; Loss, S.R., 2017. Magnitude and correlates of bird collisions at glass bus shelters in an urban landscape. PLoS One, v. 12, (6), e0178667. https://doi.org/10.1371/journal.pone.0178667.

Bonvicino, C.R.; Oliveira, J.A.; D'Andrea, P.S., 2008. Guia dos Roedores do Brasil, com chaves para gêneros baseadas em caracteres externos. Centro Pan-Americano de Febre Aftosa - OPAS/OMS, Rio de Janeiro.

Boyd, C.; Brooks, T.M.; Butchart, S.M.; Edgar, G.J.; Fonseca, G.A.B.; Hawkins, F.; Hoffmann, M.; Sechrest, W.; Stuart, S.N.; Dijk, P.P., 2008. Spatial scale and the conservation of threatened species. Conservation Letters, v. 1, (1), 37-43. https://doi.org/10.1111/j.1755-263X.2008.00002.x.

Brasil. Ministério do Meio Ambiente. 2010. Mata Atlântica. Manual de Adequação Ambiental. MMA/SBF, Brasília, 96 pp. (Série Biodiversidade, 35).

Brasil. Ministério do Meio Ambiente. 2018a. Livro Vermelho da Fauna Brasileira Ameaçada de Extinção. ICMBio/MMA, Brasília, v. 2.

Brasil. Ministério do Meio Ambiente. 2018b. Livro Vermelho da Fauna Brasileira Ameaçada de Extinção. ICMBio/MMA, Brasília, v. 3.

Brasil. Ministério do Meio Ambiente. 2018c. Livro Vermelho da Fauna Brasileira Ameaçada de Extinção. ICMBio/MMA, Brasília, v. 4.

Brasil. Ministério do Meio Ambiente. 2018d. Livro Vermelho da Fauna Brasileira Ameaçada de Extinção. ICMBio/MMA, Brasília, v. 5.

Cardillo, M.; Purvis, A.; Sechrest, W.; Gittleman J.L.; Bielby, J.; Mace, G.M., 2004. Human population density and extinction risk in the world's carnivores. PLoS Biology, v. 2, (7), e197. https://doi.org/10.1371/journal.pbio.0020197.

Carvajal-Castro, J.D.; Ospina-L, A.M.; Toro-López, Y.; Pulido-G., A.; Cabrera-Casas, L.X.; Guerrero-Peláez, S.; García-Merchán, V.H.; Vargas-Salinas, F. 2019. Birds vs bricks: Patterns of species diversity in response to urbanization in a Neotropical Andean city. PLoS One, v. 14, (6), e0218775. https://doi.org/10.1371/journal.pone.0218775.

Cervinka, J.; Riegert, J.; Grill, S.; Salek, M., 2015. Large-scale evaluation of carnivore road mortality: the effect of landscape and local scale characteristics. Mammal Research (Online), v. 60, 233-243. https://doi.org/10.1007/s13364-015-0226-0.

Chapin, F.S.; Zavaleta, E.S.; Eviner, V.T.; Naylor, R.L.; Vitousek, P.M.; Reynolds, H.L.; Hooper, D.U.; Lavorel, S.; Sala, O.E.; Hobbie, S.E.; Mach, M.C.; Diaz, S., 2000. Consequences of changing biodiversity. Nature, v. 405, 234-242. https://doi.org/10.1038/35012241.

Clevenger, A.P.; Chruszcz, B.; Gunson, K., 2001. Drainage culverts as habitat linkages and factors affecting passage by mammals. Journal of Applied Ecology, v. 38, (6), 1340-1349. https://doi.org/10.1046/j.0021-8901.2001.00678.x.

Clevenger, A.P.; Waltho, N., 2005. Performance indices to identify attributes of highway crossing structures facilitating movement of large mammals. Biological Conservation, v. 121, (3), 453-464. https://doi.org/10.1016/j.biocon.2004.04.025.

Coffin, A.W., 2007. From roadkill to road ecology: A review of the ecological effects of roads. Journal of Transport Geography, v. 15, (5), 396-406. https://doi.org/10.1016/j.jtrangeo.2006.11.006.

Collinson, W.J.; Parker, D.M.; Bernard, R.T.F.; Reilly, B.K.; Davies-Mostert, H.T., 2015. An inventory of vertebrate roadkill in the Greater Mapungubwe Transfrontier Conservation Area, South Africa. African Journal of Wildlife Research, v. 45, (3), 301-311. https://doi.org/10.3957/056.045.0301.

Dias Junior, M.B.F.; Cunha, H.F.A.; Dias, T.C.A.C., 2013. Análise da destinação da fauna silvestre apreendida no Estado do Amapá, Brasil. Planeta Amazônia, (5), 23-36.

Ewers, R.M.; Didham, R.K., 2006. Confounding factors in the detection of species responses to habitat fragmentation. Biological Reviews, v. 81, (1), 117-142. https://doi.org/10.1017/S1464793105006949.

Fahrig, L.; Rytwinski, T., 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecology and Society, v. 14, (1), 21.

Ferreguetti, A.C.; Graciano, J.M.; Luppi, A.P.; Pereira-Ribeiro, J.; Rocha, C.F.D.; Bergallo, H.G. 2020. Roadkill of medium to large mammals along a Brazilian road (BR-262) in Southeastern Brazil: spatial distribution and seasonal variation. Studies on Neotropical Fauna and Environment, v. 55, (3), 216-225. https://doi.org/10.1080/01650521.2020.1719006.

Fischer, J.; Lindenmayer, D.B., 2007. Landscape modification and habitat fragmentation: a synthesis. Global Ecology and Biogeography, v. 16, (3), 265-280. https://doi.org/10.1111/j.1466-8238.2007.00287.x.

Freitas, S., 2010. O efeito das Estradas sobre a Vegetação Nativa e a Biodiversidade. Simpósio sobre Obras Rodoviárias, Santo André, 21 de outubro de 2010. Anais do 3° Simpósio sobre Obras Rodoviárias, RODO. Associação Brasileira de Geologia de Engenharia, São Paulo.

Forman, R.T.T.; Sperling, D.; Bissonette, J.A.; Clevenger, A.P.; Cutshall, C.D.; Dale, V.H.; Fahrig, L.; France, R.; Goldman, C.R.; Heanue, K.; Jones, J.A.; Swanson, F.J.; Turrentine, T.; Winter, T.C., 2003. Road Ecology: Science and Solutions. Island Press, Washington, D.C.

Forman, T.T.R.; Alexander, L.E., 1998. Roads and their major ecological effects. Annual Review of Ecology. Evolution and Systematics, v. 29, 207-231. https://doi.org/10.1146/annurev.ecolsys.29.1.207.

Fundação SOS Mata Atlântica; Instituto Nacional de Pesquisas Espaciais – INPE. 2020. Atlas dos remanescentes florestais da mata atlântica período 2018-2019, relatório técnico. Fundação SOS Mata Atlântica, São Paulo, 61 pp.

Gaisler, J.; Řehák, Z.; Bartonička, T., 2009. Bat casualties by road traffic (Brno-Vienna). Acta Theriologica, v. 54, 147-155. https://doi.org/10.1007/BF03193170.

Grazzini, G.; Mocchi-Junior, C.M.; Oliveira, H.; Pontes, JS.; Gatto-Almeida, F.; Tiepolo, L.M., 2015. Identidade, riqueza e abundãncia de pequenos mamíferos (Rodentia e Didelphimorphia) de área de Floresta com Araucária no estado do Paraná, Brasil. Papéis Avulsos de Zoologia, v. 55, (15), 217-230. http://dx.doi.org/10.1590/0031-1049.2015.55.15.

Grilo, C.; Ascensão, F.; Santos-Reis, M.; Bissonette, J.A., 2010. Do well-connected landscapes promote road-related mortality? European Journal of Wildlife Research, v. 57, 707-716. https://doi.org/10.1007/s10344-010-0478-6.

Grilo, C.; Bissonette, J.A.; Santos-Reis, M., 2009. Spatial-temporal patterns in Mediterranean carnivore road casaulties: consequences for mitigation. Biological Conservation, v. 142, (2), 301-313. http://dx.doi.org/10.1016/j.biocon.2008.10.026.

Gunson, K.E.; Mountrakis, G.; Quackenbush, L.J., 2011. Spatial wildlife-vehicle collision models: a review of current work and its application to transportation mitigation projects. Journal of Environmental Management, v. 92, (4), 1074-1082. http://dx.doi.org/10.1016/j.jenvman.2010.11.027.

Hilário, R.R.; Carvalho, W.D.; Gheler-Costa, C.; Rosalino, L.M.C.; Marques, T.A.; Adania, C.H.; Paulino, J.S.; Almeida, P.M.; Mustin, K. 2021. Drivers of human-wildlife impact events involving mammals in Southeastern Brazil, Science of The Total Environment, 794, 148600. https://doi.org/10.1016/j.scitotenv.2021.148600.

Huijser, M.P.; Kociolek, A.V.; McGowen, P.T.; Ament, R.; Hardy, A.; Clevenger, A.P., 2007. Wildlife-vehicle collision and crossing mitigation measures: a toolbox for the Montana Department of Transportation. Helena, Montana: The State of Montana Department of Transportation. https://doi.org/10.21949/1518298.

Instituto Brasileiro do Meio Ambiente e Recursos Naturais Renováveis – IBAMA. 2018. Centros de Triagem de Animais Silvestres (Cetas) (Accessed July 3, 2020) at: https://www.ibama.gov.br/fauna-silvestre/cetas/o-que-sao-os-cetas.

Laurance, W.F.; Useche, D.C., 2009. Environmental synergisms and extinctions of tropical species. Conservtion Biology, v. 23, (6), 1427-1437. http://dx.doi.org/10.1111/j.1523-1739.2009.01336.x.

Loss, S. R.; Lao, S.; Eckles, J. W.; Anderson, A. W.; Blair, R. B.; Turner, R. J. 2019. Factors influencing bird-building collisions in the downtown area of a major North American city. PLoS One, v. 14, (11), e0224164. https://doi.org/10.1371/journal.pone.0224164.

Myers, N.; Mittermeier, R.A.; Mittermeier, C.G.; Fonseca, G.A.B.; Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature, v. 403, 853-858. https://doi.org/10.1038/35002501.

Parkins, K.L.; Elbin, S.B.; Barnes, E., 2015. Light, glass, and bird–building collisions in an urban park. Northeastern Naturalist, v. 22, (1), 84-94. https://doi.org/10.1656/045.022.0113.

Payan, E.; Oliveira, T., 2016. Leopardus tigrinus. The IUCN Red List of Threatened Species 2016, e.T54012637A50653881. https://doi.org/10.2305/IUCN.UK.2016-2.RLTS.T54012637A50653881.en.

Randall, D.A.; Marino, J.; Haydon, D.T.; Sillero-Zubiri, C.; Knobel, D.L.; Tallents, L.T.; Macdonald, D.W.; Laurenson, M.K., 2006. An inte-grated disease management strategy for the control of rabies in Ethiopian wolves. Biological Conservation, v. 131, (2), 151-162. https://doi.org/10.1016/j.biocon.2006.04.004.

Reserva da Biosfera Mata Atlântica. 2008 (Accessed June 21, 2019) at: http://www.rbma.org.br/rbma/rbma_fase_vi_06_estados_sc.asp.

Riding, C. S.; O'Connell, T. J.; Loss, S. R., 2021. Multi-scale temporal variation in bird-window collisions in the central United States. Scientific Reports, v. 11, 11062. https://doi.org/10.1038/s41598-021-89875-0.

Rosa, C.A.; Bager, A., 2012. Seasonality and habitat types affect roadkill of neotropical birds. Journal of Environmental Management, v. 97, 1-5. https://doi.org/10.1016/j.jenvman.2011.11.004.

Sobral-Souza, T.; Lautenschager, L.; Morcatty, T.Q.; Bello, C.; Hansen, D.; Galetti, M., 2017. Rewilding defaunated Atlantic Forests with tortoises to restore lost seed dispersal functions. Perspectives in Ecology and Conservation, v. 15, (4), 300-307. https://doi.org/10.1016/j.pecon.2017.08.005.

Spanowicz, A.G., Teixeira, F.Z., Jaeger, J.A.G. 2020. An adaptive plan for prioritizing road sections for fencing to reduce animal mortality. Conservation Biology, v. 34, (5), 1210-1220. https://doi.org/10.1111/cobi.13502.

Spellerberg, I., 1998. Ecological effects of roads and traffic: a literature review. Global Ecology and Biogeography Letters, v. 7, (5), 317-333. https://doi.org/10.1046/j.1466-822x.1998.00308.x.

Symes, W.S.; Edwards, D.P.; Miettinen, J.; Rheindt, F.E.; Carrasco, L.R., 2018. Combined impacts of deforestation and wildlife trade on tropical biodiversity are severely underestimated. Nature Communications, v. 9, 4052. https://doi.org/10.1038/s41467-018-06579-2.

Trombulak, S.C.; Frissell, C.A., 2000. Review of Ecological Effects of Roads on Terrestrial and Aquatic Communities. Conservation Biology, v. 14, (1), 18-30. https://doi.org/10.1046/j.1523-1739.2000.99084.x.

Ward, A.I.; Dendy, J.; Cowan, D.P., 2015. Mitigating impacts of roads on wildlife: an agenda for the conservation of priority European protected species in Great Britain. European Journal of Wildlife Research, v. 61, 199-211. https://doi.org/https://doi.org/10.1007/s10344-015-0901-0.

Williams, S.T.; Collinson, W.; Patterson-Abrolat, C.; Marneweck, D.G.; Swanepoel, L.H., 2019. Using road patrol data to identify factors associated with carnivore roadkill counts. Peer J, e6650. https://doi.org/10.7717/peerj.6650.

Young, K.A.; Olson, K.A.; Reading, R.P.; Amgalanbaatar, S.; Berger, J., 2011. Is Wildlife Going to the Dogs? Impacts of feral and Free-roaming Dogs on Wildlife Populations. BioScience, v. 61, (2), 125-132. https://doi.org/10.1525/bio.2011.61.2.7.

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Expansion of photovoltaic systems in multicampi higher education institutions: evaluation and guidelines

Expansão de Sistemas Fotovoltaicos em Instituições de Ensino Superior Multicampi – Análise e orientações

Osvaldo Augusto Vasconcelos de Oliveira Lopes da Silva[1], *José Machado Moita Neto*[2], *Marcos Antônio Tavares Lira*[2], *Fabrício Higo Monturil de Morais*[1]

ABSTRACT

Considering the multicampi organizational structure of higher education institutions (HEIs), the expansion of photovoltaic (PV) systems previously installed in the facilities, the great potential for PV generation in Brazil, and the 2030 Agenda, the general goal of this research study is to evaluate and promote the expansion of the aforementioned PV systems. For this purpose, the PV system installed at the Federal Institute of Education, Science and Technology of Piauí comprising a future expansion is characterized by a thorough literature and documentary research. The solar resource available at the campuses of the institution was estimated using the second version of the Brazilian Atlas of Solar Energy. The technical–economic viability of the system expansion is assessed through the average parameters and minimum performance indexes required by the institution. Thus, it is possible to prove the effectiveness of the methodology to identify investment priorities and guide the construction and expansion of other PV systems, confirming that this process is technically and economically feasible as associated with strategic adherence, also bringing several environmental benefits.

Keywords: distributed generation; photovoltaic solar energy, renewable energy sources; solar atlas.

RESUMO

Considerando a estrutura organizacional multicampi de instituições de ensino superior e a recente expansão de sistemas fotovoltaicos instalados nessas organizações, além do grande potencial de geração fotovoltaica no Brasil e a Agenda 2030, este artigo tem o objetivo geral de avaliar e orientar a expansão desses sistemas nessas instituições. Para tanto, caracterizou-se o sistema fotovoltaico instalado e expansão contratada no Instituto Federal de Educação, Ciência e Tecnologia do Piauí com uma pesquisa bibliográfica e documental; estimou-se o recurso solar disponível aos seus campi utilizando-se a segunda versão do Atlas Brasileiro de Energia Solar; e verificou-se a viabilidade técnico-econômica da expansão dos sistemas com os parâmetros médios e índices mínimos de desempenho exigidos pela instituição. Por fim, pôde-se comprovar a eficácia da metodologia para identificar prioridades de investimento e orientar a construção e a ampliação de sistemas, comprovando-se que esta expansão é viável técnica-economicamente, com aderência estratégica, trazendo benefícios ambientais e à sua atividade fim.

PALAVRAS-CHAVE: Fontes Alternativas; Fontes Renováveis; Geração Distribuída; Atlas Solarimétrico.

[1]Instituto Federal de Educação, Ciência e Tecnologia do Piauí – Teresina (PI), Brazil.

[2]Universidade Federal do Piauí – Teresina (PI), Brazil.

