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Implementation of a low-cost single-family sewage treatment system utilizing end-of-life tires: a sustainable approach

Implantação de um sistema unifamiliar de tratamento de esgoto de baixo custo utilizando pneus inservíveis: uma abordagem sustentável

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ABSTRACT

Basic sanitation is crucial for a healthy and sustainable life, especially in developing countries, where sanitary sewage and management of solid waste, such as end-of-life tires, are significant challenges. This study presents a research methodology of applied nature featuring the innovative and low-cost implementation of an individual residential sewage treatment system, which uses unusable tires (TIRE-ATS) as a substitute for masonry walls. The study was divided into four phases: (I) local data collection and selection of a pilot residence, (II) design and sizing of the system, (III) system implementation, and (IV) analysis of financial and environmental advantages. The municipality studied has serious deficiencies regarding unusable tires, such as the absence of reverse logistics, the burning of these wastes in landfill areas, and the inexistence of sanitary sewage. The system proved to be effective, requiring 18 end-of-life tires for its construction, which would remove 64,782 tires from the environment for the benefit of a neighborhood, fostering the green economy with safe, durable, and watertight units. The financial advantage of TIRE-ATS over the masonry system was 18%, which is quite attractive to the local population, most of whom are economically underprivileged. The sustainability of tire reuse represents a notable environmental advantage, progressing toward the Sustainable Development Goals of the United Nations Organization.

Keywords: sanitation absence; tire reuse; sanitary sewage treatment; septic tank; circular economy; sustainability.

RESUMO

O saneamento básico é crucial para uma vida saudável e sustentável, especialmente em países em desenvolvimento, onde o esgotamento sanitário e o gerenciamento de resíduos sólidos, como os pneus inservíveis, são desafios. Este trabalho apresenta uma metodologia de pesquisa de natureza aplicada, com a implantação inovadora e de baixo custo, de um sistema individual de tratamento de esgoto sanitário residencial que utiliza pneus inservíveis (TIRE-ATS) em substituição às paredes de alvenaria. O estudo foi dividido em quatro fases: (I) levantamento de dados locais e seleção de uma residência-piloto; (II) concepção e dimensionamento do sistema; (III) implantação do sistema; e (IV) análise das vantagens financeira e ambiental. O município estudado apresenta sérias deficiências em relação aos pneus inservíveis, como a não aplicação da logística reversa, a queima desses resíduos em área de lixões, e a inexistência de esgotamento sanitário. O sistema provou ser eficaz, demandando 18 pneus inservíveis em sua construção, o que retiraria 64.782 pneus do meio ambiente para o beneficiamento de um bairro, fomentando a economia verde, com unidades seguras, de alta durabilidade e estanque. A vantagem financeira do TIRE-ATS em relação ao sistema de alvenaria foi de 18%, bastante atraente para a população local que, em sua maioria, é carente. A sustentabilidade do reaproveitamento de pneus representa uma vantagem ambiental notável, avançando em direção aos Objetivos de Desenvolvimento Sustentável da Organização das Nações Unidas.

Palavras-chave: ausência de saneamento básico; reúso de pneus; tratamento de esgoto sanitário; tanque séptico; economia circular; sustentabilidade.

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Introduction

The accelerated environmental degradation resulting from anthropic exploratory activities has prompted most nations to pursue sustainable development (Lee et al., 2020). In line with this, the United Nations (UN) endorsed a set of Sustainable Development Goals (SDGs), known as the 2030 Agenda, encouraging countries to achieve 17 SDGs over the next 15 years. Particularly, we can highlight the Goal 6 of this agenda, which includes the universalization of basic sanitation (BS) services, aiming to ensure this essential service for all by 2030 (Naciones Unidas, 2020).

Indeed, BS facilities are essential requirements for a healthy and sustainable society (Elias et al., 2021; Nunes et al., 2021). However, by 2022, over 419 million people worldwide still used open-air latrines due to poverty, inequality, insufficient funding, and poor management of public resources (WHO et al., 2023), and another 653 million people lacked essential services such as adequate handwashing facilities (Atangana and Oberholster 2023). BS service is understood as the control of physical factors harmful to humans, which can affect their social, physical, and mental well-being, fundamentally including the supply of potable water, sanitary sewage systems (SSS), urban cleanliness and solid waste (SW) management, drainage, and management of stormwater (Brasil, 2020).

Particularly in Brazil, less than 56.0% of the population is served with sewage collection, and out of this total, only 52.2% receive some form of treatment; in the Northern region, indicators report that 14.7% are provided with sewage collection and only 19.8% of the total collected is subject to some form of treatment; in the state of Pará, the indicators drop drastically, with 7.7% having sewage collection, and out of this small fraction, only 10.0% receive any type of treatment (Brasil, 2022b).

Sanitary sewage systems prevent soil and water pollution, mitigate or eliminate contact between disease vectors and sewage, and provide housing hydro-sanitary quality with hygienic standards. Some studies have focused on new SSS technologies, some centralized and others decentralized (Arias et al., 2020; Sharma et al., 2022; Atangana and Oberholster, 2023; Simone Souza et al., 2023). The latter is generally conducted in developing countries, where centralized SSS receive more attention in large cities (capitals); smaller municipalities or rural areas have little centralized SSS coverage or, in many cases, are neglected by public authorities (Schrecongost et al., 2020). In fact, due to the complex operational supplies and costly maintenance and operation measures of centralized treatment technologies, decentralized approaches are increasingly being discussed among countries with more limited resources, such as Brazil. Additionally, public authorities have made efforts through the creation of programs and laws to promote SSS, highlighting the Basic Sanitation Law (Brasil, 2007) and the New Legal Framework for Sanitation (Brasil, 2020).