Correspondence address: Osvaldo Augusto Vasconcelos de Oliveira Lopes da Silva – Rua Antilhon Ribeiro Soares, 5000, apto. A-161 – Santa Isabel – CEP: 64053-070 – Teresina (PI), Brazil. E-mail: osvaldo.augusto@ifpi.edu.br

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Introduction

Considering the need to grant universal access to energy, increase the share of renewable energy sources, double the global energy efficiency index, as well as strengthen international cooperation in research and technology transfer, the member countries of the United Nations (UN) committed to the seventh Sustainable Development Goal (SDG), namely, accessible and clean energy (UN, 2015a). This is a global cooperative planning and action program (Agenda 2030) composed of member countries, comprising 17 goals to be pursued in the subsequent 15 years (UN, 2015b).

The electric energy can be regarded as an infrastructure tool that promotes citizenship. However, the population growth, and especially the economic development, generates an increasing demand that must be met with high energy efficiency or the implementation of new energy generating plants, causing significant social and environmental impacts (Brasil, 2019b). As a consequence, the rapid depletion of conventional energy sources and the concern with environmental issues have driven the search for new, more efficient energy alternatives (Villela et al., 2017). Thus, renewable energy sources become relevant and indispensable for the development of a sustainable electricity generation system (Khan and Arsalan, 2016).

Renewable energy sources are currently used worldwide to reduce the impact of modern society on the environment (Goel and Sharma, 2017). Photovoltaic (PV) solar energy stands out as one of the most promising solutions, since it has nearly unlimited availability and accessibility throughout the planet and can be integrated into distinct types of buildings in the urban environment. Dávi et al. (2016) reported that the greenhouse gas emissions associated with this source are much lower than those of conventional fossil fuel-based electricity generation technologies. Most of the impacts of the PV systems are related to the production of cells (Silva, L.R. et al., 2018). Such impacts were assessed by Bezerra et al. (2018) who, when carrying out the life-cycle analysis of a PV module from the "cradle to the gate," could verify the large amount of fossil fuels used in its production. Other harmful effects include the great impact on ecotoxicity, eutrophication of fresh water, and human toxicity, mainly due to the presence of heavy metals and other toxic substances in its composition.

In 2018, 11 countries installed more than 1 GW of PV facilities. Brazil and other 30 countries reached this cumulative capacity by adding a total of 103 GW worldwide, corresponding to an increase of 25.18% compared with the previous year, thus totaling 512 GW (2.9% of the world electricity matrix) (IEA, 2019). Even though it represents only 0.13% of the Brazilian energy matrix, the capacity of PV solar energy increased by 92.29% in 2019, reaching 1,798 MW. This is mainly due to the construction of large PV plants (centralized generation) and installation of grid-connected PV systems (GCPVSs) in consumer units (distributed generation) (Brasil, 2019a). Sommerfeldt and Madani (2016) stated that the increased use of such energy source is mainly observed in countries whose government policies created favorable economic conditions. In Brazil, the publication of normative resolution RN No. 482/2012 by the Brazilian National Electric Energy Agency (ANEEL), which standardized the inclusion of PV solar energy in the energy matrix through distributed micro- and mini-generation units, as well as its subsequent amendment RN No. 687/2015 of ANEEL (ANEEL, 2015), established conditions and incentives for consolidating the distributed generation in the forthcoming years.

Such regulatory actions associated with advances in PV technology, cost reduction, and subsidies were responsible for the significant increase in distributed generation in Brazil, mainly in the context of GCPVSs (Vale et al., 2017). Even with its significant role in the diversification of the Brazilian energy matrix, the increase in centralized generation is characterized by the need for new transmission and distribution lines that connect the plants to the load centers, as well as large areas needed for the implementation and operation of facilities, causing adverse socio-environmental impacts (Camargos et al., 2016). Thus, distributed generation becomes more advantageous from this perspective.

In turn, higher education institutions (HEIs) in Brazil experienced a significant expansion from the 1960s onward, thus requiring more efficient academic and administrative policies to ensure good performance in this new multicampi configuration (Nez, 2016). Recognizing this need, Silva et al. (2016) highlighted that consolidating the institutionalization of environmental management in universities is mandatory. It should be treated as a management model aiming at efficiency, efficacy, and effectiveness, which relies on economic and financial analyses and uses standardized procedures. Therefore, an environmental management system (EMS) is regarded as a continuous process and part of the management system of organizations. It is also used to develop and implement environmental policies that ensure acceptable management results on manageable environmental aspects, which include the use of energy.

Thus, the implementation of EMSs in HEIs should include energy management aspects, since the use of energy is the input quantity with the highest environmental risk index (Senna et al., 2014). HEIs should become an example of sustainability for the entire community, encouraging solid changes in the local reality not only through their core activity (teaching, research, and extension) but also through the articulation of management and building infrastructure to consolidate it as a sustainable space.

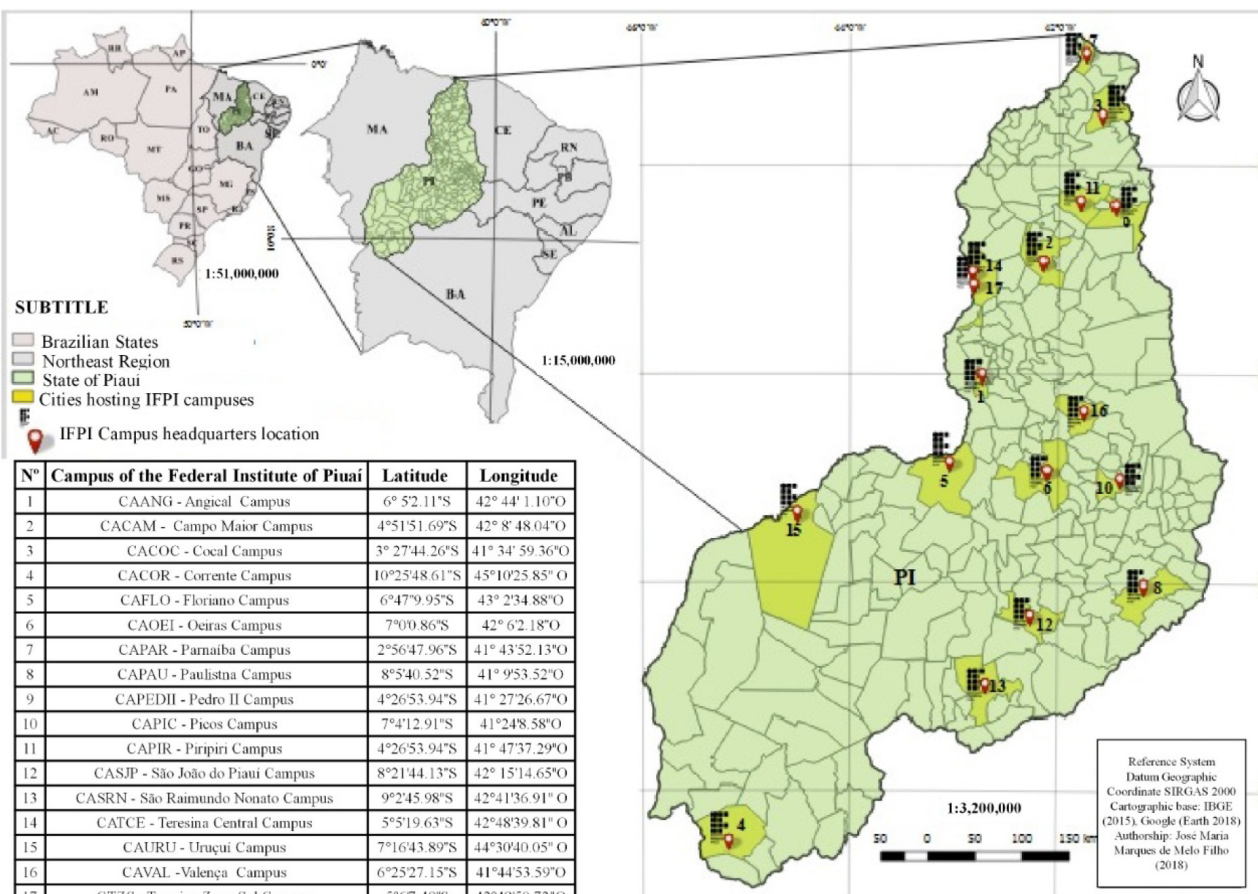
Brazil has a great potential for PV generation owing to its large territorial extension and solar irradiation levels higher than those of European countries, which are the among the top PV generators (Pereira et al., 2017). Furthermore, Urbanetz Junior et al. (2014), Gomes et al. (2015), Buiatti et al. (2016), Morais et al. (2017), and Morais et al. (2019) highlighted the implementation of GCPVSs in several Brazilian HEIs, which include the Federal Technological University of Paraná (UFTPR), Federal University of Uberlândia (UFU), Federal Institute of Education, Science and Technology of Rio Grande in North (IFRN), Federal University of Piauí (UFPI), and Federal Institute of Education, Science and Technology of Piauí (IFPI). The aforementioned facilities are characterized as micro- and mini-generation units, with good performance levels and proved technical feasibility.

In November 2019, the Brazilian government invested R$60 million for the installation of 852 PV plants in federal technological education institutions, with estimated annual savings of R$17.7 million (Brasil, 2019c). The savings can bring social and environmental benefits and applied in the core activities of HEIs. However, the feasibility of installing such systems may vary according to technical and economic factors associated with the installation sites, such as the solar irradiation levels and electricity tariffs, which can be determined by multicriteria assessment (Azizkhani et al., 2016; Sagbansua and Balo, 2016; Ebrahimi et al., 2018). Thus, as a follow-up investigation of the studies developed by Silva, O.A.V. de O.L. da et al. (2018), and Silva (2020), the general goal of this article is to evaluate and guide the expansion process of PV systems in a multicampi HEI. For this purpose, the IFPI is adopted as a case study because it has a GCPVS installed in the institution (Sá et al., 2017; Morais et al., 2019). It is also worth mentioning that the PV facilities are currently under expansion (Brasil, 2019c).

Methodology

The IFPI is a Brazilian federal HEI created in 2008 by Federal Law No. 11892. It aims to "be consolidated as a center of excellence in professional and scientific education and technology, standing among the best educational institutions in the country" (IFPI, 2020). From the Support Program for Federal Universities Restructuring and Expansion Plans, which contributed to the increase in the number of cities that host campuses, the IFPI could expand itself with the installation of 12 new campuses in the past 10 years. Thus, it has been consolidated as a multicampi organizational structure (Silva et al., 2017).

The institution currently has 17 campuses, distributed in all regions of the state of Piauí (Figure 1). Morais et al. (2019) highlighted the existence of a 150-kWp system installed at the Floriano Campus. Besides, Silva et al. (2017) and de Silva, Moita Neto, and Lira (2021)



Nº	Campus of the Federal Institute of Piauí	Latitude	Longitude
1	CAANG - Angical Campus	6° 5'2.11"S	42° 44' 1.10"O
2	CACAM - Campo Maior Campus	4°51'51.69"S	42° 8' 48.04"O
3	CACOC - Cocal Campus	3° 27'44.26"S	41° 34' 59.36"O
4	CACOR - Corrente Campus	10°25'48.61"S	45°10'25.85" O
5	CAFLO - Floriano Campus	6°47"9.95"S	43° 2'34.88"O
6	CAOEI - Oeiras Campus	7°0'0.86"S	42° 6'2.18"O
7	CAPAR - Parnaíba Campus	2°56'47.96"S	41° 43'52.13"O
8	CAPAU - Paulistna Campus	8°5'40.52"S	41° 9'53.52"O
9	CAPEDII - Pedro II Campus	4°26'53.94"S	41° 27'26.67"O
10	CAPIC - Picos Campus	7°4'12.91"S	41°24'8.58"O
11	CAPIR - Piripiri Campus	4°26'53.94"S	41° 47'37.29"O
12	CASJP - São João do Piauí Campus	8°21'44.13"S	42° 15'14.65"O
13	CASRN - São Raimundo Nonato Campus	9°2'45.98"S	42°41'36.91" O
14	CATCE - Teresina Central Campus	5°5'19.63"S	42°48'39.81" O
15	CAURU - Uruçuí Campus	7°16'43.89"S	44°30'40.05" O
16	CAVAL -Valença Campus	6°25'27.15"S	41°44'53.59"O
17	CTZS - Teresina Zona Sul Campus	5°6'7.49"S	42°48'50.72"O

Figure 1 – Distribution of IFPI campuses.
Source: Silva, O.A.V. de O.L. da (2018).

showed the need for investments in energy efficiency projects in the whole institution. Therefore, it is reasonable to state that all campuses are part of the scope of this research.

The study starts with the characterization of the GCPVS installed at the Floriano Campus from a thorough bibliographical research on the technical–economic and environmental performance associated with the reduction of carbon dioxide emissions. Then, an electronic price registration auction was carried out for the eventual installation of a microgeneration unit at the HEI (IFPI, 2018). This process can be regarded as a benchmark for the latter acquisition of GCPVSs in HEIs located at seven distinct states, namely, Bahia, Rondônia, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Ceará, and Piauí, totaling 3,234 kWp, among which the IFPI is included (Brasil, 2019c).

Some available official documents were analyzed to study the expansion of PV systems in the institution, with special attention given to the Transparency Portal of the Brazilian Government (Brasil, 2020a). Specific information was also requested directly to the institution through the electronic citizen information service (E-SIC) (Brasil, 2020b). The purpose is to identify in which campuses the systems will be installed and their technical–economic characteristics, comparing them with the previously installed GCPVS (Morais et al., 2019).

With regard to the technical performance, the parameters commonly used for monitoring and analysis, i.e., the figures of merit are the final productivity (Y) given in kWh/kWp, defined as the ratio of the liquid power flow of the entire system (E) to the total peak power of PV modules (P_o) in Equation 1 (IEC, 1998); the average overall performance or performance ratio (PR), this being a dimensionless quantity that express the ratio between the final productivity (Y_f) and the reference productivity (Y_r), determined based on the rated parameters of the system components according to Equation 2 (IEC, 1998); and the capacity factor (CF), which is a dimensionless quantity representing the activity level of a generation system through the relationship between the energy effectively produced (E) and the expected production at the rated power P_o during the very same period (Δt) as defined in Equation 3 (Nakabayashi, 2015). However, only the results provided by the first index will be used in the analysis of the new systems contracted by the HEI since they are not yet installed.

$$Y = \frac{E}{P_o} \quad (1)$$

$$PR = \frac{Y_f}{Y_r} \quad (2)$$

$$CF = \frac{E}{P_o \times \Delta t} \quad (3)$$

It is necessary to assemble a measurement system for assessing the available solar resource and determining the performance of PV systems. The setup comprises calibrated reference modules placed on the same plane of the system or pyranometers installed together with the system (IEC, 1998). However, the installation of such equipment as required by official standards in all the campuses would make the study cost-prohibitive. Therefore, the authors used the database of the second version of the Brazilian Atlas of Solar Energy (Pereira et al., 2017), which also served as a reference for determining the irradiation levels in the studies by Carneiro et al. (2019), Deschamps and Rüther (2019), Ferreira et al. (2018), Morais et al. (2019), and Paim et al. (2019).

To determine the solar irradiation levels, the geographical coordinates of each of campus were obtained. The average value of the annual overall irradiation available in the metadata of the second edition of the Brazilian Atlas of Solar Energy (Pereira et al., 2017) at the reference point closest to each campus was then calculated using Equation 4. The distance (d, in km) between the reference point of the Atlas and each campus was determined based on the mean Earth radius (r = 6,371 km) in the respective latitudes (*lat1* and *lat2*) and longitudes (*long1* and *long2*) of the points, where "$\cos^{-1}\theta$" is measured in radians (Santos and Oliveira, 2018).

$$D = R \times \cos^{-1} [\sin(lat1) \times \sin(lat2) + \cos(lat1) \times \cos(lat2) \times \cos(long1 - long2) \quad (4)$$

One can determine the PV system productivity from Equation 1 using the irradiation data associated with each campus, the characterization of contracted systems, and the minimum parameters required for the systems as established in the bidding process. In such analysis of technical viability, the annual energy generation (E) resulting from the installation of the GCPVSs in the campus could be determined from Equation 5 and the result is divided by the estimated power for the PV modules. It is possible to calculate E from the annual irradiation at the place of installation of GCPVS (H), the surface area of the modules (A), the efficiency of the modules (η), and the number of modules (N) (Villalva, 2015). This estimative was still multiplied by the maximum loss factor, considering the global losses established by the HEI depending on the losses inherent in the GCPVS (IFPI, 2018), which are mainly due to the PV modules and inverters (Teles et al., 2018). The same factor was still divided by the system power to estimate the total power of the PV modules (Macêdo and Zilles, 2007; Pérez-Higueras et al., 2018).

$$E = H \times A \times \eta \times N \quad (5)$$

As for the analysis of economic viability, the basic unit cost (BUC) was determined by dividing the system cost by the total power, as well as taking into account the capital inflow due to the energy produced by the GCPVS. Considering the average monthly energy costs of year 2019 for the installation site, one could estimate the potential annual cost reduction associated with electricity consumption, as well as the capital outflow due to the implementation, operation, and maintenance of the system. In addition, typical metrics used in economic engineering were adopted, such as the net present value (NPV) in Equation 6, so that the difference between the capital inflow and outflow (A_n) in each of the periods (n) is incorporated into the decision-making process of the project. This analysis also considers its respective useful life (t) and the discount rate (r); the internal rate of return (IRR), which is the discount rate that makes the NPV equal to zero; the payback when the NPV becomes positive; and the benefit-to-cost ratio (BCR), this being the ratio between the NPVs of capital inflows and outflows (Silva et al., 2019).

$$VPL = \sum_{n=1}^{t} \frac{A_n}{(1+r)^n} \quad (6)$$

The metrics were calculated considering the maximum annual degradation rate of the estimated generation and its minimum useful life, which results from the loss of system efficiency, in addition to maintenance and operation costs of 1% of the initial investment impacting the cash flow every 10 years (Nakabayashi, 2015). The discount rate is considered the difference between the average tariff adjustments of the local utility during the past 10 years and the estimated values for the Special System for Settlement and Custody (Selic) rate indicated as a reference by ANEEL (2018) (Figure 2).

Similarly, the irradiation data of all campuses were used to create rankings of generation potential, reduction of carbon dioxide emissions, and economic benefits, once again taking into account the energy tariffs for the year 2019. The hypothetical installation of PV systems in all campuses was considered in terms of the average values assumed by the parameters of other systems recently contracted by the HEI (Brasil, 2020a) and with the minimum efficiency defined for the systems (IFPI, 2018). The potential for reducing carbon dioxide emissions was determined only during the useful life of the project based on data from the Energy Research Company (EPE), which calculates this parameter annually as a function of the amount of energy generated in the country in kWh (Brasil, 2019a).

In addition to the aforementioned analysis involving absolute values, two scales were created for measuring the benefits related to energy consumption and electricity costs. Finally, just as for the systems already contracted, the economic analysis for this proposed expansion was carried out in six scenarios, as given in Table 1. The maximum, minimum, and average BUCs of the systems (excluding outliers) were considered according to the offers presented by the companies in the electronic price registration auction carried out by the HEI (IFPI, 2018), in addition to the best and the worst economic benefit according to the defined ranking.

Results and discussion

The Floriano Campus has a built area of 9,481.41 m² and is used by 80 professors, 62 members of the administrative staff, 39 outsourced workers, and a total of 1,300 students during the morning, afternoon, and night shifts. The GCPVS of this campus was the first mini-generation system installed in Piauí, with a rated power greater than 75 kW and less than 5 MW. It started operating in June 2016, with a monthly average generation of 21,333 kWh in the first year of operation, corresponding to 32.44% of the overall energy consumption, while avoiding the emission of 25.93 tons of CO_2 during the same period (Sá et al., 2017).

This system is composed of 660 polycrystalline PV modules rated at 260 Wp, model CS6P-260P by Canadian Solar. The inverters correspond to one model SIW500 ST010, one model SIW500 ST015, and five models SIW500 ST025 by SMA Sunny Tripower, which can process a peak power up to 150 kWp (Morais et al., 2019). The modules are mounted on a fixed metallic structure with an inclination of 15°,

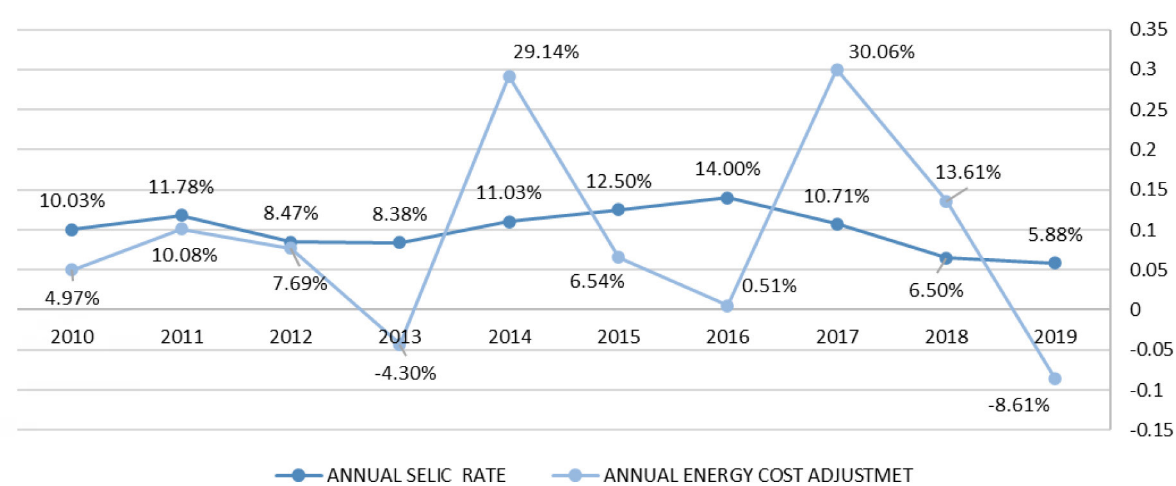


Figure 2 – Selic rate and tariff readjustment of the local energy utility from 2010 to 2019.
Source: Prepared by the authors using data obtained from Aneel (2020) and BCB (2020).

Table 1 – Scenarios for the economic analysis of the proposed expansion for the IFPI.

Scenarios	Initial investment	Economic benefits
1	Lowest BUC	Higher financial return
2	Average BUC	Higher financial return
3	Highest BUC	Higher financial return
4	Lowest BUC	Lower financial return
5	Average BUC	Lower financial return
6	Highest BUC	Lower financial return

Figure 3 – Detailed view of the GCPVS installed at IFPI's Floriano Campus.
Source: Morais et al. (2019).

oriented to the Northeast (azimuth deviation of 5°) on roofs 1, 2, 3, and 4N and to the Southwest (azimuth deviation of −175°) on roofs 4S and 5 (Figure 3).

The GCPVS has productivity, CF, and PR of 1,493.12 kWh/kWp, 17.04%, and 73.54%, respectively. It is reasonable to state that this is a technically viable project, especially considering that the aforementioned figures of merit assume higher values than those typically observed in other HEIs studied by Urbanetz Junior et al. (2014), Gomes et al. (2015), and Buiatti et al. (2016), mainly due to the high average daily irradiation levels of 5,641 kWh/m²/day. However, even with high strategic adherence, its economic viability is called into question considering the high initial investment (R$ 1,150,000.00) and high BUC (R$ 7.67/Wp), low financial return (cost-effectiveness ratio equal to 4.37), and high payback period (19 years after installation) (Morais et al., 2019).

This system motivated the creation of a subject entitled "renewable energy sources" in the Technical Course in Electromechanics, which is regularly offered by the institution. It also led to the implementation of the PV solar energy laboratory in the campus, as well as the development of a research project and three extension projects (Sá, 2019). In addition, two master's dissertations (Morais, 2018; Sá, 2019) and one doctoral thesis (Silva, 2020) focused on the system were presented by professors from the institution, who also published some scientific articles. In addition to technical, economic, and environmental benefits, the PV system installed in the Floriano Campus brought significant advances with regard to teaching, research, and extension activities.

One could find the closest reference points of each of the 17 campuses in the database of the second version of the Brazilian Solar Energy Atlas (Pereira et al., 2017), considering their geographic coordinates in Figure 1 and using Equation 4. The distances between them are estimated based on the mean Earth radius, also identifying the annual average of daily global irradiation at each campus, as shown in Figure 4. Thus, it seems that most cities with the greatest potential for the installation of PV systems are located in the southeast region of the state.

One could then determine new sites for the installation of GCPVSs: eight microgeneration units with an average power of 53 kWp and two mini-generation systems whose peak powers are 80 and 119 kWp, totaling 625 kWp with an average BUC of R$ 3.06/Wp (Table 2) (Brasil, 2020a). However, even though it was contracted at the same time as the other systems, it should be noted that the Teresina Central Campus (CATCE) was assigned to other company than the other systems, with an average BUC 34% higher.

Except for CATCE, whose contract has not yet been consolidated by the HEI, the remaining systems were contracted through the electronic price registration system in the "turnkey" modality, this being a model that provides the material, installation, and commissioning for carrying out the project. The contract also includes a training course for operating the system, a 1-year maintenance period, and the monitoring system. The system must also meet minimum performance indices, with a maximum loss factor of 23%, among which the following ones stand out for PV modules: minimum rated power (260 Wp), minimum power per area unit (155 Wp/m²), minimum efficiency (15.89%), minimum service life (25 years), and maximum level of power degradation during the warranty period (10%) (IFPI, 2018).

Considering the average solar irradiation (Pereira et al., 2017) at the closest reference points to each of the campuses in Figure 4, all the aforementioned parameters were used in the technical–economic analysis of the contracted systems. A maintenance and operation cost corresponding to 1% of the initial investment is included, whereas the process is carried out every 10 years (Morais et al., 2019) (Table 2). The new contracted systems should result in a profit of R$ 11,780,974.91 at the end of the useful life. They are also supposed to present technical–economic parameters superior to those of the system installed in 2016, with an estimated average productivity 15.63% higher and an average BUC 60.10% lower.

Table 2 – Technical–economic analysis of existing GCPVSs already installed and contracted by IFPI from November 20, 2019 to April 20, 2020.

Campus	Total Power (kWp)	BUC (R$/Wp)	Global Solar Irradiation (Wh/m²×day)	Estimated System Productivity (kWh/kWp)	NPV (R$)	*Payback* (years)	IRR (%)	BCR
CAFLO*	**150**	**7.67**	**5,641**	**1,506.21**	**263,172.06**	**19**	**1.91**	**4.37**
CASRN**	60	2.84	5,894	1,700.80	1,148,063.20	3	36.31	0.15
CAPAU**	51	2.89	5,856	2,195.11	1,287,112.73	3	46.59	0.11
CACOR**	65	2.82	5,768	1,663.55	1,213,591.72	3	35.72	0.15
CACAM**	60	3.16	5,702	1,644.51	1,084,755.89	4	31.31	0.17
CAPEDII**	80	3.07	5,686	1,639.90	1,449,184.33	3	32.21	0.17
CAVAL**	60	2.84	5,683	1,639.03	1,099,972.87	3	34.92	0.15
CAPIR**	57	3.18	5,666	1,644.82	1,023,442.03	4	31.09	0.18
CATCE**	18	3.98	5,572	2,088.16	424,984.34	4	31.56	0.17
CTZS**	119	2.99	5,527	1,613.35	2,130,621.18	3	32.52	0.17
CAURU**	55	2.88	5,467	1,586.54	919,246.62	4	31.88	0.17
TOTAL**	**625**	–	–	–	**11,780,974.91**	–	–	–
AVERAGE**	**62**	**3.06**	**5,682**	**1,741.58**	**1,178,097.49**	**3.40**	**34.41**	**0.16**

*Existing system; **contracted systems. Source: Prepared by the authors using data from IFPI (2018), Morais et al. (2019), and Brasil (2020a).

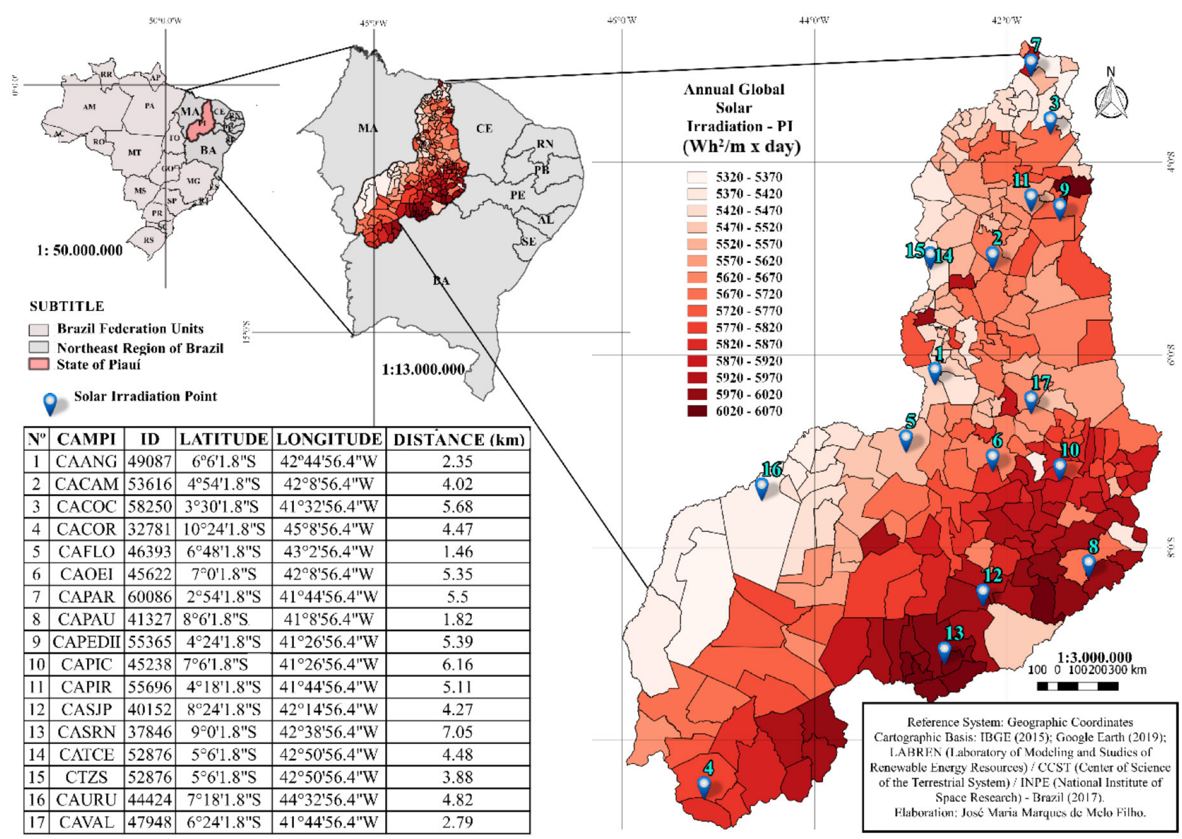


Figure 4 – Space distribution of the reference irradiation sites closest to the IFPI's campuses.
Source: Prepared by the authors based on IBGE (2015), Pereira et al. (2017), and Google Earth (2018).

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The energy supply contract of the campuses corresponds to the green tariff, which charges a single value for the contracted demand and distinct values for the consumed energy depending on the period of day. For the estimation of economic benefits, the GCPVSs are supposed to generate energy from the dawn until late afternoon. Therefore, the average cost of electricity during off-peak hours (from 9:30 p.m. to 5:29 p.m. of the next day) in the year 2019 was considered, resulting in an average of R$ 0.495571/kWh, that is, 49.59% higher than the cost initially considered for the existing system. In addition, a discount rate of 0.91 was adopted for the new systems (52.35% lower), resulting in a difference between the average of the past 10 years associated with annual adjustments in the electricity tariffs and the average of the latest annual projections of the Selic rate (Figure 2). A service life of 25 years, system degradation rate of 0.8% per year, and operation and maintenance costs of 1% of the initial investment every 10 years were considered in the analysis. Thus, the return on investments is likely to occur in a maximum of 4 years, with an average BCR of 0.16, corresponding to a reduction of 78.95 and 96.34% when compared with the existing system, respectively. The IRR in this case is 34.41%, i.e., 17.01 times greater.

It is reasonable to state that the contracted expansion is viable and should be actually installed. The project presents technical–economic conditions superior to those initially found in the year of installation of the first system in terms of higher productivity, lower BUC, more expensive energy tariffs, and lower interest rate. However, even with a difference of 2 years between the installation of the former GCPVS at the Floriano Campus and the contracting of new systems, it is noteworthy the high initial investment required for the installation of the first system, with a BUC 160% higher, that is, more than twice that of the new contracted units. It also leads to a difference of 34% involving the BUCs, which is not in compliance with the efficiency requirements established by the Sustainable Public Procurement regulated by the Brazilian government (Brasil, 2010).

Thus, to guide the expansion process of PV systems in multicampi HEIs and eliminate the temporal aspect of the analysis, also considering the identification of the closest reference point of each campus and the solar resource available in each site (Pereira et al., 2017), an expansion of the GCPVS was projected resulting from the existing systems in Table 3. The average values of the parameters associated with the systems recently contracted by the HEI were taken into account for the estimates (Table 2), as well as the minimum allowable efficiency (IFPI, 2018). This expansion is technically and economically feasible, with an estimated profit of R$ 19,025,567.73 after an expected service life of

Table 3 – Available solar resource and estimated energy generation, reduction of carbon dioxide emissions, and electricity costs after the installation of GCPVSs.