Another aggravating factor is the inadequate management of SW. According to the latest report from Kaza et al. (2018), approximately 2.01 billion metric tons of municipal SW are generated annually worldwide, indicating a daily per capita of 0.74 kilograms. In Brazil, 90.4% of the population regularly receives collection services; however, a large portion of this SW is irregularly disposed of in 1,572 open-air dumpsites, and approximately 2.3% of the generated SW volume ends up being recovered, meeting the sustainable economic cycle of the green economy; in the Northern region, the SW collection rate is the lowest compared to other regions of the country (79.2%) (Brasil, 2022a).

Among the various types of SW, end-of-life tires (ELTs) stand out as they are considered an environmental liability that is difficult to recycle (Abbas-Abadi et al., 2022). ELT production is expected to rebound post-pandemic, driven by fleet demand. It is estimated that over 1.6 billion rubber tires are produced annually worldwide (GLOBALSTEIN, 2021), and approximately 50.0% of one billion tires that reach the end of their useful life are discarded without any treatment (Thomas et al., 2016). In the tire report prepared by the Brazilian Institute of Environment and Renewable Natural Resources (Brasil, 2019b), it was related that Brazil produced 73,752,585 units (1,118,791.60 tons) of tires and exported 12,190,194 units (263,299.50 tons) in 2019; in the same year, it placed 62,914,819 units (859,994.68 tons) of new tires on the market. Out of the total produced, the national destination target calculated for the same year was 601,996.27 tons, with 585,391.08 tons (97.24%) properly disposed of, through processes such as co-processing (62.55%), shredding (2.14%), granulation (18.94%), and pyrolysis (16.35%).

Based on these numbers, and the notable danger of ELTs to the environment if poorly handled, new options for managing this SW should be developed (Grammelis et al., 2021). ELT management is a major challenge and a threat to the environment and public health, an environmental liability that takes over 600 years to completely biodegrade (Thives et al., 2022). Their storage is unsafe, as they act as fuels in case of fires and emit a range of toxic pollutants when burned (Mohajerani et al., 2020), contaminating soil, water, and air (Lin et al., 2008). Additionally, they favor environments suitable for the production of bacteria and viruses (Rashid and Balouch, 2017) when improperly disposed of in the environment (Oliveira et al., 2023).

There are different techniques and treatments available: aggregates in mortar compounds (Ferrández et al., 2023), sports facilities, coatings (Patricio et al., 2021), energy recovery (Petronijević et al., 2020), material recovery (Guclu et al., 2021), devulcanization for the production of rubber grains or powder and tire-like rubber (Bockstal et al., 2019), utilization of the steel contained in their structure (Polydorou et al., 2022), and ELT management, and their use as textile fiber alternatives (Grammelis et al., 2021).

However, most of these processes are complex, labor-intensive, and often expensive (Lemieux and Ryan, 1993), requiring specific equipment not available in some locations (Escobar-Arnanz et al., 2018). On the other hand, there is great interest in exploring other applications/markets for ELTs, although they are small compared to the number of tires generated each year. The reuse of ELTs in their entirety is an attractive solution, in addition to being cheaper. For example, ELTs can be used in marine applications such as ship/dock protection bumpers, wave break materials, artificial reef construction, and in the aquaculture industry (Lin et al., 2008), limiting sports territory, filling landfills (Ramos, 2005), containment barriers, protection on construction sites, and playgrounds (Thives et al., 2022).

Similarly to wastewater treatment, Brazil has created fundamental laws aimed at ELT management, mainly the National Solid Waste Policy (Brasil, 2010) and the resolution of the National Environment Council (CONAMA — *Conselho Nacional do Meio Ambiente*) (Brasil, 2009), which provide for the prevention of environmental degradation caused by ELTs and their environmentally adequate disposal, among other measures. In fact, the discussion on ELTs dates back to the 1990s, with the prohibition of importing retreated tires from other countries. In 1999, the CONAMA resolution was published with the principle of producer, importer, and state responsibilities for collecting, through reverse logistics (RL), and disposing of ELTs adequately and environmentally. RL is the reverse exercise of the conventional production flow (Prajapati et al., 2019) and a beneficial process for sustainable competitiveness among producers. Despite these regulations, both for wastewater treatment and ELTs, the practices adopted in the country cannot be considered adequate, given the deficiencies in BS services in the national territory (Thives et al., 2022).

Overall, major gaps in BS services leave countries more vulnerable. Brazil has made great progress in reducing health inequities in recent decades but still faces significant challenges in BS facilities coverage (Carcará et al., 2019). It is particularly prevalent in small and medium-sized municipalities and rural areas, which are often overlooked by BS infrastructure, as already mentioned. The most isolated residences commonly use individual sewage treatment systems, often outside technical construction and operation standards. In this sense, so-called sustainable sanitation, which prioritizes resource recycling and must protect the environment and conserve natural resources, is sabotaged, hindering the growth of other areas; therefore, the development of acceptable, economically viable, technically flexible, and environmentally correct sanitation technologies requires efforts and research (Zhou et al., 2018), to meet the local needs of resource-deprived populations and social security (Liu et al., 2020).