Campus	Global solar irradiation (Wh/m²×day)	Annual energy generation (kWh)	Reduction of CO_2 emissions (kg)	Energy generation ranking	Energy cost reduction (R$)	Benefit-cost Ranking
CASRN*	5,894	136,947.63	12,051.39	1	68,127.98	1
CAPAU*	5,856	136,064.70	11,973.69	2	67,688.74	2
CASJP	5,850	135,925.28	11,961.43	3	67,616.74	3
CAPIC	5,804	134,856.47	11,867.37	4	67,110.88	4
CAOEI	5,777	134,229.12	11,812.16	5	66,770.29	5
CACOR*	5,768	134,020.01	11,793.76	6	66,668.94	6
CACAM*	5,702	132,486.49	11,658.81	7	65,903.44	7
CAPEDII*	5,686	132,114.73	11,626.10	8	65,723.73	8
CAVAL*	5,683	132,045.02	11,619.96	9	65,683.84	9
CAPIR*	5,666	131,650.03	11,585.20	10	65,492.55	10
CAFLO**	5,641	131,069.15	11,534.09	11	65,226.14	11
CAANG	5,607	130,279.16	11,464.57	12	62,743.93	16
CAPAR	5,577	129,582.10	11,403.23	13	64,486.11	12
CATCE*	5,572	129,465.93	11,393.00	14	64,428.30	13
CTZS*	5,572	129,465.93	11,393.00	15	64,428.30	14
CACOC	5,570	129,419.46	11,388.91	16	64,382.90	15
CAURU*	5,467	127,026.24	11,178.31	17	68,127.98	17

*Contracted system; **existing system. Source: Prepared by the authors using data from Pereira et al. (2017) and Brasil (2019a).

25 years and an initial investment of R$ 3,229,332.35, corresponding to a BCR and an IRR of 0.17 and 32.13%, respectively. It is also verified that the payback occurs 4 years after the installation.

The proposed expansion allows obtaining an average generation of 132,155.73 kWh. This amount is higher than all the energy consumed individually by any of the 17 campuses and represents 32.49% of the overall consumption. In addition, one can avoid the emission of an average of 11.63 tons of CO_2, bringing environmental benefits and enabling the creation of a ranking of technical and environmental benefits. From the energy costs for the year 2019, an average annual benefit of R$65,483.88 could be estimated. However, since there is no uniform distribution of the solar resource in the state (Figure 4) and also that the cost of electricity may not be the same in every campus, these aspects also impact the performance of the systems in absolute terms, generating a new ranking of economic benefits.

The São Raimundo Nonato and Uruçuí Campuses presented the best and worst results, respectively. The Floriano Campus, which has a GCPVS already installed, is only in 11th position in the rankings for technical, economic, and environmental benefits. Regarding the contracted systems, it is observed that the campus with the best technical, economic, and environmental benefits (São Raimundo Nonato Campus) would be the on the top list of priorities, whereas the one with the worst indices (Uruçuí Campus) would be the last option. The Teresina Zona Sul Campus, which has the largest contracted system (120 kWp), would be only in the 14th place in terms of the economic benefits and in the 15th place with respect to technical and environmental benefits. Therefore, it is clear that the choice for the installation of systems was not based on a priority order.

The percent energy generation estimated for each campus in relation to the total consumption, as well as the percent economic benefits of the proposed systems with respect to the total energy tariff, were determined and ordered according to the first indicator in Figure 5. The average values of benefits related to consumption and electricity costs are 42.55 and 23.60%, respectively, thus creating two rankings of benefits. It is possible to observe a different ranking from the one found previously when considering only the solar resource. Even when considering the energy cost, the benefit can be seen differently in absolute or relative terms.

Finally, it is possible to obtain the metrics for the economic analysis of six scenarios provided in Table 1. The highest and lowest economic benefits were estimated for the São Raimundo Nonato and Uruçuí Campuses (R$ 68,127.98 and R$ 60,743.11 per year, respectively). To determine the BUC, 32 proposals from different companies that were presented to two groups of cities in the state were analyzed: four cities in the north region (Teresina, Campo Maior, Pedro II, and Piripiri) and six cities in the south region (Uruçuí, Corrente, Paulistana, São Raimundo Nonato, and Valença do Piauí), totaling 58 proposals after the exclusion of six outliers. The highest, lowest, and average BUCs are R$ 5.32, R$3.48, and R$ 4.35 per watt-peak, respectively.

From the relationship between the NPVs of capital inflows and outflows in all analyzed scenarios, one can state that the expansion is economically viable. This is due to the fact that all scenarios are located above the line that represents the financial balance, where the NPV is the same for the capital inflows and outflows (Figure 6). However, the initial investment required for the installation of the system and the return on investment varied by 52.87 and 23.05% between the best and worst cases of the analyzed scenarios (scenarios 1 and 6 in Table 4, re-

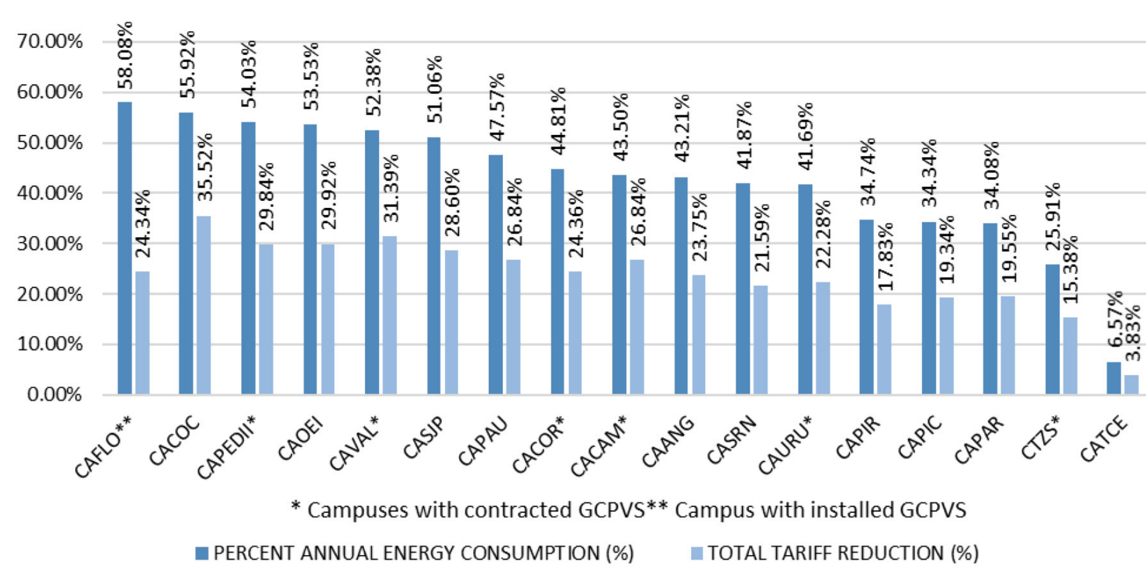

Figure 5 – Benefits related to electricity consumption and cost.

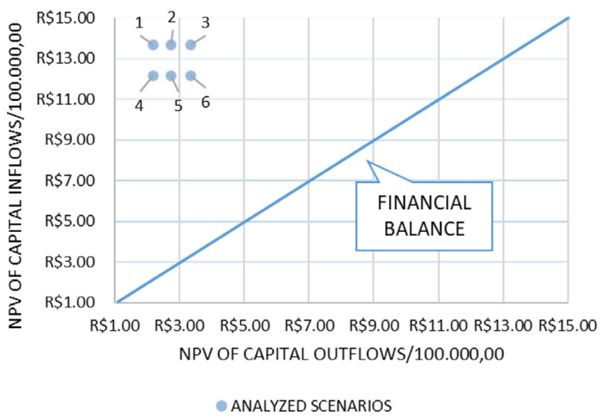

Figure 6 – Relationship between the NPVs associated with the capital inflows and outflows in the analyzed scenarios.

Table 4 – Best- and worst-case scenarios for the economic analysis of the proposed expansion.

	Scenario #1	Scenario #6
Power (kWp)	73.33	73.33
Initial investment (R$)	216,333.33	390,133.33
Annual energy savings (R$)	62,256.44	55,508.04
Discount rate (%)	0.91	0.91
Service life	25	25
NPV (R$)	1,027,632.87	715,542.70
BCR	0.21	0.55
Payback (years)	4	8
IRR (%)	26.49	11.62

spectively), causing a negative impact on the economic efficiency of the projects.

From one scenario to the other, the payback time increased by 50% and the BCR increased by 98.66%, decreasing the IRR by 45.17%. Thus, considering the economy of scale when contracting new systems, the lowest BUC should be chosen so as to achieve metrics similar to those found in scenario 1 (Table 1), since the natural tendency is that the higher the system power, the lower the BUC (Brito and Melo, 2018).

Conclusion

This work has presented a thorough analysis of a GCPVS installed at the Floriano Campus of the IFPI, as well as the expansion contracted by the institution in 2020. The first system was found to be the first mini-generation system installed in the state of Piauí, while presenting technical feasibility, good merit indices, and solid strategic adherence. It also represents a significant project that meets the expectations of the institution associated with education, research, and extension activities.

However, the economic feasibility of the system must be carefully analyzed. Even with a positive NPV, the project has a high payback time and a high BCR due to the high initial investment. The study demonstrated that contracted expansion is feasible and should be encouraged, with technical–economic conditions superior to those initially found in the year of installation of the first PV system. In other words, the new systems present prominent characteristics in terms of higher productivity, lower BUC, a more expensive energy tariff, and lower interest rate.

It was possible to use a solar atlas to verify the feasibility of expanding the PV systems in a multicampi HEI. Thus, one could identify the cities in the state of Piauí with the highest generation potential, which are located in the southeast region. The study has also confirmed the technical–economic feasibility and the great strategic adherence, in addition to the possible benefits associated with the reduction of energy costs, implementation of sustainable environmental practices, and support to the core activity of the institution, especially in the aforementioned region.

The methodology is quite effective in identifying investment priorities in PV solar energy, also enabling the creation of rankings of benefits that consider the energy generation and cost reduction in absolute and relative values, reduction in CO_2 emissions, as well as economic metrics. However, even with the possibility of creating rankings, such technical criteria may not be sufficient, since they are not decisive in defining a solid criterion for the HEI under study. Thus, it was not possible to choose exactly in which campus the GCPVS should be installed first, this being the scope of future work.

From the perspective of sustainable public procurement, one should also ensure equality, efficiency in public spending, and the promotion of sustainable development to analyze the bidding processes associated with the PV systems. The reasons for the differences in implementation costs and the choice of installation sites with lower technical, economic, and environmental returns should be understood in order to determine alternatives aiming at the better cost-effectiveness of future systems. This is especially important considering the economy of scale, since the larger the system, the lower the BUC. No ranking is definitive and there is no default size for the GCPVS to be installed. The best option for the manager is to analyze all scenarios and determine the best option.

Based on the present study, it is possible to recommend the installation of small systems (microgeneration) in the campuses that provide less technical and economic benefits for promoting the environmental education. Such actions should encourage the creation of a sustainable educational space and bring benefits to teaching, research, and extension activities. The largest investments should primarily focus on campuses where the greatest technical, economic, and environmental benefits exist. Finally, it is expected that this methodology can be applied in other multicampi HEIs and guide the implementation and expansion of PV systems, bringing environmental benefits and contributing to the achievement of SDGs.

Contribution of authors:

Silva, O. A. V. O. L.: Formal analysis, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. Moita Neto, J. M.: Funding acquisition, Project administration. Lira, M. A. T.: Supervision, Validation, Visualization, Writing – review & editing. Morais, F. H. M.: Conceptualization, Data curation, Investigation.

References

Agência Nacional de Energia Elétrica – ANEEL. 2015. Resolução normativa nº 678, de 1º de setembro de 2015. v. 177. Brasília (Accessed December 4, 2020) at: https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/32853619/do1-2015-09-16-resolucao-normativa-n-678-de-1-de-setembro-de-2015-32853615.

Agência Nacional de Energia Elétrica – ANEEL. 2018. Procedimentos do programa de eficiência energética – PROPEE. Agência Nacional de Energia Elétrica, Brasília (Accessed December 4, 2020) at: https://www.cpfl.com.br/energias-sustentaveis/eficiencia-energetica/chamada-publica/SiteAssets/Paginas/chamada-publica/Procedimentos%20do%20Programa%20de%20Efici%C3%AAncia%20Energ%C3%A9tica%20-%20PROPEE.pdf.

Agência Nacional de Energia Elétrica – ANEEL. 2020. Resultado dos processos tarifários de distribuição. ANEEL (Accessed December 4, 2020) at: https://www.aneel.gov.br/resultado-dos-processos-tarifarios-de-distribuicao.

Azizkhani, M.; Vakili, A.; Noorollahi, Y.; Naseri, F., 2016. Potential survey of photovoltaic power plants using analytical hierarchy process (AHP) method in Iran. Renewable and Sustainable Energy Reviews, v. 75, 1198-1206. https://doi.org/10.1016/j.rser.2016.11.103.

Banco Central do Brasil. 2020. Taxas de Juros Básicas – Histórico (Accessed December 4, 2020) at: https://www.bcb.gov.br/controleinflacao/historicotaxasjuros.

Bezerra, J.L.; Lira, M. A. T.; Silva, E. A. da, 2018. Avaliação do ciclo de vida aplicada a painéis fotovoltaicos. In: Congresso Brasileiro de Energia Solar, 7. Proceedings.

Brasil. Empresa de Pesquisa Energética. 2019a. Brazilian Energy Balance. EPE, Rio de Janeiro (Accessed December 4, 2020) at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-377/topico-494/BEN 2019 Completo WEB.pdf.

Brasil. Empresa de Pesquisa Energética. 2019b. Plano decenal de expansão de energia 2029. EPE, Rio de Janeiro (Accessed December 4, 2020) at: https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/Documents/PDE 2029.pdf.

Brasil. Controladoria-Geral da União. 2020a. Detalhamento do contrato. Portal da transparência. Controladoria Geral da União, Brasil (Accessed December 4, 2020) at: http://www.portaltransparencia.gov.br/contratos/consulta?de=01%2F01%2F2020&ate=31%2F12%2F2020&ordenarPor=-dataFimVigencia&direcao=desc.

Brasil. Controladoria-Geral da União. 2020b. Fala.BR - plataforma integrada de ouvidoria e acesso à informação. Controladoria Geral da União, Brasil (Accessed December 6, 2020) at: https://esic.cgu.gov.br/falabr.html.

Brasil. Governo Federal. 2010. Lei nº 12.349, de 15 de dezembro de 2010. Brasília (Accessed December 4, 2020) at: http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12349.htm.

Brasil. Ministério da Educação e Cultura. 2019c. MEC libera R$ 60 milhões para instalação de usinas fotovoltaicas em instituições federais de educação tecnológica – MEC (Accessed December 4, 2020) at: https://www.gov.br/pt-br/noticias/educacao-e-pesquisa/2020/01/mec-libera-r-60-milhoes-para-instalacao-de-usinas-fotovoltaicas-em-institutos-federais-do-pais#:~:text=Economia-,MEC%20libera%20R%24%2060%20milh%C3%B5es%20para%20instala%C3%A7%C3%A3o%20de%20usinas,em%20Institutos%20Federais%20do%20Pa%C3%ADs&text=O%20Minist%C3%A9rio%20da%20Educa%C3%A7%C3%A3o%20(MEC,a%20economia%20nos%20gastos%20p%C3%BAblicos.

Brito, B.H.; Melo, M.L.F.G. de, 2018. análise financeira de sistemas de microgeração fotovoltaica financiados em Palmas - TO. In: Congresso Brasileiro de Energia Solar, 7., Gramado (Accessed December 4, 2020) at: https://anaiscbens.emnuvens.com.br/cbens/article/view/539/539.

Buiatti, G.M., Silva Junior, F.R. da; Wanderley, A.C.F.; Maciel, S.B., 2016. Desempenho de micro e mini usinas fotovoltaicas no Instituto Federal no Rio Grande do Norte. Belo Horizonte.

Camargos, R.S.C., Shayani, R.A.; Oliveira, M.A.G. de, 2016. Método para análise comparativa dos impactos técnicos da geração distribuída fotovoltaica concentrada e pulverizada. Revista Brasileira de Energia Solar, v. 7, (2), 115-122. https://doi.org/10.20906/cps/sbse2016-0069.

Carneiro, J.M., Dias, A.F.; Barros, V. da S.; Giongo, V.; Matsuura, M.I. da S.F.; Figueirêdo, M.C.B. de, 2019. Carbon and water footprints of Brazilian mango produced in the semiarid region. International Journal of Life Cycle Assessment, 24, (4), p. 735-752. https://doi.org/10.1007/s11367-018-1527-8.

Dávi, G.A.; Caamaño-Martín, E.; Rüther, R.; Solano, J., 2016. Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil. Energy and Buildings, v. 120, 19-29. https://doi.org/10.1016/j.enbuild.2016.03.058.

Deschamps, E.M., Rüther, R., 2019. Optimization of inverter loading ratio for grid connected photovoltaic systems. Solar Energy, 179, 106-118. https://doi.org/10.1016/j.solener.2018.12.051.

Ebrahimi, M.; Aramesh, M.; Khanjari, Y., 2018. Innovative ANP model to prioritization of pv/t systems based on cost and efficiency approaches: with a case study for Asia. Renewable Energy, v. 117, 434-446. https://doi.org/10.1016/j.renene.2017.10.098.

Ferreira, A.; Kunh, S.S.; Fagnani, K.C.; Souza, T.A. de; Tonezer, C.; Santos, G.R. dos; Coimbra-Araújo, C.H., 2018. Economic overview of the use and production of photovoltaic solar energy in Brazil." Renewable and Sustainable Energy Reviews, v. 81, (part 1), 181-191. https://doi.org/10.1016/j.rser.2017.06.102.