In this context, this work presents an applied methodology detailing the innovative and low-cost construction of a single-family sewage treatment system, using ELTs in their entirety to replace traditional masonry walls, suitable for areas where SW and SSS management are nonexistent or neglected. In the literature, this type of approach is scarce, limited to the study by Martins et al. (2021), which analyzed the technical-economic pre-feasibility in the construction of decentralized domestic sewage treatment units using ELTs. The present study has a different and more detailed construction methodology compared to the aforementioned study, facilitating its reproducibility. Thus, the objective of this research was to analyze the financial and environmental feasibility of using ELTs as raw materials in the construction of individual domestic sewage treatment systems. It should be noted that the implementation of the system is not to promote the consumption of new tires, but rather to reduce those that have not returned to the production chain with the application of RL, and are illegally disposed of in landfills or waste open-air dumpsites.

Methodology

This study represents accessible research aimed at generating actionable knowledge and tackling specific challenges prevalent in low-income regions: the lack of BS infrastructure, notably the absence of sanitary sewer collection services and treatment facilities, along with the inadequate disposal of ELTs. A cost-effective constructive methodology has been proposed for individual/single-family treatment units of domestic sewage, employing ELTs as a replacement for conventional masonry walls. This innovative approach was termed the Tire-Constructed Anaerobic Single-Family Treatment System (TIRE-ATS). In Figure 1, the schematic flowchart outlines the stages of the proposed methodology: I. data collection to assess current sanitation conditions and select a suitable residence for TIRE-ATS implementation; II. system design and sizing; III. system implementation involving excavation, reactor assembly, fixation, and waterproofing; and IV. analysis of TIRE-ATS advantages, with focus on circular economy principles.

Step 1

Data collection

The study commenced with data gathering to understand the local demand for a single-family sewage treatment solution and the inadequate disposal of ELTs, aiming to identify the suitable neighborhood for implementing the system and the household willing to host the reactor implementation. This involved hard research through documentaries and reports. Also, an intensive literature review was provided focusing on the current conditions of BS, particularly regarding SW management and sewage treatment.

Case study

The study was conducted in the urban area of Tucuruí (PA), a municipality in the Northern region of Brazil, within the Legal Amazon, situated on the left bank of the Tocantins River, where the Tucuruí Hydroelectric Plant is located. The municipality has a population of 91,306 inhabitants, with 41.60% earning up to half the minimum wage monthly, classified as low income (Brasil, 2021). Among the main municipal problems is the lack of BS: only 17.62% of its sewage is adequately managed, either through centralized collection and treatment systems or individual solutions, with 82.38% left untreated and uncollected, forcing most of the population to resort to technically inadequate individual solutions (IAS, 2013).

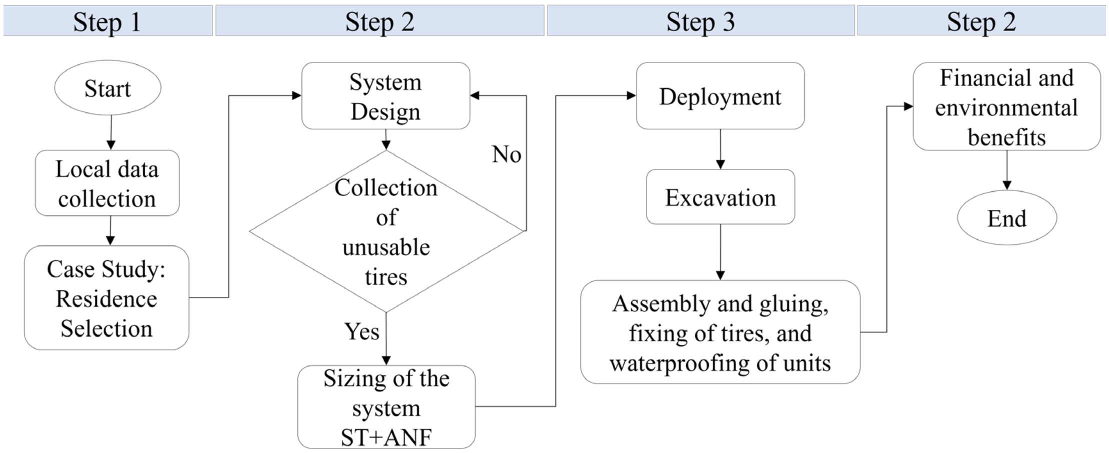

Figure 1 – Steps in the proposed methodology.
ST: septic tank; AnF: anaerobic filter.

In the municipality, SW management is deficient, with the persistent existence of unregulated waste open-air dumpsites. In 2020, 4,011 ELTs were discarded monthly, of which 58.43% (2,343) were collected as domestic waste and disposed of in open-air dumpsites, 19.80% were resold for revitalization, and 21.77% were passed on to artisans, resold to tire shops, or used on private properties for various purposes (Mousinho and Mesquita, 2020).

Given this scenario, a household in the municipality's most densely populated neighborhood was chosen, taking into account the residents' interest. The proposed system constitutes an individual, single-family solution designed to safeguard public health, water resources, and soil integrity. Previously, the residence's effluents were discharged into a septic tank (ST) without any structural masonry waterproofing — a common practice in the municipality. Figure 2 presents the geographic positioning of Tucuruí in Brazil, highlighting the selected residence, and the inadequately constructed ST from before.

TIRE-ATS design

End-of-life tires selected

The ELTs were collected from a tire repair shop totaling 35 units, measuring 1,051 m in diameter and 0.241 m in width each, commonly used on buses and trucks, without structural damage that could compromise the experimental system's function. If the tires were unsuitable, additional collections would be necessary.

System design: septic tank followed by anaerobic filter

The system was designed under specific Brazilian standards for individual domestic sewage treatment systems (ABNT, 1997a, 1997b), constructed like a conventional system, but with necessary adaptations, to determine the number of tires for each reactor. The system's reinforced concrete components followed the environmental aggressiveness and coverage recommendations specified in ABNT (2004). The design comprised an ST followed by an anaerobic filter (AnF). In Brazil, this structure is commonly used to serve small municipalities or communities lacking SSS.