Goel, S.; Sharma, R. 2017. Performance evaluation of stand alone, grid connected and hybrid renewable energy systems for rural application: a comparative review. Renewable and Sustainable Energy Reviews, v. 78, 1378-1389. https://doi.org/10.1016/j.rser.2017.05.200.

Gomes, H.S.; Godoi, R.R. de; Melo, F.C.; Freitas, L.C.G., 2015. Sistemas fotovoltaicos distribuídos: estudo de caso de UFV de 2,16 KWp instalada no núcleo de pesquisa em eletrônica de potência. In: Conferência Brasileira de Qualidade de Energia Elétrica, 11., Campina Grande.

Google Earth. 2018. Google Earth. (Accessed September 13, 2018) at: https://www.google.com/earth/.

Instituto Brasileiro de Geografia e Estatística – IBGE. 2015. Índice de organização - malhas territoriais (Accessed November 10, 2019) at: ftp://geoftp.ibge.gov.br/organizacao_do_territorio/malhas_territoriais/malhas_municipais/municipio_2015/UFs/PI/.

International Electrotechnical Commission – IEC. 1998. Photovoltaic IEC standard 61724: system performance monitoring - guidelines for measurement, data exchange, and analysis. IEC, Geneva.

International Energy Agency – IEA. 2019. IEA PVPS report - trends in photovoltaic applications 2019. IEA, Onehemisphere (Accessed December 4, 2020) at: www.iea-pvps.org.

Instituto Federal de Educação, Ciência e Tecnologia do Piauí – IFPI. 2018. Pregão eletrônico nº 06/2018 – sistema de registro de preços. IFPI, Teresina.

Instituto Federal de Educação, Ciência e Tecnologia do Piauí – IFPI. 2020. Plano de desenvolvimento institucional 2020-2024 – construindo para o futuro. IFPI, Teresina.

Khan, J.; Arsalan, M.H., 2016. Solar power technologies for sustainable electricity generation – a review. Renewable and Sustainable Energy Reviews, v. 55, 414-425. https://doi.org/10.1016/j.rser.2015.10.135.

Macêdo, W.N.; Zilles, R. 2007. Operational results of grid-connected photovoltaic system with different inverter's sizing factors (ISF). Progress in Photovoltaics: Research and Applications, v. 15, (4), 337-352. https://doi.org/10.1002/pip.740.

Morais, F.H.M. de., 2018. Desempenho operacional de sistemas fotovoltaicos instalados em instituições de ensino multicampi. Master's Dissertation, Universidade Federal do Piauí, Teresina.

Morais, F.H.M. de; Moraes, A.M. de; Barbosa, F.R., 2019. technical-economic analysis of the first mini-generation photovoltaic system of Piauí, Brazil. IEEE Latin America Transactions, v. 17, (10), 1706-1714. https://doi.org/10.1109/TLA.2019.8986449.

Morais, F.H.M. de; Silva, O.A.V. de O.L.; Barbosa, F. da R.; Moraes, A.M. de, 2017. Avaliação estudo de viabilidade do sistema fotovoltaico de 36,48 KWp instalado na Universidade Federal do Piauí. In: Seminário de Pesquisa em Energia Solar, 2., Teresina.

Nakabayashi, R. 2015. Microgeração fotovoltaica no Brasil: viabilidade econômica. USP, São Paulo (Accessed December 5, 2020) at: http://200.144.182.130/iee/lsf/sites/default/files/Dissertacao_Rennyo_vfinal.pdf.

Nez, E. de, 2016. Os dilemas da gestão de universidades multicampi no Brasil. Revista Gestão Universitária na América Latina, v. 9, (2), 131-153. https://doi.org/10.5007/1983-4535.2016v9n2p131.

Paim, M.; Dalmarco, A.R.; Yang, C.; Salas, P.; Lindner, S.; Mercure, J.; Guerra, J.B.S.O. de; Derani, A.C.; Silva, T.B. da; Viñuales, J.E., 2019. Evaluating regulatory strategies for mitigating hydrological risk in brazil through diversification of its electricity mix. Energy Policy, v. 128, 393-401. https://doi.org/10.1016/j.enpol.2018.12.064.

Pereira, E.B.; Martins, F.R.; Gonçalves, A.R.; Costa, R.S.; Lima, F.J.L. de; Rüther, R.; Abreu, S.L. de; Tiepolo, G.M.T.; Pereira, S.V.; Souza, J.G. de, 2017. Atlas Brasileiro de Energia Solar. 2ª ed. v. 2. INPE, São José dos Campos. http://doi.org/10.34024/978851700089.

Pérez-Higueras, P.J.; Almonacid, F.M.; Rodrigo, P.M.; Fernández, E.F., 2018. Optimum sizing of the inverter for maximizing the energy yield in state-of-the-art high-concentrator photovoltaic systems. Solar Energy, v. 171, 728-739. https://doi.org/10.1016/j.solener.2018.07.013.

Sá, F.N., 2019. Análise Interdisciplinar do sistema de energia solar fotovoltaica do Instituto Federal do Piauí – Campus Floriano. Master's Dissertation, Universidade Federal do Piauí, Teresina.

Sá, F.N.; Santos, F.F.P. dos; Moraes, A.M. de; Lopes, O.S., 2017. Análise ambiental e econômica do primeiro ano de operação do sistema fotovoltaico de uma instituição federal de ensino no Brasil. In: Reunión Asades - Asociación Argentina de Energías Renovables y Ambiente, 40., San Juan.

Sagbansua, L.; Balo, F., 2016. A multi-criterion analysis for choosing photovoltaic panel. IJARS International Journal of Engineering, v. 2, (4). https://doi.org/10.20908/ijarsije.v2i4.6659.

Santos, R. A.; Oliveira, J. de, 2018. Trigonometria triangular esférica. Revista de Ciência e Tecnologia, v. 4 (6).

Senna, A.J.T.; Alves, R.R.; Santos, N.R.Z. dos; Costa, F.L., 2014. Determinação do índice de risco ambiental das instalações de uma unidade de uma instituição federal multicampi de ensino superior. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental, v. 18, (1), 555-565. https://doi.org/10.5902/2236117012651.

Silva, L.R. de J.R.; Shayani, R.A.; Oliveira, M.A.G. de, 2018. Análise comparativa das fontes de energias solar fotovoltaica, hidrelétrica e termelétrica com levantamento de custos ambientais, aplicada ao Distrito Federal. In: Congresso Brasileiro de Energia Solar, 7., Gramado.

Silva, O.A.V. de O.L. da, 2020. Etiquetagem do uso de eletricidade para a conformidade da gestão energética em instituições de ensino superior multicampi. Doctoral Thesis, Universidade Federal do Piauí, Teresina.

Silva, O.A.V. de O.L. da; Moita Neto, J.M.; Lira, M.A.T., 2018. Análise envoltória de dados para a gestão energética em instituições de ensino superior multicampi. Revista Brasileira de Ciências Ambientais (Online), (50), 78-96. https://doi.org/10.5327/z2176-947820180401.

Silva, O.A.V. de O.L. da; Moita Neto, J.M.; Lira, M.A.T., 2021. An analysis of energy efficiency in multicampi higher education institutions and a novel environmental labeling proposal. Revista Brasileira de Ciências Ambientais (Online), v. 56, (1), 76-90. https://doi.org/10.5327/z2176-947820200722.

Silva, O.A.V. de O.L. da; Morais, F.H.M. de; Leite, C. de S.; Cardoso, J.R.A.; Sousa, W.V.C., 2017. Use of energy bills for energy management in multicamp universities. Revista Espacios, v. 38, (12), 20-35 (Accessed December 5, 2020) at: https://www.revistaespacios.com/a17v38n12/a17v38n12p20.pdf.

Silva, O.A.V. de O.L. da; Santos, F.F.P. dos; Barbosa, F. da R., 2019. Viabilidade técnico-econômica da eficiência energética em edificações. Appris, Curitiba.

Silva, O.A.V. de O.L. da; Santos, F.F.P. dos; Barbosa, F. da R.; Leite, C. de S., 2016. Gestão do uso da energia elétrica baseada em protocolo internacional: uma proposta para UFPI, Brasil. Revista Espacios, v. 37, (11), 26.

Sommerfeldt, N.; Madani, H., 2016. Revisiting the techno-economic analysis process for building-mounted, grid-connected solar photovoltaic systems: part one-review. Renewable and Sustainable Energy Reviews, v. 74, 1379-1393. https://doi.org/10.1016/j.rser.2016.11.232.

Teles, M.B.; Rodrigues, M. de J. dos S.; Monteiro, W.L.; Costa, A.F.P.; Pinho, J.T.; Macêdo, W.N., 2018. Avaliação operacional de um sistema fotovoltaico conectado à rede com conversores C.C.-C.C. In: Congresso Brasileiro de Energia Solar, 7., Gramado (Accessed December 5, 2020) at: https://anaiscbens.emnuvens.com.br/cbens/article/view/95/95.

United Nations – UN. 2015a. Plataforma Agenda 2030 (Accessed December 5, 2020) at: http://www.agenda2030.com.br/.

United Nations – UN. 2015b. Transforming our world: the 2030 agenda for sustainable development. ONU, New York.

Urbanetz Junior, J.; Fassi, E.; Junior, C.; Tiepolo, G.M., 2014. Acompanhamento do desempenho do sistema fotovoltaico conectado à rede elétrica do escritório verde da UTFPR. In: Congresso Brasileiro de Planejamento Energética, 9., Florianópolis.

Vale, A.M.; Felix, D.G.; Fortes, M.Z.; Borba, B.S.M.C.; Dias, B.H.; Santelli, B.S., 2017. Analysis of the economic viability of a photovoltaic generation project applied to the Brazilian housing program "Minha Casa Minha Vida". Energy Policy, v. 108, 292-298. https://doi.org/10.1016/j.enpol.2017.06.001.

Villalva, M.G. 2015. Energia solar fotovoltaica: conceitos e aplicações. Érica, São Paulo.

Villela, J.N.; Rapozo, F. de O.; Domingos, M. de L. C.; Quelhas, O.L.G., 2017. Energia em tempo de descarbonização: uma revisão com foco em consumidores fotovoltaicos. Revista Brasileira de Ciências Ambientais (Online), (45), 130-144. https://doi.org/10.5327/z2176-947820170264.

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Effect of a temperature rise on metal toxicity for the aquatic biota: a systematic review

Efeito da elevação da temperatura sobre a toxicidade de metais para a biota aquática: uma revisão sistemática

Carla Juliana Nin[1], *Suzelei Rodgher*[1]

ABSTRACT

Ecosystems are subject to various stress factors, such as temperature rises due to climate changes and metal disposal. Thermal stress can amplify or mask the effects of metals on aquatic organisms. This study aims to carry out a systematic review on the effects of temperature rises due to climate changes on the toxicity of metals for freshwater organisms. Searches were made in different electronic databases and article selection was based on the following inclusion criteria: concordance with the question of a systematic review; publication in English, Spanish, and Portuguese between 1960 and 2020; and the use of standard methodology. Forty-three articles were included, which were classified with respect to the year and country of publication, test-organisms and metals studied, temperatures tested, and the effects observed. In 80% of the studies analyzed, a temperature rise was responsible for increasing the toxicity of metals for the aquatic organisms. The temperatures studied contemplated the temperature rise predicted by the Intergovernmental Panel for Climate Change at the end of the 21st century. Brazil stood out among the countries for having the greatest number of research studies in this area, although there is still the need for an increase in studies in tropical climate regions. Based on the literature review, it was shown that the metals most studied were copper and cadmium and the test-organisms most used in the research projects were fish. The information obtained from ecotoxicological studies is essential to predict the effects and prevent the risks associated with the metal contamination of aquatic ecosystems due to climate changes.

Keywords: ecotoxicology; climate changes; microalgae; zooplankton; fish.

RESUMO

Ecossistemas estão sujeitos a diversos estressores, como o aumento da temperatura em razão das mudanças climáticas e do lançamento de metais. O estresse térmico pode amplificar ou mascarar os efeitos dos metais nos organismos aquáticos. Este estudo teve como objetivo realizar uma revisão sistemática dos efeitos do aumento da temperatura, associado às mudanças climáticas, na toxicidade dos metais para organismos de água doce. Foram realizadas buscas em diferentes bases de dados eletrônicas, e a seleção dos artigos teve como critérios de inclusão: concordância com a questão da revisão sistemática, publicação em inglês, espanhol e em português entre 1960 e 2020 e emprego de metodologias padronizadas. Incluíram-se 43 artigos, que foram classificados com relação ao ano e país de publicação, organismos-teste e metais estudados, temperaturas testadas e efeitos observados. Em 80% dos estudos analisados, o aumento da temperatura foi responsável por elevar a toxicidade dos metais para os organismos aquáticos. As temperaturas estudadas contemplam o aumento previsto pelo Painel Intergovernamental de Mudanças Climáticas no fim do século 21. O Brasil destaca-se entre os países com maior número de pesquisas nesta área, embora seja necessário o aumento dos estudos em regiões de clima tropical. Com base na revisão bibliográfica, constatou-se que os metais mais estudados foram o cobre e o cádmio, e os organismos-teste mais utilizados nas pesquisas foram os peixes. As informações obtidas com estudos ecotoxicológicos são essenciais para a previsão dos efeitos e a prevenção dos riscos associados à contaminação por metais dos ecossistemas aquáticos mediante as mudanças climáticas.

Palavras-chave: ecotoxicologia; mudanças climáticas; microalgas; zooplâncton; peixes.

[1]Institute of Science and Technology, Universidade Estadual Paulista "Júlio de Mesquita Filho" – São José dos Campos (SP), Brazil.

Correspondence address: Suzelei Rodgher – Rodovia Presidente Dutra, km 137,8 – Eugênio de Melo – CEP: 12247-004 – São José dos Campos (SP), Brazil. E-mail: suzelei.rodgher@unesp.br

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Introduction

One important variable to be considered in aquatic ecosystems is the temperature, due to its importance in maintaining the species and the metabolism of the aquatic systems (Esteves, 2011). Climate change, deforestation of the riparian forest, the construction of reservoirs, canalization of aquatic bodies, and the disposal of hot water used in the refrigeration processes of refineries, steel mills, and thermoelectric plants are related to the temperature rise of aquatic systems (Qiu, 2012; Raptis et al., 2016).

The aquatic ecosystem biota is especially vulnerable to temperature variations since most of the species are ectothermic, that is, their body temperatures change with alterations in the environmental temperature (Hochachka and Somero, 2002) and temperature rises are associated with alterations in the distribution and a decline in the diversity of phytoplankton (Lenard et al., 2019), zooplankton (Adamczuk, 2016), and fish (Herrera-R et al., 2020) in freshwater systems.

Temperature rises and the entrance of pollutants are considered stressors that affect the occurrence of species in the ecosystems (Noyes and Lema, 2015; Gill et al., 2020). According to the fifth report of the Intergovernmental Panel for Climate Change (IPCC, 2014), the temperature rise could remain below 2°C in 2100 in a scenario of low greenhouse gas release, with the highest predicted increase being above 2°C in 2037 and more than 4.8°C in 2100 in a scenario of elevated gas emission. Freshwater ecosystems are particularly more sensitive to climate change due to the temperature rise and changes in the precipitation patterns and water flow (Da Silva et al., 2020).

An understanding of the consequences of releasing and dispersing pollutants in aquatic ecosystems is one of the challenges of aquatic ecotoxicology. Aquatic ecotoxicology is the study of the effects of toxic chemical substances on representative organisms of aquatic ecosystems (Hoffman et al., 2003). Aquatic organisms belonging to different trophic levels are used to evaluate the potential toxicity of environmental samples, effluents, and chemical substances. Toxicity tests should be carried out with species belonging to different trophic levels to cover the natural variability in sensitivity among the species (Zagatto and Bertoletti, 2006).

The diverse contaminants released into aquatic ecosystems metals are of special concern due to their persistence, bioaccumulation, and toxicity, demanding particular attention from the human and environmental health points of view (Ali et al., 2019). In aquatic ecosystems, metallic ions come from natural sources such as the weathering of rocks and soils, volcanic eruptions, and anthropogenic sources such as untreated industrial and domestic effluents, mining residues, the application of agricultural pesticides to crops, and rainfall in places with atmospheric pollution (Esteves, 2011; Amoatey and Baawain, 2019).

The aquatic biota is subject to a combination of stress agents. In this context, some studies have revealed that a temperature rise can increase the toxicity of some metals in freshwater organisms. In a study concerning the effects of high temperatures and exposure to copper on the microalgae *Scenedesmus quadricauda*, Yong et al. (2018) determined that the combination of these factors caused significant disturbances in the metabolism of the microalgae. Bae et al. (2016) also showed that a temperature rise of the water was responsible for increasing the toxicity of copper for the microcrustacean *Daphnia magna*. The same tendency was observed by Park et al. (2020) for the fish species *Danio rerio*, in a study aimed at determining any physiological damage in fish exposed to the metal lead and to high temperatures. According to Val et al. (2016), the interactions between metals, temperature, and organisms are too complex to predict the effects on the aquatic biota, since a temperature rise also stimulates detoxification processes and the excretion of certain metals by the individuals, reducing the toxicity of the metal ions.

Various reviews concerning different aspects of temperature rises in freshwater ecosystems due to climate change and thermal pollution (release of hot effluents from thermoelectric and hydroelectric factories) and their effects on hydrology, biogeochemistry (Xu et al., 2019; Copetti and Salerno, 2020), biological diversity (Madden et al., 2013; O'Briain, 2019), and the risks associated with human diseases (Ahmed et al., 2020) have been reported in the literature. Within this context, one of the important effects, as yet little studied, is the change in action of metals with a temperature rise, on aquatic organisms belonging to the different trophic levels. Metals are one of the stressors that affect aquatic ecosystems, and as the climate changes occur, it becomes necessary to understand the combined effect of the thermal and chemical stresses on the biota of these environments (Radinger et al., 2016). There are no studies that compare and discuss the combined effect of temperature rise and the presence of metals for representative species of freshwater ecosystems. From this perspective, systematic reviews make it possible to reunite and discuss the scientific evidence concerning the combined action of physical (temperature) and chemical (metal) stressors on the aquatic biota.

Based on the above, the goal of this study was to carry out a systematic review of the effects of a temperature rise on the toxicity of metals for freshwater organisms. The hypothesis presented was that a rise in temperature influences the toxicity of metals for aquatic organisms. In addition, some gaps in the literature were highlighted and recommendations made concerning new directions for future studies. Papers discussing studies concerning this theme are certainly important for students, professors, and researchers in environmental sciences.

Methodology

The steps of a systematic review contemplate the limits of the question (question formulated containing the description of the theme), search for evidence (identify the databases to be examined), review and selection of papers, and the checking of the methodological quality of the research and description of the results (Sampaio and Mancini, 2007). In this present survey, the guiding question was, What is the effect of a temperature rise on metal toxicity for the aquatic biota? Scientific articles available in the databases Scielo, Science Direct, Web of

Science, and the Google Academic search system were used, as well as a search among the references of the selected articles. Articles published in English, Spanish, and Portuguese between 1960 and 2020 were analyzed. This period was chosen because the standardization of ecotoxicological research methodologies dates from the sixties (Zagatto and Bertoletti, 2006).

The following descriptors were used: "systematic review AND toxicity AND temperature," "toxicity AND algae AND temperature," "toxicity AND zooplankton AND temperature," "toxicity AND fish AND temperature," and "toxicity AND climate change AND metal." For the search according to the metals, the following descriptors were used: "toxicity AND metal AND temperature," and this structure was used for the search for the remaining metals of the periodic table.

During the selection of the studies, the articles were evaluated independently by two researchers, one being an undergraduate student in environmental engineering and the other a researcher in the same area, following the inclusion and exclusion criteria. An analysis of the titles and abstracts identified in the initial search was carried out. When the title and abstract were not explicative, the entire articles were analyzed. Divergencies were discussed. The inclusion and exclusion criteria were according to Martins and Carmo Junior (2018) and include:

- The question guiding the review (in agreement with the review question) and studies considering the effect of the exposure of freshwater organisms to metals at different temperatures were included. Studies concerning saltwater and land organisms were excluded as well as those that did not analyze the metal toxicity and articles already reviewed that were reselected during the search;
- Search period defined (60 years);
- Use of standardized methods and methodological criteria (described in articles, books, protocols, and research norms in the ecotoxicology area) according to standardization agencies such as American Society for Testing and Materials (ASTM), *Associação Brasileira de Normas Técnicas* (ABNT), Environment Canada, Organisation for Economic Co-operation and Development (OECD), International Organization for Standardization (ISO), Standard Methods (APHA), and the U.S. Environment Protection Agency (USEPA).

For the data analysis, the studies were separated in blocks distributed according to the publication year, country, and results encountered. Tables and graphs were also elaborated to analyze the number of publications per year, the articles published per country, and the effects observed on the test-species due to the combined exposure to high temperatures and metals.

Results

After carrying out the literature review in the databases, 218 articles were found as from the descriptors used. The abstracts were then read, and after applying the exclusion and inclusion criteria, 43 articles were selected.

Tables 1, 2 and 3 present the studies selected after the literature reviews for microalgae, zooplankton, and fish, respectively, and their descriptions per author, year, country, test-organism, metal, temperature tested, and effect were observed.

Based on the review carried out, 4 studies were published before 2000, 12 between 2000 and 2009, and 27 as from 2010 (Figure 1).

As shown in Figure 2, the articles were published in 19 different countries and most of the studies found in this review were published in Belgium (6), Brazil (6), the USA (4), and France (4).

With respect to the distribution of studies per continent, Europe published the largest number of articles (17) on the subject, followed

Table 1 – Studies with microalgae test-organisms and principal characteristics.

Authors	Year	Country	Species	Metal	T (°C) tested	Effect observed
Oukarroum et al.	2012	Canada	*Chlorella vulgaris*	Cu	24, 28, and 31	Decrease in emission of fluorescence by chlorophyll with 3°C rise in the presence of Cu
Lambert et al.	2016	France	Peripheral community	Cu	8, 13, 18, and 23	Decrease in metal toxicity with rise from 8°C to 23°C
Val et al.	2016	Spain	Peripheral community	Hg	17, 19, and 22	Increase in toxicity with 5°C temperature rise
Morin et al.	2017	France	Diatomaceous species	Cu	8, 13, 18, and 23	For some species, metal toxicity increased at 23°C
Lambert et al.	2017	France	Peripheral community	Cu	18 and 28	Cu inhibited photosynthesis with temperature rise
Yong et al.	2018	Malaysia	*Scenedesmus quadricauda*	Cu	25 and 35	Cell density increased with temperature rise
Silva et al.	2018	Portugal	*Raphidocelis subcapitata*	Cu	15, 20, and 25	Algal growth inhibited by metal at temperatures of 20°C and 25°C

Table 2 – Studies with zooplankton test-organisms and principal characteristics.

Authors	Year	Country	Species	Metal	T (°C) tested	Effect observed
Stuhlbacher et al.	1993	UK	*Daphnia magna*	Cd	3, 10, 20, 25, and 30	Increase in Cd toxicity with 10°C rise
Heugens et al.	2003	Holland	*D. magna*	Cd	10, 13, 16, 20, 26, 29, 32, and 35	Increase in metal toxicity with 3°C rise
Tsui and Wang	2004	China	*D. magna*	Hg	14, 19 and 24	Hg elimination by organism not influenced by temperature
Gama-Flores et al.	2005	Mexico	*Brachionus rotundiformis*	Cu	20 and 25	Species growth inhibited by temperature rise when exposed to Cu
Boeckman and Bidwell	2006	USA	*Daphnia pulex*, and *Diaptomus clavipes*	Cu	10, 20, and 30	*D. clavipes*: greatest toxicity at 30°C. *D. pulex*: least toxicity at 20°C
Heugens et al.	2006	Holland	*D. magna*	Cd	10, 20, and 26	Cd reduces reproduction of cladoceran at 20°C and 26°C
Nandini et al.	2007	Mexico	*Moina macrocopa*	Cu and Zn	22 and 27 °C	Adverse effects on organism due to metal exposure and temperature rise
Martínez-Jerónimo et al.	2008	Mexico	*Daphnia exilis*	Cr	20 and 25	Increase in toxic effect of metal with 5°C rise
Ferreira et al.	2010	Portugal	*D. magna*	Ni	4, 12, 20, 25, and 30	Greatest Ni toxicity for species at 25°C and 30°C
Messiaen et al.	2010	Belgium	*D. magna*	Cd	20 and 24	Reduction in birth rate with temperature rise and presence of Cd
Gama-Flores et al.	2014	Mexico	*Brachionus calyciflorus*	Cd	20, 25, and 30	Metal reduced mean survival time of organism with 5°C rise
Bae et al.	2016	South Korea	*D. magna*	Cu	20 and 25	Increase in toxicity with temperature rise
Pereira et al.	2017	Belgium	*D. magna*	Cu, Ni, and Zn	15, 20, and 25	Decrease in Ni toxicity with temperature rise from 15°C to 25°C. Decrease in Cu and Zn toxicity with temperature rise from 15 °C to 20 °C
Pereira et al.	2019	Belgium	*D. magna*	Ni	15, 19, and 25	Decreases in assimilation and elimination rates for Ni with rise from 19°C to 25°C. Both rates showed similar values at 15 °C and 19 °C
Van Ginneken et al.	2019	Belgium	*Asellus aquaticus*	Cd, Cu, and Pb	15 and 20	Increase in mortality rate for metal exposure with temperature rise. Greatest mortality for Cd and Pb exposure at 20 °C

by North America (8). No studies were found concerning this question in Oceania.

Of the test-species employed in the studies, fish were the most used (21), followed by zooplankton (15) and microalgae (7). Of the zooplankton species used, the microcrustacean *D. magna* was the most used, corresponding to 64% of the studies carried out with cladocerans. Of the 55 species studied, 33 were from temperate regions and 22 from tropical regions, a result compatible with the numbers of studies carried out in these regions, since 53.8% of the studies were carried out in Europe and North America. Most of the species of tropical origin studied were fish, where 18 species of tropical origin were included. Nine metals were studied in the articles analyzed: aluminum, arsenic, cadmium, lead, copper, chromium, mercury, nickel, and zinc. Of these, the elements most frequently studied were copper (20 articles) and cadmium (15 articles).

Another aspect considered referred to acclimatation of the test-organisms to the temperatures tested before starting the toxicity. Of the 43 studies analyzed, 20 carried out acclimatation, corresponding to

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Table 3 – Studies with fish test-organisms and principal characteristics.

Authors	Year	Country	Species	Metal	T (°C) tested	Effect observed
Rehwoldt et al.	1972	USA	*Cyprinus carpio*, *Fundulus diaphanus* and *Lepomis gibbosus*	Cd, Cu, Cr, Hg, Ni and Zn	15 and 28	Increase in Hg toxicity to species with temperature rise. Temperature did not influence on toxicity of Cd, Cu, Cr, Ni and Zn to fishes
Hilmy et al.	1987	Egypt	*Tilapia zilli* and *Clarias lazera*	Zn	9.3, 15.3, 18.5 and 25	Increase in Zn toxicity to species with temperature rise to 25 °C
Nussey et al.	1996	South Africa	*Oreochromis mossambicus*	Cu	19 and 29	Increase in Cu toxicity with temperature rise
Hallare et al.	2005	Germany	*Danio rerio*	Cd	21, 26 and 33	Cd toxicity increased with temperature rise from 21°C to 33°C
Perschbacher	2005	USA	*Ictalurus punctatus*	Cu	21, 23, 25 and 27	Decrease in mortality with temperature rise of 2°C
Kumar and Gupta	2006	India	*Catla catla*, *Cirrhinus mirigala* and *Labeo rohita*	Hg	16 and 35	Increase in Hg toxicity with temperature rise for the three species
Carvalho and Fernandes	2006	Brazil	*Prochilodus scrofa*	Cu	20 and 30	Rise in water temperature does not influence copper toxicity
Salazar-Lugo et al.	2009	Venezuela	*Colossoma macropomum*	Cd	25 and 30	Cd reduces blood cells at high temperature
Sassi et al.	2010	Tunisia	*Gambusia affinis*	Cd	24 and 32	Cd reduces body size of species with temperature rise
Vergauwen et al.	2013	Belgium	*D. rerio*	Cd	12, 18, 26 and 34	Increase in mortality rate at 18°C, 26 °C and 34°C
Abdel-Tawwab and Wafeek	2014	Egypt	*Oreochromis niloticus*	Cd	20, 24, 28 and 32	The survival rate was the same at temperatures of 20°C and 24°C, greater at 28°C and smaller at 32°C
Braz-Mota et al.	2017	Brazil	*Hoplosternum littorale*	Cu	28 and 34	Metal reduced species survival with temperature rise
Abdel-Tawwab and Wafeek	2017	Egypt	*O. niloticus*	Cd	20, 24, 28 and 32	Decrease in Cd toxicity from 20°C to 28°C & increase in toxicity from 28°C to 32°C
Philippe et al.	2018	Belgium	*Nothobranchiusfurzeri*	Cd	24 and 28	Reduction in body size & delay in female maturation with temperature rise
Kumar et al.	2019	India	*Pangasianodon hypophthalmus*	As	25 and 34	Increase in toxicity with temperature rise
Hani et al.	2019	France	*Gasterosteus aculeatus*	Cd	16 and 21	Decrease in survival & in the number of embryos with temperature rise
Merçon et al.	2019	Brazil	*Geophagus brasiliensis*	Pb	25 and 28	Decrease in Pb concentration in tissues with temperature rise
Zebral et al.	2019	Brazil	*Poecilia vivipara*	Cu	22 and 28	Increase in Cu concentration in liver & reduction in antioxidant capacity with temperature rise
Pinheiro et al.	2019	Brazil	*Astyanax altiparanae*	Al	20, 25 and 30	Increase in Al concentration in tissues with temperature rise from 25 to 30°C
Zebral et al.	2020	Brazil	*P. vivipara*	Cu	22 and 28	Inhibition of metabolism due to temperature rise and increase in Cu
Park et al.	2020	South Korea	*D. rerio*	Pb	26 and 34	Pb reduced species survival with temperature rise

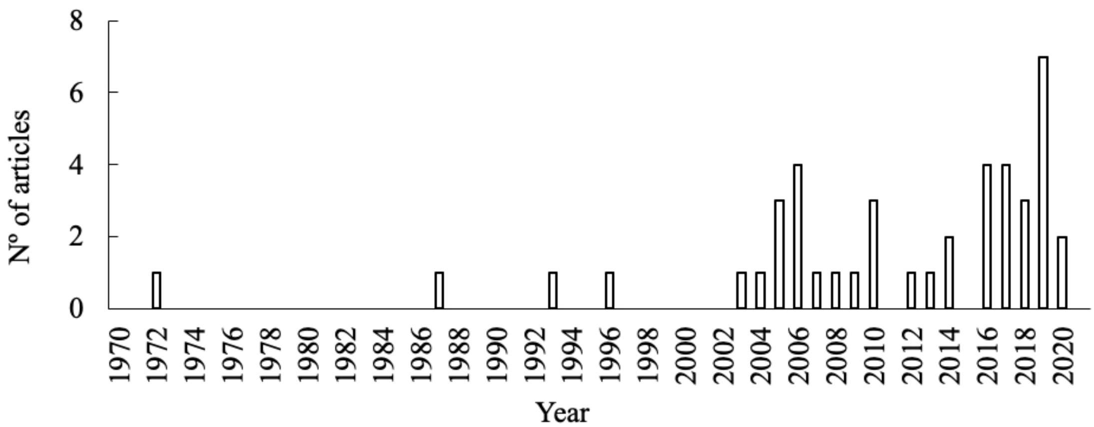

Figure 1 – Number of articles published per year.

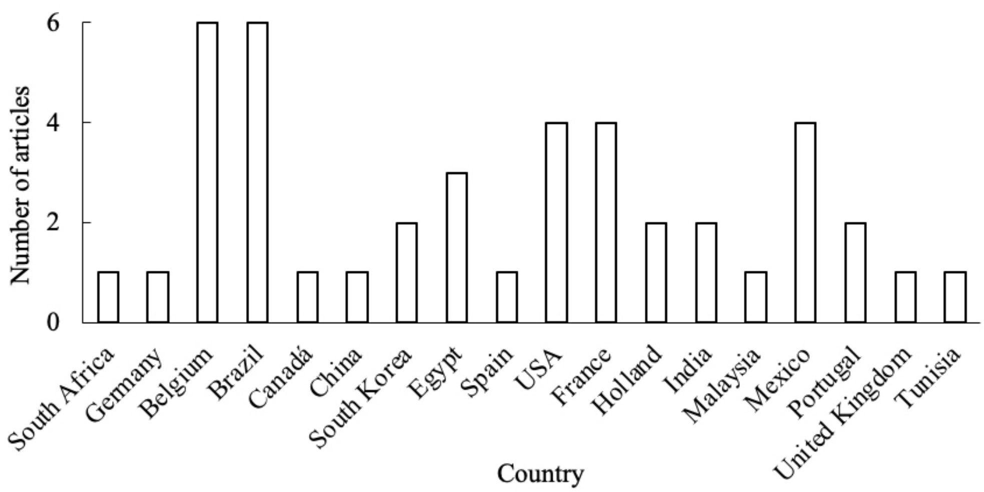

Figure 2 – Number of articles published per country.

45.45% of the articles. The proportion of studies which acclimatized the organisms decreased as the years went by, being 60% before 2000, 50% between 2000 and 2010, and 40.74% as from 2010.