The ST volume was determined by Equation 1, where *Vut* is the useful volume of the ST in m^3; *N* is the number of persons or units contributing [person]; *C* is the waste contribution [m^3/person.day]; *T* is the hydraulic retention time [day]; *K* is the sludge accumulation rate [day] equivalent to the time of fresh sludge accumulation; and *Lf* is the fresh sludge contribution [m^3.person^{-1}.day^{-1}]. Conventional tank dimensions vary horizontally and vertically, but for TIRE-ATS, only the vertical dimension varied due to the fixed characteristics of the ELTs used. Each tire's volume was 0.20 m^3, calculated as a cylinder by multiplying the circle's area by the tire's height (0.241 m), when placed horizontally. The relationship between *Vut* and the volume of a tire (*vp*) determined the number of tires used in the ST construction, as shown in Equation 2, where *Npt* is the number of tires used in the ST construction.

$$Vut = 1{,}000 + N(CT + KLf) \quad (1)$$

$$Npt = \frac{Vut}{vp} \quad (2)$$

With the number of tires defined, it was decided to build two ST reactors in series (ST-I and ST-II), reducing the depth of each unit while ensuring they could contain the produced household's sewage volume. The total number of calculated tires (*Np*) was divided to maintain proportionality in volume and the minimum recommended useful depth specified in ABNT (1997a). Thus, ST-I receives domestic effluent and directs it to ST-II via a polyvinyl chloride (PVC) pipe.

The AnF reactor should have a filter bed height limited to 1.2 m (ABNT, 1997b), with half of a false bottom (0.6 m), including the bottom slab's thickness. The useful volume of the filter bed (*Vuf*), in m^3, was determined by Equation 3. The number of tires (*Npf*) was calculated by Equation 4, considering the recommended minimum height, where *hf* is the filter bed height equal to 1.2 m, and *hp* is the height of each tire.

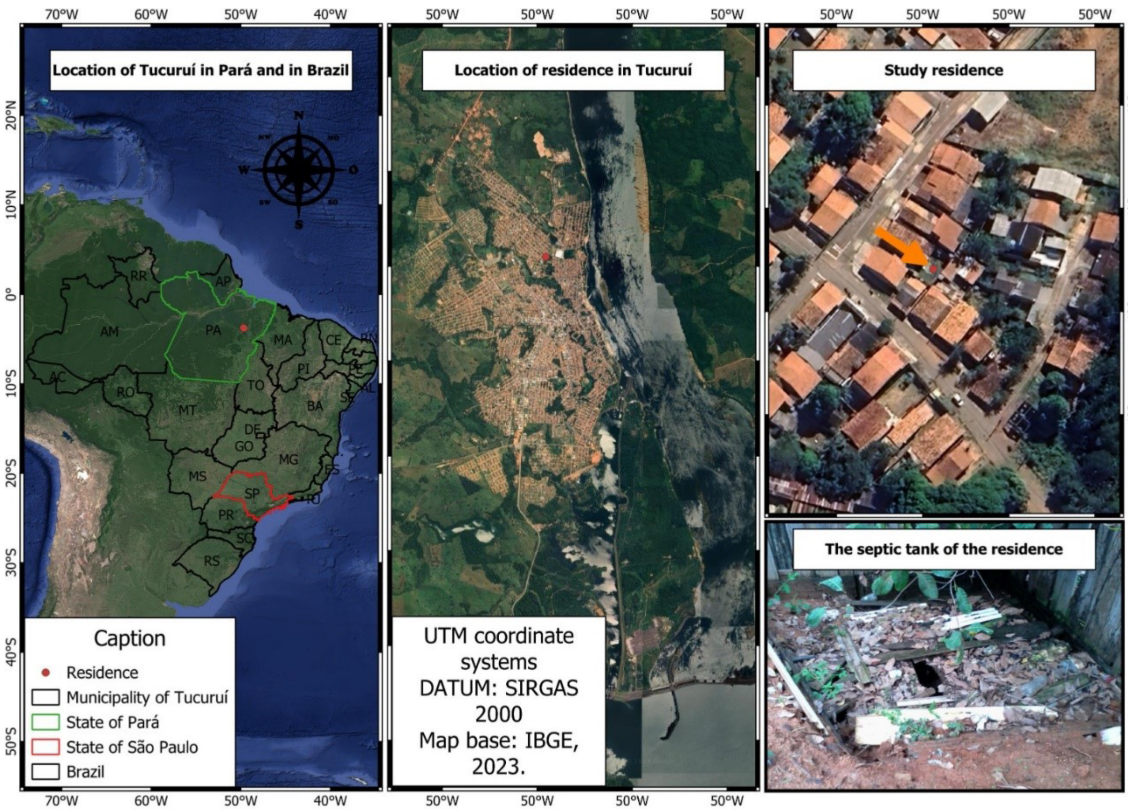

Figure 2 – Geographic location of Tucuruí in Brazil (A), the selected household (B), and the previously existing septic tank (C).
UTM: Universal Transverse Mercator; SIRGAS: Geodesic Reference System for the Americas; IBGE: Brazilian Institute of Geography and Statistics.

$$Vuf = 1.6\,NCT \quad (3)$$

$$Npf = \frac{hf}{hp} \quad (4)$$

Step 3: TIRE-ATS implementation

Excavation

The excavation was carried out manually. Despite the region's marked characteristics of the Amazonian winter, with significant precipitation volumes (10.4 mm.day^{-1}) (Paccini et al., 2018), no groundwater table rise was observed. The trenches were excavated in an "L" shape to utilize available space and accommodate TIRE-ATS at different levels to facilitate sewage transportation by gravity. Subsequently, a concrete piece was built at the bottom of the three trenches (ABNT, 2004). During concreting, a tire was added to the base of each unit to prevent leaks or seepage at the system's base.

Reactors construction, assembly, gluing, tire fixation, and waterproofing

Asphaltic mass, resulting from the mixture of RL-1C asphalt emulsion and sand (in a 1:2 ratio), was used for gluing and fixing the tires and waterproofing the system. The mixture followed ABNT (2006) recommendations and the Viapol Manual (2015) procedures. The material was chosen for its easy accessibility, relatively low cost, resistance to sewage treatment by-products, and non-interference with the domestic sewage purification process. Figure 3 shows the asphaltic mass produced (Figure 3A) and the mass applied to the tires for fixation and unit waterproofing (Figure 3B).

The tires were arranged and glued to structure the STs. For the AnF's false bottom, a reinforced concrete slab was prepared on two tires, with 15 holes of 0.025 m, equipped with two PVC pipes of diameters 0.10 and 0.15 m for effluent discharge and cleaning, respectively. The holes were arranged according to the reinforcement's spaces, ensuring the steel was not covered by less than 45 mm, affecting its strength (ABNT, 2004).

The three-day curing process was observed for concrete and asphaltic mass. Subsequently, the other half of the filter bed was filled with gravel nº 4 (ABNT, 1997b). A PVC pipe cut in half served to collect the treated effluent, directing it to the ground. The units were drilled, and 100 mm PVC pipes were inserted for effluent drainage without compromising the system's structure. A leak test was performed by filling with water for 24 hours (ABNT, 1997a, 1997b), yielding positive results. The reactors were adequately sealed with a slab, allowing access for cleaning. The layout of the installed system is depicted in Figure 4.

Figure 3 – Asphaltic mass production (A) and tire-constructed septic tank with fixed end-of-life tires (B).

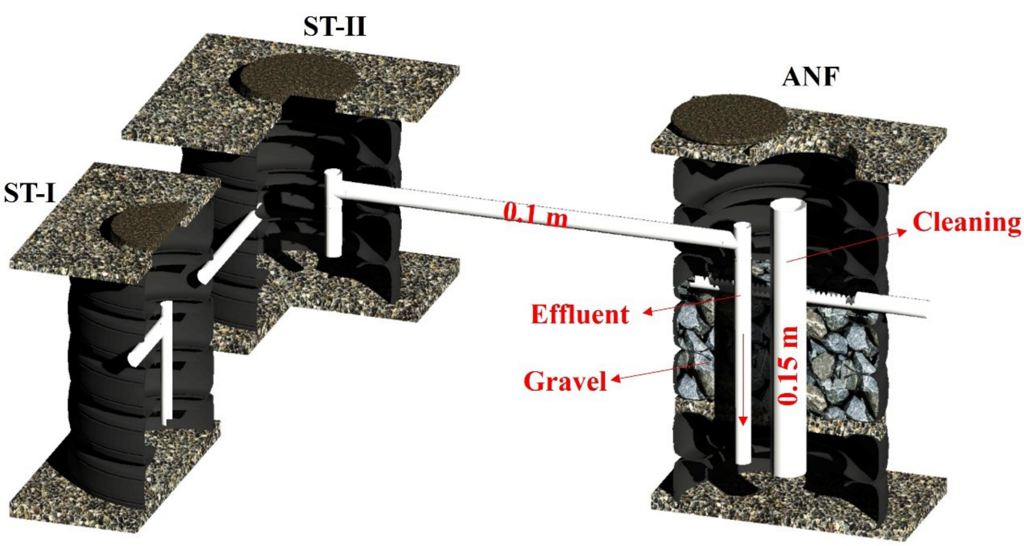

Figure 4 – Final layout of the implemented Tire-Constructed Anaerobic Single-Family Treatment System.

Step 4: financial and environmental advantages

The financial advantage was analyzed by comparing budgets for TIRE-ATS and conventional masonry systems, both sized for the same residential number of persons. Materials were purchased from Tucuruí's market to adjust the systems' prices to local reality. The environmental benefit involved estimating the number of tires that would be removed from the environment and reused in system construction. Equation 5 presents the estimate if all households in the studied neighborhood adopted TIRE-ATS, where *Ntpr* is the total number of tires reused to serve the neighborhood, *Nr* is the number of households in the neighborhood (3,599) (Eletronorte, 2023), and *Nps* is the number of ELTs reused to build the system.

$$Ntpr = Nr.(Nps) \tag{5}$$

Results And Discussion

Basic sanitation conditions

In Tucuruí, the SW collected is inadequately disposed of in an unregulated open-air dumpsite, which still persists in the municipality. During a visit, the burning of ELTs was observed, as depicted in Figure 5. It is interesting to highlight that this observed event was deliberate and on a small scale, which usually goes unrecorded. This complicates monitoring on a global scale and fosters ignorance of its frequency (Downard et al., 2015). Depending on the number of tires, a pseudo-controlled situation can result in an uncontrolled fire, which is difficult to extinguish. In fact, it is proven that burning, as well as other conventional methods generally adopted to manage ELTs, such as storage and disposal in landfills, causes substantial adverse impacts on human health, the environment, and ecological systems (Yadav and Tiwari, 2019).

Figure 5 – Burning of end-of-life tires at a waste open-air dumpsite in Tucuruí.