Based on the literature review carried out, the influence of temperature on metal toxicity for the test-organisms was studied (Table 4). For all the groups of organisms, the main effect observed was an increase in toxicity of the metals analyzed with rise in temperature—71.4% of the articles used microalgae, 86.7% zooplankton, and 77.3% fish. Of the studies carried out with zooplankton and fish, 6.7 and 4.6%, respectively, showed no variation in the toxicity of the metal analyzed with rise in temperature. In addition, 4.5% of the studies with fish first observed a decrease followed by an increase in metal toxicity with temperature rise.

Table 4 – Effect observed (in percent articles) on the test-organisms with temperature rise.

Effect observed	Microalgae	Zooplankton	Fish
Increase in toxicity	71.4	86.7	77.3
Decrease in toxicity	28.6	6.6	13.6
Decrease followed by increase	–	–	4.5
No variation	–	6.7	4.6

For the groups of microalgae and zooplankton studied, effects on metal toxicity were observed as from a rise of 2°C. However, for most of the studies carried out with these organisms, a variation in metal toxicity was only observed with a temperature rise of 5°C. With respect to the studies with fish, differences in metal toxicity occurred as from a temperature rise of 4°C, and the main variation in temperature studied was between 5 and 7°C.

Discussion

In this systematic review, a comparative analysis was carried out between the studies which analyzed the effects of temperature rises on metal toxicity for different groups of aquatic organisms. The present investigation provided evidence that in 80% of the studies analyzed, a temperature rise was responsible for increasing the toxicity of metals for the aquatic organisms studied. The data published in this review also indicated an increase over the past few decades in the number of research projects concerning the effects of temperature rises on metal toxicity for aquatic organisms. This increasing concern of the scientific community in understanding the combined effect of temperature rises of the water and aquatic contaminants occurred due to some studies and forecasts showing that thermal pollution and climate changes are threats to biodiversity (Cardoso-Mohedano et al., 2015; Gill et al., 2020). The current rise in the water temperature already exceeds the capacity of some species to adapt, causing changes in the structure and functions of aquatic ecosystems (Schiedek et al., 2007; Pound et al., 2021).

Despite the increase in number of articles published over the past few decades concerning the influence of temperature on the action of metals, there are still some questions that need to be approached concerning the countries where the studies were developed, the test-organisms employed, and the metals studied.

The present survey demonstrated that most of the scientific investigations were carried out by research institutions in countries with temperate climates, as compared to the amount produced in countries with tropical climates. Thus, research on the potential effects of contaminants on the biota have concentrated on species and test conditions representative of temperate regions (Daam et al., 2020). Of the South American countries, Brazil had the largest number of articles published on this theme. The absence of studies in Oceania and the scarcity of studies in Africa and South America revealed the need to amplify investment in the ecotoxicology area in regions with tropical climates, since species from regions with different climatic characteristics do not react in the same way to temperature rises or a combination of this factor with exposure to metals (Graham and Harrod, 2009). For this reason, the use of results obtained for temperate region species to predict risks for the tropical fish biota should be done with caution. The use of native species can provide more realistic results concerning the toxicity of chemical agents, since they reflect local environmental conditions (Harmon et al., 2003; Raymundo et al., 2019).

With respect to the groups of organisms tested, it is important to note the scarcity of studies on microalgae. These organisms are the base of the food chain in aquatic ecosystems, and toxic effects in their communities can influence the upper trophic levels (Wetzel, 2001). On the other hand, fish were the test-organisms most studied in the theme of this review. There is adequate knowledge for some fish species and their cultivation presents a low level of difficulty, showing ecological and commercial importance (Zagatto and Bertoletti, 2006; Esteves, 2011). Nevertheless, the toxic effects of metals associated with thermal stress should be evaluated in species from different trophic levels, due to variation in sensitivity to the contaminants (Hoffman et al., 2003) and in the thermal tolerance limits (Silva et al., 2020) existent among the organisms, and also the accumulation of metals via the trophic chain (DeForest and Meyer, 2015). Hence, studies with microalgae must be amplified and the species used within each group of test-organism diversified.

The literature survey indicated a predominance of studies on the metals copper and cadmium and the absence of research on other metals. Copper, an essential micronutrient for the organisms in determined concentrations, was the metal most used in research with the three groups of test-organisms evaluated. Cadmium, differently from copper, has no known metabolic function and is toxic even in low concentrations. Both metals reached the water bodies via the discharge of industrial effluents and by way of mining residues (Vardhan et al., 2019). The fact that these metals were the most used in the research projects found in this review can be explained by the great number of studies concerning these elements already existent, making data collection, comparative analysis, and a discussion based on already published articles much easier. Based on the finding of the present survey, the authors consider it necessary to amplify investigations concerning the effect of temperature rises on the action of other metals, for example, aluminum, chromium, lead, iron, manganese, and nickel. These metals come from mining, electroplating, civil construction, tanneries, and the production of pigments, batteries, metal alloys, and agrochemicals and can enter aquatic systems via direct or indirect ways (Azevedo and Chasin, 2003).

The research projects analyzed reported the effects on metal toxicity as from 3°C temperature rises for microalgae and zooplankton, and as from 4°C rises for fish, in experiments carried out in laboratories. Therefore, the temperature ranges studied contemplated the temperature rises predicted by the IPCC (2014) at the end of the 21st century. In ecotoxicological studies carried out under laboratory conditions, the test-species are exposed to the chemical agents at the standard temperature, within the temperature range considered adequate for the organisms (Zagatto and Bertoletti, 2006). The evident impact of temperature rises on the toxicity of chemicals, as revealed by the present systematic review, emphasizes the need for the standard protocols in the area to consider standard temperatures and those to be registered under natural conditions.

With respect to acclimatation of the species to the temperatures, in recent years, the number of research projects with acclimatized organisms for toxicity studies has decreased. Acclimatation is necessary to guarantee that the toxic effects observed in the experiments are a consequence of the metal toxicity at high temperature, without the occurrence of thermal shock by the individual. The acclimatation potential of organisms is an aspect of global climate changes that should be considered in the studies (Delorenzo, 2015). According to Silva et al. (2020), acclimatation can collaborate to a better understanding of the strategies used by organisms to deal with environmental changes, considering their capacity to adapt to unfavorable environmental conditions. It is, therefore, fundamental that future research considers the acclimatation of the organisms, guaranteeing that the results obtained are more representative.

The present review also indicated adverse effects on the test-species due to temperature rises in the medium and their association with an intensification of the toxicity of the metals. For microalgae, the increase in metal toxicity with temperature rise was due to a decrease in photosynthetic efficiency (Oukarroum et al., 2012) and to growth inhibition due to metabolic changes and in the levels of amino acids, fatty acids, and sugars (Yong et al., 2018). For zooplankton, it was observed that the increase in toxicity due to a temperature rise was due to a greater accumulation of metal, protein denaturation, and a destabilization of homeostasis, with a reduction in reproduction and survival (Lannig et al., 2006). For fish, the increase in metal toxicity due to the temperature rise was due to an accumulation of metal in different body tissues and a reduction in the metabolism and antioxidant capacity of the organisms to deal with the metal toxicity (Pinheiro et al., 2019; Zebral et al., 2019). In consequence, the heartbeat was reduced, bad body formation and reproductive damage occurred, and the fish mortality rates were high (Park et al., 2020). Thus, considering the toxic effects registered in important representatives of the biota of aquatic systems, the loss of the ecosystem services they offer is likely to occur under possible climate change scenarios in metal-containing environments.

Considering that the duration and intensity of heat waves will probably increase in coming decades as a function of climate change, this increases the concern with the potential effects of a simultaneous temperature rise and pollution of aquatic environments and emphasizes the need for wider environmental monitoring to better forecast the impacts on the biota (Jacquin et al., 2019). Thus, an adequate protection of the biodiversity depends on the advance of research concerning the sensitivity of aquatic organisms to different pollutants (metals, agrochemicals, nanoparticles, for example) under current climatic conditions and under those projected for the future, and of the population's ability to understand the possible effects of changes to the ecosystems when faced with this scenario.

Conclusions

There is evidence that temperature rises can increase or decrease the effects of metals on aquatic organisms and can also show no influence on these contaminants. This systematic review showed that according to most of the studies concerning the effects of metals with temperature rises, there was an increase in toxicity for microalgae, zooplankton, and fish species. In addition, an increase in interest concerning this theme within the scientific community was found, possibly due to the increase in importance given to questions of climate change and to the increase in research institutions and the training of human resources. Despite the increase in publications in recent decades, there is a need to amplify the number of metals and organisms analyzed. Attention should be given to the diversification of the test-organisms studied, principally among the bacterioplankton, phytoplankton, and zooplankton species.

It is important to acclimatize the individuals, such that the laboratory conditions represent the stress factors found in the natural environment in the most realistic manner. There is also a need for research that improves the understanding of the effects of temperature on the toxicity of other aquatic contaminants. Considering the temperature rise predicted for future decades due to climate change, an advance in research concerning the effects of temperature rises associated with chemical stressors on aquatic biodiversity is primordial, especially in tropical regions. Ecotoxicological analyses are of great importance in forecasting and preventing threats associated with the contamination of water bodies by toxic agents within the scenario of climate change.

Contribution of authors:

Nin, C.J: Conceptualization, Methodology, Formal analysis, Writing – original draft. Rodgher, S: Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

References

Abdel-Tawwab, M.; Wafeek, M., 2014. Influence of water temperature and waterborne cadmium toxicity on growth performance and metallothionein–cadmium distribution in different organs of Nile tilapia, *Oreochromis niloticus* (L.). Journal of Thermal Biology, v. 45, 157-162. https://doi.org/10.1016/j.jtherbio.2014.09.002.

Abdel-Tawwab, M.; Wafeek, M., 2017. Fluctuations in water temperature affected waterborne cadmium toxicity: Hematology, anaerobic glucose pathway, and oxidative stress status of Nile tilapia, *Oreochromis niloticus* (L.). Aquaculture, v. 477, 106-111. https://doi.org/10.1016/j.aquaculture.2017.05.007.

Adamczuk M., 2016. Past, present, and future roles of small cladoceran *Bosmina longirostris* (O. F. Muller, 1785) in aquatic ecosystems. Hydrobiologia, v. 767, 1-11. https://doi.org/10.1007/s10750-015-2495-7.

Ahmed, T.; Zounemat-Kermani, M.; Scholz, M., 2020. Climate change, water quality and water-related challenges: a review with focus on Pakistan. International Journal of Environmental Research and Public Health, v. 17, (22), 8518. https://doi.org/10.3390/ijerph17228518.

Ali, H.; Khan, E.; Ilahi I., 2019. Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. Journal of Chemistry, v. 2019, 6730305. https://doi.org/10.1155/2019/6730305.

Amoatey, P.; Baawain, M. S., 2019. Effects of pollution on freshwater aquatic organisms, Water Environment Research, v. 91, (10), 1272-1287. https://doi.org/10.1002/wer.1221.

Azevedo, F.A.; Chasin, A.A.M., 2003. Metais. Gerenciamento da Toxicidade. Atheneu InterTox, São Paulo, 554 pp.

Bae, E.; Samanta P.; Yoo J.; Jung J., 2016. Effects of multigenerational exposure to elevated temperature on reproduction, oxidative stress, and Cu toxicity in *Daphnia magna*. Ecotoxicology and Environmental Safety, v. 132, 366-371. https://doi.org/10.1016/j.ecoenv.2016.06.034.

Boeckman, CJ.; Bidwell, J.R., 2006. The effects of temperature, suspended solids, and organic carbon on copper toxicity to two aquatic invertebrates. Water, Air, & Soil Pollution, v. 171, (1-4), p. 185-202. https://doi.org/10.1007/s11270-005-9036-3.

Braz-Mota, S.; Fé, L.M.L.; Delunardo, F.A.C.; Sadauskas-Henrique, H.; Almeida-Val, V.M.F.; Val, A.L., 2017. Exposure to waterborne copper and high temperature induces the formation of reactive oxygen species and causes mortality in the Amazonian fish *Hoplosternum littorale*. Hydrobiologia, v. 789, (1), 157-166. https://doi.org/10.1007/s10750-016-2847-y.

Cardoso-Mohedano, J.G.; Bernardello, R.; Sanchez-Cabeza, J.A.; Ruiz-Fernández, A.C.; Alonso-Rodriguez, R.; Cruzado, A., 2015. Thermal impact from thermoelectric power plant on tropical coastal lagoon. Water, Air, & Soil Pollution, v. 226, (1), 2202. https://doi.org/10.1007/s11270-014-2202-8.

Carvalho, C.S.; Fernandes, M.N., 2006. Effect of temperature on copper toxicity and hematological responses in the neotropical fish *Prochilodus scrofa* at low and high pH. Aquaculture, v. 251, (1), 109-111. https://doi.org/10.1016/j.aquaculture.2005.05.018.

Copetti, D.; Salerno, F., 2020. Climate–water–ecosystem–interactions: insights from four continent's case studies. Water, v. 12, (5), 1445. http://doi.org/10.3390/w12051445.

Daam, M.A.; Garcia, M.V.; Scheffczyk, A.; Römbke, J., 2020. Acute and chronic toxicity of the fungicide carbendazim to the earthworm *Eisenia fetida* under tropical versus temperate laboratory conditions. Chemosphere, v. 255, 126871. https://doi.org/10.1016/j.chemosphere.2020.126871.

Da Silva, G.; Silveira, C.; Silva, M.; Marcos Júnior, A.; Souza Filho, F.; Guimarães, S., 2020. Analysis of climate change projections on precipitation and temperature in Brazilian hydrographic regions for the 21st century. Brazilian Journal of Environmental Sciences (Online), v. 55, (3), 420-436. https://doi.org/10.5327/Z2176-947820200624.

DeForest, D.K.; Meyer, J.S., 2015. Critical review: toxicity of dietborne metals to aquatic organisms. Critical Reviews in Environmental Science and Technology, v. 45, (11), 1176-1241. http://dx.doi.org/10.1080/10643389.2014.955626.

Delorenzo, M.E., 2015. Impacts of climate change on the ecotoxicology of chemical contaminants in estuarine organisms. Current Zoology, v. 61, (4), 641-652. https://doi.org/10.1093/czoolo/61.4.641.

Esteves, F.A., 2011. Fundamentos de limnologia. Interciência, Rio de Janeiro, 790 pp.

Ferreira, A.L.G.; Serra, P.; Soares, M.V.M.; Loureiro, S., 2010. The influence of natural stressors on the toxicity of nickel to *Daphnia magna*. Environmental Science and Pollution Research, v. 17, (6), 1217-1229. https://doi.org/10.1007/s11356-010-0298-y.

Gama-Flores, J.L.; Salas, M.E.H.; Sarma, S.S.S., 2014. Combined effects of temperature (level and oscillation) and cadmium concentration on the demography of *Brachionus calyciflorus* (Rotifera). International Review of Hydrobiology, v. 99, (1-2), 173-177. https://doi.org/10.1002/iroh.201301722.

Gama-Flores, J.L.; Sarma, S.S.S.; Nandini, S., 2005. Interaction among copper toxicity, temperature and salinity on the population dynamics of *Brachionus rotundiformis* (Rotifera). Hydrobiologia, v. 546, (1), 559-568. https://doi.org/10.1007/s10750-005-4300-5.

Gill, K.C.; Fovargue, R.E.; Neeson, T.M., 2020. Hotspots of species loss do not vary across future climate scenarios in a drought-prone river basin. Ecology and Evolution, v. 10, (17), 9200-9213. https://doi.org/10.1002/ece3.6597.

Graham, C.T.; Harrod, C., 2009. Implications of climate change for the fishes of the British Isles. Journal of Fish Biology, v. 74, (6), 1143-1205. https://doi.org/10.1111/j.1095-8649.2009.02180.x.

Hallare, A.V.; Schirling, M.; Luckenbach, I.; Köhler, H.-R.; Triebskorn, R., 2005. Combined effects of temperature and cadmium on developmental parameters and biomarker responses in zebrafish (*Danio rerio*) embryos. Journal of Thermal Biology, v. 30, (1), 7-17. https://doi.org/10.1016/j.jtherbio.2004.06.002.

Hani, Y.M.I.; Turies, C.; Palluel, O.; Delahaut, L.; Bado-Nilles, A.; Geffard, A.; Dedourge-Geffard, O.; Porcher, J.M., 2019. Effects of a chronic exposure to different water temperatures and/or to an environmental cadmium concentration on the reproduction of the threespine stickleback (*Gasterosteus aculeatus*). Ecotoxicology and Environmental Safety, v. 174, 48-57. https://doi.org/10.1016/j.ecoenv.2019.02.032.

Harmon, S.M.; Specht, W.L.; Chandler, G.T.A., 2003. Comparison of the daphnids *Ceriodaphnia dubia* and *Daphnia ambigua* for their utilization in routine toxicity testing in the Southeastern United States. Archives of Environmental Contamination and Toxicology, v. 45, (1), 0079-0085. https://doi.org/10.1007/s00244-002-0116-8.