To mitigate this problem, the implementation of RL is highlighted as a potent strategy for managing these hazardous wastes. Unfortunately, this practice remains notably absent in the municipality, which lacks an official collection point for ELTs, initial RL stages, and termed ecopoints (Reciclanip, 2021). Consequently, it can be stated that the absence of such infrastructure compromises the effective return of ELTs to the supply chain for further processing (Shahidzadeh and Shokouhyar, 2022). The nearest collection point is 76 km away, in a neighboring municipality (Reciclanip, 2021). Given that governments have mandated waste management practices through regulatory requirements (Govindan et al., 2020), it is essential for the municipal government and tire distributors/retailers to collaborate in establishing and maintaining a functional RL chain. This involves periodically collecting and transporting the ELTs to designated facilities, thereby preventing them from being illegally deposited in dumpsites, with a focus on addressing social and environmental concerns alongside economic considerations.

Currently, oversight of SW disposal falls under the purview of the Endemic Unit of Tucuruí, an entity under municipal jurisdiction primarily tasked with disease eradication efforts (Prefeitura Municipal de Tucuruí, 2020). Unfortunately, this oversight does not extend to monitoring discarded tires, with existing efforts limited to periodic surveillance, particularly during the Amazonian rainy season, when diseases associated with water accumulation in tires become more prevalent (Mousinho and Mesquita, 2020).

When tires are left in open-air environments, their curved structure becomes prone to accumulating stagnant water, creating breeding grounds for pests such as rats and mosquitoes. This phenomenon, as noted by Thives et al. (2022), poses a significant public health concern. Brazil, with its predominantly tropical climate and high precipitation levels, has long grappled with issues related to mosquito-borne diseases, and the persistent proliferation of vectors in urban areas exacerbates this challenge (Merver Tunali et al., 2021). Illegally discarded tires serve as ideal habitats for mosquitoes that transmit diseases such as malaria, leishmaniasis, and arboviruses including dengue, Zika virus, and chikungunya, some of which can be fatal to humans.

TIRE-ATS implementation

For the implementation of the system, labor was provided by researchers from the Federal University of Pará (UFPA), with assistance from the residents themselves. Sampaio (2011) mentioned that Brazil's accumulated experience underscores the importance of considering the social and cultural organization and technological adaptability of the served population when involving them in such initiatives. The proposed system is unknown, and its introduction implies radical changes in habits, which can cause rejection by the family, who needs to understand that not treating effluents can harmfully impact their lives (Salles Figueiredo, 2019). In this case, the participation of residents indicated acceptance of the technology, which was confirmed when other people became aware of the installation and showed interest. A few centimeters of PVC pipe were the SW resulting from the implementation of the TIRE-ATS. All steps were carefully designed to avoid generating construction waste.

The sizing parameters for the TIRE-ATS are presented in Table 1, comprising both values, calculated and fixed tabulated. Figure 6 exhibits: a. the trenches excavated in "L" shape at appropriate levels for gravity flow (ST-I: 1.46 m, ST-II: 1.30 m, and AnF: 1.79 m); b. concrete piece placement at the trench bottom, with dimensions of 1.2 × 1.2 × 0.1 m; and c. fixation of the tires at the base of the units. Figure 7 depicts: a. assembly stages of the TIRE-ATS set (organization and gluing of the tires to structure ST-I and ST-II; b. construction of the false bottom of the AnF with reinforced concrete slab on two tires and PVC pipes (0.1 and 0.15 m in diameter); c. AnF filling with gravel, and installation of the treated sewage collection pipe; d. drilling of the reactors to interconnect the units with PVC pipes, and completion of backfilling the entire system to level the ground; and e. closure of the reactors with reinforced concrete slab and paving of the area.The researchers' team, including residents, conduct ongoing monitoring of the system's performance through planned collections of treated effluents and are prepared to address any maintenance needs, aiming to ensure the long-term viability of the entire system. These activities adhere to a monthly schedule, with residents conducting visual inspections and reporting irregularities based on guidance from researchers. In turn, UFPA researchers conduct monthly visits to monitor soil conditions, analyzing samples collected around the units for potential leaks, and collect treated effluent at the AnF outlet.

This evaluation will continue until a significant number of treated sewage samples is obtained, and will then transition to quarterly assessments aimed at identifying the system's lifespan. Currently, the TIRE-ATS has not yet produced treated effluent due to its short operating time. Conventional systems (ST+AnF) typically achieve removal rates ranging from 60 to 95% (ABNT, 1997a, 1997b). Monitoring the TIRE-ATS effluent and its long-term integrity is crucial to confirming its effective and sustainable operation, its status as a low-cost alternative, and the durability of its entire structure. In fact, these procedures are indispensable for the overall success of this project.

Financial advantage

Table 2 displays the budgetary comparison between the TIRE-ATS and the conventional masonry system. Implementing the TIRE-ATS is USD 169.47 (18%) cheaper than the conventional system, a significant cost difference, particularly considering that the beneficiaries of this technology are typically economically disadvantaged. For example, in Brazil, where the minimum wage is USD 275.40, the savings from implementing TIRE-ATS represent 14.0% of this income. Considering that 41.6% of the urban population of Tucuruí earns up to half the minimum wage, these savings could be even more impactful. Furthermore, it is worth mentioning the initiative to reuse ELTs that would be inadequately deposited in dumpsites, and the fact that the use of ELTs as raw material for the TIRE-ATS fosters a market for these SW, especially for regions where RL is not practiced or neglected, and ELTs is considered an environmental liability. The provision of centralized systems became unfeasible in certain regions of Brazil (Brasil, 2018), thereby encouraging the decentralization of treatment and promoting the regulation and continuous improvement of individual treatment (Tchobanoglous and Leverenz, 2013). Consequently, this form is viewed as complementary rather than opposed to centralized method, thereby fostering ongoing research in the field to enhance the single-family treatment technology. As advancements occur, more robust individual technologies with increased durability must be provided. However, due to the materials and technologies used in their construction, the final price is not attractive to the most economically disadvantaged, reaching approximately 73.0% (USD 293.20) higher than the TIRE-ATS (AZU, 2023; FORTLEV, 2023), rendering it unviable for most families in Tucuruí. Therefore, considering the cost and sustainability of the proposed system, this unit appears to be a promising solution for individual domestic sewage treatment, especially where ELTs represent an environmental liability.

The implementation cost of the TIRE-ATS could be even lower if sourcing more affordable raw materials for its construction is considered. On the other hand, labor is a point that deserves attention due to the increased detailing in the construction of the system, which could raise the final price. In this case, it is suggested that the implementation of the system involve the beneficiaries themselves, avoiding expenses on specialized labor. According to Tonetti et al. (2018), one way to reduce implementation costs is through collective work efforts. Another approach to cost reduction is the use of alternative materials available locally (Salles Figueiredo, 2019). Since ELTs are abundant in Tucuruí, this represents a sustainable way to reuse them.

Table 1 – Calculated values and fixed tabulated values used for sizing the TIRE-ATS.

Sizing				Fixed tabulated values	
ST		**AnF**		*N**	4 persons
Vut	1.70 m³	*Vuf*	0.765 m³	*C**	130 liters.person^{-1}.day^{-}
Npt	9	*Npf*	5	*T**	1 day
Npt ST-I	5	*Npf base*	2	*K**	57
Npt ST-II	4	Total ELTs	7	*Lf**	1 liters.person^{-1}.day^{-1}
Npt base	2	-		*T (AnF)***	0.92 day
Total ELTs	11	-		Height ELT	0.241 m
Total ELT system		**18**		Diameter ELT	1.051 m
				Volume ELT	0.20 m³

Fonte: *(ABNT, 1997a); **(ABNT, 1997b).
ST: septic tank; AnF: anaerobic filter; Vut: useful tank volume; Npt: number of tank tires; ELTs: end-of-life tires; Vuf: useful volume of the filter bed; Npf: number of filter tires; N: number of persons; C: waste contribution; T: hydraulic retention time; K: sludge accumulation rate; Lf: fresh sludge contribution.

Figure 6 – Excavation of the trench for accommodating the TIRE-ATS (A); concrete piece at the bottom of the trenches (B); fixation of tires at the base of the units (C).

Figure 7 – Assembly and fixation of ST-I and ST-II (A); arrangement of pipes, construction of the concrete plate (false bottom) (B); filling of the AnF with gravel and installation of the treated sewage adhesive tube (C); drilling of the units and final arrangement (D); closure and system design (E).

Environmental advantages

It was estimated that 64,782 ELTs are needed to implement the TIRE-ATS in the residences of a single neighborhood in Tucuruí. With an average of 18 ELTs required for system implementation, and 1,405 (60% of 2,343 ELTs) discarded and collected as common SW per month in Tucuruí (Mousinho and Mesquita, 2020), it would be possible to benefit 78 households with the proposed system construction in just one month. While the quantity of tires may vary depending on the number of residents and the system's sizing, this estimate is highly relevant and sheds light on the ELTs discarded in the municipality. Moreover, the system offers high durability, given the difficulty of ELT decomposition. Its construction is characterized by reusing SW, as the repurposed ELTs undergo no alterations in their physical, physicochemical, or biological properties that could transform them into inputs or new products (Brasil, 2010).

Environmental aspects are typically addressed when discussing decentralized systems, especially when they operate incorrectly. For instance, rudimentary ST and any excavation in soil without protection on the sides and bottom facilitate sewage infiltration and subsequent percolation of sewage and pathogens into the subsoil, contaminating aquifers (Rowles et al., 2020). When poorly constructed, these units cause soil damage, which is strongly linked to public health, environmental protection, and the population's water needs (Kheirandish et al., 2020). In Brazil, pollutant incidence in shallow wells has been reported due to groundwater contamination by sewage from precarious individual installations (Sales e Souza et al., 2021). To prevent this, the use of decentralized sewage treatment units with impermeable materials (Ahmada and Ghanem, 2021) such as polyethylene, fiberglass, or prefabricated materials is recommended (Brasil, 2019a). Since TIRE-ATS's impermeability has been tested and verified, its implementation is highly justified and recommended.

In essence, this presents an advantageous opportunity to ensure access to efficient sewage treatment while facilitating an ecologically sound solution for reusing ELTs, conserving water resources, and enhancing public health. For instance, the municipality is traversed by two waterbodies, both tributaries of the Tocantins River. Due to the lack of sanitation in the municipal headquarters, many households along these rivers discharge their waste directly into them, jeopardizing the water quality of this hydrographic system and posing risks to local population life and water-based tourism. Furthermore, the implementation of TIRE-ATS contributes to the achievement of at least five of the 17 UN SDGs, especially Goal 6 - Clean Water and Sanitation (Romano et al., 2023). As most ELT reuse and recycling processes are costly (Hejna et al., 2020), the proposed system represents an extremely cost-effective solution with notable environmental advantages.