Herrera-R, G.A.; Oberdorff, T.; Anderson, E.P.; Brosse, S.; Carvajal-Vallejos, F.M.; Frederico, R.G.; Hidalgo, M.; Jézéquel, C.; Maldonado, M.; Maldonado-Ocampo, J.A.; Ortega, H.; Radinger, J.; Torrente-Vilara, G.; Zuanon, J.; Tedesco, P.A., 2020. The combined effects of climate change and river fragmentation on the distribution of Andean Amazon fishes. Global Change Biology, v. 26, (10), 5509-5523. https://doi.org/10.1111/gcb.15285.

Heugens, E.H.W.; Jager, T.; Creyghton, R.; Kraak, M.H.S.; Hendriks, A.J.; Van Straalen, N.M.; Admiraal, W., 2003. Temperature-dependent effects of cadmium on *Daphnia magna*: accumulation versus sensitivity. Environmental Science & Technology, v. 37, (10), 2145-2151. https://doi.org/10.1021/es0264347.

Heugens, E.H.W.; Tokkie, L.T.B.; Kraak, M.H.S.; Hendriks, A.J.; Van Straalen, N.M.; Admiraal, W., 2006. Population growth of *Daphnia magna* under multiple stress conditions: joint effects of temperature, food, and cadmium. Environmental Toxicology and Chemistry, v. 25, (5), 1399-1407. https://doi.org/10.1897/05-294R.1.

Hilmy, A.M.; El-Domiaty, N.A.; Daabees, A.Y.; Latife, H.A., 1987. Toxicity in *Tilapia zilli* and *Clarias lazera* (Pisces) induced by zinc, seasonally. Comparative biochemistry and physiology. C, Comparative Pharmacology and Toxicology, v. 86, (2), 263-265. https://doi.org/10.1016/0742-8413(87)90077-6.

Hochachka, P.W.; Somero, G.N., 2002. Biochemical adaptation: mechanism and process in physiological evolution. Oxford University Press, New York, 480 pp.

Hoffman, D.J.; Rattner, B.A.; Burton Jr., A.; Cairns, J.C., 2003. Handbook of ecotoxicology. Taylor & Francis Group, New York, 1312 pp.

Intergovernmental Panel on Climate Change – IPCC. 2014. Climate Change 2014: impacts, adaptation, and vulnerability. Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, United Kingdom and New York, 1132 pp.

Jacquin, L.; Gandar, A.; Aguirre-Smith, M.; Perrault, A.; Le Hénaff, M.; De Jong, L.; Paris-Palacios, S.; Laffaille, P.; Jean, S., 2019. High temperature aggravates the effects of pesticides in goldfish. Ecotoxicology and Environmental Safety, v. 172, 255-264. https://doi.org/10.1016/j.ecoenv.2019.01.085.

Kumar, A.; Gupta, A. K., 2006. Acute toxicity of mercury to the fingerlings of Indian major carps (catla, rohu and mrigal) in relation to water hardness and temperature. Journal of Environmental Biology, v. 27, (1), 89-92.

Kumar, N.; Gupta, S.K.; Bhushan, S.; Singh, A., 2019. Impacts of acute toxicity of arsenic (III) alone and with high temperature on stress biomarkers, immunological status and cellular metabolism in fish. Aquatic Toxicology, v. 214, 105233. https://doi.org/10.1016/j.aquatox.2019.105233.

Lambert, A.S.; Dabrin, A.; Morin, S.; Gahou, J.; Foulquier, A.; Foulquier, A.; Coquery, M.; Pesce, S., 2016. Temperature modulates phototrophic periphyton response to chronic copper exposure. Environmental Pollution, v. 208, (part B), 821-829. https://doi.org/10.1016/j.envpol.2015.11.004.

Lambert, A.S.; Dabrin, A.; Foulquier, A.; Morin, S.; Rosy, C.; Coquery, M.; Pesce, S., 2017. Influence of temperature in pollution-induced community tolerance approaches used to assess effects of copper on freshwater phototrophic periphyton. Science of the Total Environment, v. 607-608, 1018-1025. https://doi.org/10.1016/j.scitotenv.2017.07.035.

Lannig, G.; Cherkasov, A.S.; Sokolova, I.M., 2006. Temperature-dependent effects of cadmium on mitochondrial and whole-organism bioenergetics of oysters (*Crassostrea virginica*). Marine Environmental Research, v. 62, (suppl. 1), S79-S82. https://doi.org/10.1016/j.marenvres.2006.04.010.

Lenard, T.; Ejankowski, W.; Poniewozik, M., 2019. Responses of phytoplankton communities in selected eutrophic lakes to variable weather conditions. Water, v. 11, (6), 1207. https://doi.org/10.3390/w11061207.

Madden, N.; Lewis, A.; Davis, M., 2013. Thermal effluent from the power sector: an analysis of once-through cooling system impacts on surface water temperature. Environmental Research Letters, v. 8, (3), 035006. https://doi.org/10.1088/1748-9326/8/3/035006.

Martínez-Jerónimo, F.; Rodríguez-Estrada, J.; Martínez-Jerónimo, L., 2008. *Daphnia exilis* Herrick, 1895 (Crustacea: Cladocera). una especie zooplanctónica potencialmente utilizable como organismo de prueba en bioensayos de toxicidad aguda en ambientes tropicales y subtropicales. Revista Internacional de Contaminación Ambiental, v. 24, (4), 153-159.

Martins, T.S.; Carmo Junior, G.N.R., 2018. Avaliação de impacto ambiental: uma revisão sistemática sob a ótica metodológica. E&S Engineering and Science, v. 7, (2), 29-41. https://doi.org/10.18607/ES201876616.

Merçon, J.; Pereira, M.P.; Passos, L.S.; Lopes, I.O.; Coppo, G.; Barbosa, B.; Cabral, D.; Gomes, C.G.L., 2019. Temperature affects the toxicity of lead-contaminated food in *Geophagus brasiliensis* (QUOY & GAIMARD, 1824). Environmental Toxicology and Pharmacology, v. 66, 75-82. https://doi.org/10.1016/j.etap.2018.12.013.

Messiaen, M.; De Schamphelaere, K.A.C.; Muyssen, B.T.A.; Janssen, C.R., 2010. The micro-evolutionary potential of *Daphnia magna* population exposed to temperature and cadmium stress. Ecotoxicology and Environmental Safety, v. 73, (6), 1114-1122. https://doi.org/10.1016/j.ecoenv.2010.05.006.

Morin, S.; Lambert, A.S.; Rodriguez, P.; Dabrin, A.; Coquery, M.; Pesce, S., 2017. Changes in copper toxicity towards diatom communities with experimental warming. Journal of Hazardous Materials, v. 334, 223-232. https://doi.org/10.1016/j.jhazmat.2017.04.016.

Nandini, S.; Picazo-Paez, E.A.; Sarma, S.S.S., 2007. The combined effects of heavy metals (copper and zinc), temperature and food (*Chlorella vulgaris*) level on the demographic characters of *Moina macrocopa* (Crustacea: Cladocera). Journal of Environmental Science and Health, Part A, v. 42, (10), 1433-1442. https://doi.org/10.1080/10934520701480789.

Noyes, P.D.; Lema, S.C., 2015. Forecasting the impacts of chemical pollution and climate change interactions on the health of wildlife. Current Zoology, v. 61, (4), 669-689. https://doi.org/10.1093/czoolo/61.4.669.

Nussey, G.; Vuren, J.H.J.V.; Preez, H.H.D., 1996. Acute toxicity tests of copper on juvenile Mozambique tilapia, *Oreochromis mossambicus* (Cichlidae), at different temperatures. South African Journal of Wildlife Research, v. 26, (2), 47-55. https://hdl.handle.net/10520/EJC116995.

O'Briain, R., 2019. Climate change and European rivers: an eco-hydromorphological perspective. Ecohydrology, v. 12, (5), e2099. https://doi.org/10.1002/eco.2099.

Oukarroum, A.; Perreault, F.; Popovic, R., 2012. Interactive effects of temperature and copper on photosystem II photochemistry in *Chlorella vulgaris*. Journal of Photochemistry and Photobiology B: Biology, v. 110, 9-14. https://doi.org/10.1016/j.jphotobiol.2012.02.003.

Park, K.; Han, E.J.; Ahn, G.; Kwak, I.-S., 2020. Effects of thermal stress-induced lead (Pb) toxicity on apoptotic cell death, inflammatory response, oxidative defense, and DNA methylation in zebrafish (*Danio rerio*) embryos. Aquatic Toxicology, v. 224, 105479. https://doi.org/10.1016/j.aquatox.2020.105479.

Pereira, C.M.S.; Blust, R.; De Schamphelaere, K.A.C., 2019. Effect of temperature on nickel uptake and elimination in *Daphnia magna*. Environmental Toxicology and Chemistry, v. 38, (4), 784-793. https://doi.org/10.1002/etc.4352.

Pereira, C.M.S.; Deruytter, D.; Blust, R.; De Schamphelaere, K.A.C., 2017. Effect of temperature on chronic toxicity of copper, zinc, and nickel to *Daphnia magna*. Environmental Toxicology and Chemistry, v. 36, (7), 1909-1916. https://doi.org/10.1002/etc.3714.

Perschbacher, P.W., 2005. Temperature effects on acute copper toxicity to juvenile channel catfish *Ictalurus punctatus*. Aquaculture, v. 243, (1-4), 225-228. https://doi.org/10.1016/j.aquaculture.2004.10.006.

Philippe, C.; Hautekiet, P.; Gregoir, A. F.; Thore, E. S. J.; Pinceel, T. S. R.; Brendonck L.; De Boeck, G., 2018. Combined effects of cádmium exposure and temperature on the annual killifish (*Nothobranchius furzeri*). Environmental Toxicology and Chemistry, 37, (9), 2361-2371. https://doi.org/10.1002/ETC.4182.

Pinheiro, J.P.S.; Assis, C.B.; Muñoz-Peñuela, M.; Barbosa Júnior, F.; Correia, T.G.; Moreira, R.G., 2019. Water temperature and acid pH influence the cytotoxic and genotoxic effects of aluminum in the freshwater teleost *Astyanax altiparanae* (Teleostei: Characidae). Chemosphere, v. 220, 266-274. https://doi.org/10.1016/j.chemosphere.2018.12.143.

Pound, K.L.; Larson, C.A.; Passy, S.I., 2021. Current distributions and future climate-driven changes in diatoms, insects and fish in US streams. Global Ecology and Biogeography, 30, 63-78. https://doi.org/10.1111/geb.13193.

Qiu, J., 2012. Trouble on the Yangtze. Science, v. 336, (6079), 288-291. https://doi.org/10.1126/science.336.6079.288.

Radinger, J.; Hölker, F.; Horký, P.; Slavík, O.; Dendoncker, N.; Wolter, C., 2016. Synergistic and antagonistic interactions of future land use and climate change on river fish assemblages. Global Change Biology, v. 22, (4), 1505-1522. https://doi.org/10.1111/gcb.13183.

Raptis, C.E.; van Vliet, M.T.H.; Pfister, S. 2016. Global thermal pollution of rivers from thermoelectric power plants. Environmental Research Letters, v. 11, 104011. https://doi.org/10.1088/1748-9326/11/10/104011.

Raymundo, L.B.; Rocha, O.; Moreira, R.A.; Miguel, M.; Daam, M.A., 2019. Sensitivity of tropical cladocerans to chlorpyrifos and other insecticides as compared to their temperate counterparts. Chemosphere, v. 220, 937-942. https://doi.org/10.1016/j.chemosphere.2019.01.005.

Rehwoldt, R.; Menapace, L.W.; Nerrie, B.; Alessandrello, D., 1972. The effect of increased temperature upon the acute toxicity of some heavy metal ions. Bulletin of Environmental Contamination and Toxicology, v. 8, (2), 91-96. https://doi.org/10.1007/BF01684513.

Salazar-Lugo, R.; León, A.; Lemus, M., 2009. Efecto del cadmio y de la temperatura sobre el conteo de células sanguíneas del pez dulceacuícola *Colossoma macropomum*. Revista Científica (Maracaibo), v. 19, (1), 1-11.

Sampaio, R.F.; Mancini, M.C., 2007. Estudos de Revisão Sistemática: um guia para síntese criteriosa da evidência científica. Brazilian Journal of Physical Therapy, v. 11, (1), 77-82. http://dx.doi.org/10.1590/S1413-35552007000100013.

Sassi, A.; Annabi, A.; Kessabi, K.; Kerkeni, A.; Saïd, K.; Messaoudi, I., 2010. Influence of high temperature on cadmium-induced skeletal deformities in juvenile mosquitofish (*Gambusia affinis*). Fish Physiology and Biochemistry, v. 36, (3), 403-409. https://doi.org/10.1007/s10695-009-9307-9.

Schiedek, D.; Sundelinet, B.; Readman, J.W.; Macdonald, R.W., 2007. Interactions between climate change and contaminants. Marine Pollution Bulletin, v. 54, (12), 1845-1856. https://doi.org/10.1016/j.marpolbul.2007.09.020.

Silva, L.C.M.; Daam, M.A.; Gusmao, F., 2020. Acclimation alters glyphosate temperature-dependent toxicity: Implications for risk assessment under climate change. Journal of Hazardous Materials, v. 385, 121512. https://doi.org/10.1016/j.jhazmat.2019.121512.

Silva, V.; Marques, C.R.; Campos, I.; Vidal, T.; Keizer, J.J.; Gonçalves, F.; Abrantes, N., 2018. Combined effect of copper sulfate and water temperature on key freshwater trophic levels–approaching potential climatic change scenarios. Ecotoxicology and Environmental Safety, v. 148, 384-392. https://doi.org/10.1016/j.ecoenv.2017.10.035.

Stuhlbacher, A.; Bradley, M.C.; Naylor, C.; Calow, P., 1993. Variation in the development of cadmium resistance in *Daphnia magna* Straus; effect of temperature, nutrition, age and genotype. Environmental Pollution, v. 80, (2), 153-158. https://doi.org/10.1016/0269-7491(93)90141-A.

Tsui, M.T.K.; Wang, W.X., 2004. Temperature influences on the accumulation and elimination of mercury in a freshwater cladoceran, *Daphnia magna*. Aquatic Toxicology, v. 70, (3), 245-256. https://doi.org/10.1016/j.aquatox.2004.09.006.

Val, J.; Muñiz, S.; Gomà J.; Navarro, E., 2016. Influence of global change-related impacts on the mercury toxicity of freshwater algal communities. Science of the Total Environment, v. 540, 53-62. https://doi.org/10.1016/j.scitotenv.2015.05.042.

Van Ginneken, M.; Blust, R.; Bervoets, L., 2019. The impact of temperature on metal mixture stress: Sublethal effects on the freshwater isopod *Asellus aquaticus*. Environmental Research, v. 169, 52-61. https://doi.org/10.1016/j.envres.2018.10.025.

Vardhan, K.H.; Kumar, P.S.; Panda, R.C., 2019. A review on heavy metal pollution, toxicity and remedial measures: current trends and future perspectives. Journal of Molecular Liquids, v. 290, 111197. https://doi.org/10.1016/j.molliq.2019.111197.

Vergauwen, L.; Hagenaars, A.; Blust, R.; Knapen, D., 2013. Temperature dependence of long-term cadmium toxicity in the zebrafish is not explained by liver oxidative stress: evidence from transcript expression to physiology. Aquatic Toxicology, v. 126, 52-62. https://doi.org/10.1016/j.aquatox.2012.10.004.

Wetzel, R.G., 2001. Limnology: lake and river ecosystems. Academic Press, San Diego, 1006 pp.

Xu, X.; Wang, Y.-C.; Kalcic, M.; Muenich, R.L.; Yang, Y.C.E.; Scavia, D., 2019. Evaluating the impact of climate change on fluvial flood risk in a mixed-use watershed. Environmental Modelling and Software, v. 122, 104031. https://doi.org/10.1016/j.envsoft.2017.07.013.

Yong, W.-K.; Sim, K.S.; Poong, S.W.; Wei, D.; Phang, S.M.; Lim, P.E., 2018. Interactive effects of temperature and copper toxicity on photosynthetic efficiency and metabolic plasticity in *Scenedesmus quadricauda* (Chlorophyceae). Journal of Applied Phycology, v. 30, (6), 3029-3041. https://doi.org/10.1007/s10811-018-1574-3.

Zagatto, P.A.; Bertoletti, E., 2006. Ecotoxicologia aquática: princípios e aplicações. Rima, São Carlos, 464 pp.

Zebral, Y.D.; Fonseca, J.S.; Roza, M.; Costa, P.G.; Robaldo, R.B.; Bianchini, A., 2020. Combining elevated temperature with waterborne copper: impacts on the energy metabolism of the killifish *Poecilia vivipara*. Chemosphere, v. 253, 126631. https://doi.org/10.1016/j.chemosphere.2020.126631.

Zebral, Y.D.; Roza, M.; Fonseca, J.S.; Costa, P.G.; De Oliveira, C.S.; Zocke, T.G.; Dal Pizzol, J.L.; Robaldo, R.B.; Bianchini, A., 2019. Waterborne copper is more toxic to the killifish *Poecilia vivipara* in elevated temperatures: Linking oxidative stress in the liver with reduced organismal thermal performance. Aquatic Toxicology, v. 209, 142-149. https://doi.org/10.1016/j.aquatox.2019.02.005.