Limitations and disadvantages of TIRE-ATS

Despite the various advantages presented by the proposed system, it is worth noting that the Brazilian Association of Technical Standards (ABNT — *Associação Brasileira de Normas Técnicas*) does not regulate this type of structure composed of ELTs, and Brazilian environmental legislation does not permit such construction. Therefore, the implementation of TIRE-ATS provides a valuable opportunity to analyze and confirm its structural efficiency and potential for domestic sewage treatment, which can only be evaluated over time. Due to the short implementation period of the system, no data collection was performed. Additionally, it is observed that the literature on the proposed theme and methodology in this work is scarce, making it difficult to compare, validate, and discuss this technology based on previous research. This scenario was expected, considering that the motivation behind this work is the absence and/or neglect of BS services.

Since TIRE-ATS constitutes a sustainable construction technology, the focus of the study was to benefit only one household with the implementation of the first unit considered as a test. At this initial stage, the environmental and economic gains of removing ELTs from the environment for the most populous neighborhood of Tucuruí were estimated, assuming the verticalization of this technology. To implement TIRE-ATS on a larger scale, greater investments and unrestricted support from the government would be necessary to identify projects, select and transport ELTs, and purchase the necessary materials.

Despite its constructive success thus far, potential environmental impacts inherent in the permeabilization of sewage contained in the unit, leaching of contaminants from ELTs that could pollute water sources, chemical interaction between ELTs and sewage, and inhibition of the sewage treatment process due to tire degradation, have been disregarded. These factors can only be assessed over time. As previously mentioned, this research aimed to provide a low-cost, decentralized construction alternative for sewage treatment in regions where such systems are nonexistent — a goal that has been achieved.

An important limitation is the lack of studies on the efficiency of geotechnical stability between the soil and the installed system. However, due to the shallow depth of each unit, it is expected that this stability will not be affected, especially since no water table rise was observed during the Amazonian winter prior to TIRE-ATS implementation. Additionally, the scarcity of ELTs is considered a limitation; their implementation may be unfeasible in small isolated rural areas where automobiles (buses and trucks) are nonexistent, thus ELTs are also absent. Another unfavorable aspect is the difficulty in acquisition, availability, and transportation of tires, which is hindered by the absence of monitoring of tire disposal, especially in medium and small municipalities, and rural areas.

Table 2 – Budgetary comparison of systems.

Material	TIRE-ATS		Conventional masonry-built system	
	Consumed material	Total cost (R$)	Consumed material	Total cost (R$)
Tire (unit)	18	0.00	-	-
Ceramic brick (unit)	-	-	417	77.26
Washed Fine Sand (m^3)	0.04	0.58	0.35	5.12
Asphalt Emulsion (m^3)	0.02	40.72	-	-
Gravel (m^3)	1.11	16.23	0.71	10.38
Portland Cement with Addition of Pozzolan - 32 RS (kg)	389	74.35	408.33	78.04
PVC Pipe 25 mm (m)	1.50	0.93	8.00	4.93
PVC Pipe 100 mm (m)	7.82	9.81	7.74	9.70
PVC Pipe 150 mm (m)	2.90	9.05	1.40	4.36
100 mm Connection (unit)	3	6.13	3	6.13
Steel deformed bar with 500 MPa – 8.0 mm (kg)	20.60	4.46	20.00	4.33
Steel deformed bar with 600 MPa – 4.2 mm (kg)	18.50	3.86	20.00	4.17
Steel deformed bar with 600 MPa – 6.3 mm (kg)	4.90	1.02	-	-
Binding Wire (m)	1.00	2.32	4.00	2.31
Total (R$)		**169.47**		**206.73**

Conclusion

This study reports a methodology detailing the implementation of a conventional ST as an individual sewage treatment unit, where its construction incorporates ELTs as substitutes for traditional masonry walls. The initiative targets single-family domestic sewage treatment, thereby promoting circular economy principles by integrating ELTs resulting from inefficient RL practices and discouraging inadequate tire disposal practices. The study demonstrates the effectiveness of this innovative technology thus far, resulting in an 18% reduction in implementation costs compared to conventional masonry systems. This constitutes a low-cost technology that not only promotes public health but also mitigates environmental impacts associated with the unrestricted discharge of sewage and ELTs disposal.

The sustainability of tire reuse represents a significant environmental advantage, contributing to the fulfillment of at least five SDGs. Considering the quantity of ELTs discarded in the studied municipality, which are not effectively managed by current RL practices, it is possible to implement TIRE-ATS in 78 households per month. Moreover, the project's applicability extends worldwide, especially in areas lacking sanitation infrastructure and efficient ELT management strategies. It offers an effective approach to removing or reducing ELTs from clandestine areas of small and medium-sized municipalities, where tire disposal practices are lacking, and ELTs represent an environmental liability. Despite the constructive success of the primary objective of the proposed methodology with TIRE-ATS thus far, periodic monitoring is essential for ensuring the overall success of this system. This monitoring aims to verify its impermeability, sewage treatability, and long-term structural integrity. Over time, to further enhance this technology, future studies must conducted to comprehensively assess the potential environmental impacts associated with the use of ELTs in construction systems, analyze chemical reactions between effluent and tires, and evaluate the geotechnical stability between the soil and TIRE-ATS.

Authors' Contributions

FREITAS, P.V.: conceptualization; data curation; methodology; software; project administration; writing – original draft. SA, J.H.M.: writing – original draft. SOUSA, T.A. T.: formal analysis; writing – original draft; writing – review & editing. CASTRO, M.M.: implementation; project administration, resources; visualization; software. PADILHA, J.L.: implementation; methodology; writing – original draft. PINHEIRO, A. G.: implementation; software. SOUZA, D.E.S.: implementation; conceptualization; formal analysis; project administration; supervision; writing – original draft; writing – review & editing.

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