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Water consumption in the production process of the sugar-energy industry: case study in the northwest of São Paulo (Brazil)

Consumo de água no processo produtivo da indústria sucroenergética: estudo de caso no noroeste paulista (Brasil)

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ABSTRACT

Brazil is the world's largest producer of sugarcane. The importance of rational, sustainable, and efficient management of resources in the production process of the Brazilian sugar-energy industry is remarkable, mainly related to water use. In this context, the present paper aimed to analyze, in the last decade, the consumption of water in the productive process of Vale do Paraná S/A Álcool e Açúcar plant, in addition to elucidating the technologies implemented in the industrial area that contributed to the reduction of consumption. The methodology adopted consisted of obtaining data and information from bibliographic researches, technical bulletins, and field visits. The sugar-energy plant showed a 34.88% reduction in water consumption in the last decade, obtaining 0.86 m^3 ton^{-1} in 2012 and 0.56 m^3 ton^{-1} in 2021 of processed sugarcane, which can be particularly important in intense periods of drought, such as those experienced in recent years. The main technologies that contributed to this reduction were: the dry cleaning of sugarcane; the use of closed circuits; condensate recovery; water reuse; and the implementation of a flow rate measurement system. The company reached a lower consumption than required for the year 2024, but there is no limit to reduction. In the case of the plant under study, it was observed that special attention should be given to industrial effluents, mainly vinasse, with the possible implementation of more treatment steps before application in the field as fertigation.

Keywords: sugarcane; industrial technologies; water reuse; water resources planning.

RESUMO

O Brasil é o maior produtor mundial de cana-de-açúcar. É notável a importância da gestão racional, sustentável e eficiente dos recursos no processo produtivo da indústria sucroenergética brasileira, principalmente relacionada ao uso da água. Nesse contexto, o presente trabalho buscou analisar, na última década, o consumo de água no processo produtivo da Vale do Paraná S/A Álcool e Açúcar, além de elucidar as tecnologias implantadas na área industrial que contribuíram para a redução do consumo. A metodologia adotada consistiu na obtenção de dados e informações de pesquisas bibliográficas, boletins técnicos e visitas de campo. A usina sucroenergética apresentou redução de 34,88% no consumo de água na última década, obtendo 0,86 (2012) e 0,56 (2021) m^3 ton^{-1} de cana-de-açúcar processada, o que pode ser particularmente importante em períodos intensos de estiagem, como os vivenciados nos últimos anos. As principais tecnologias que contribuíram para essa redução foram: reúso da água; limpeza de cana-de-açúcar a seco; utilização de circuitos fechados; recuperação de condensados; e implantação do sistema de medição de vazão. A companhia atingiu consumo inferior ao requerido para o próximo ano, porém não existe um limite para a redução. No caso da usina em estudo, observou-se que uma atenção especial deve ser dada para os efluentes industriais, principalmente a vinhaça, com possível implantação de mais etapas de tratamento antes da aplicação no campo como fertirrigação.

Palavras-chave: cana-de-açúcar; tecnologias industriais; reúso de água; planejamento de recursos hídricos.

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Introduction

Sugarcane accounted for approximately 20% of global agricultural production from 2000 to 2018, almost double the participation of corn, the second most produced crop in the world (FAO, 2020). Despite its importance for Brazilian economic development (regional growth and income generation through jobs and better working conditions), the sugar-energy agro-industry has always had its image linked to environmental damage (Loarie et al., 2011; Zhang et al., 2015; Jaiswal et al., 2017; Monteiro et al., 2018; Zheng et al., 2022). In the past, water resources were used extensively by the sector and the final disposal of the effluents generated was carried out, in most cases, without proper control, which can negatively impact the receiving water courses (Bega et al., 2021; Bega et al., 2022; Ribeiro et al., 2022). However, in the 1990s, the sector began to worry about the sustainability of its production processes amid the competitive market that emerged, strategically shifting to a more organized production model (Santos, 2009). The main positive signs pointed out by the sugar-energy market nowadays are the management of its processes, the large-scale technological incorporation, and environmental preservation strategies, in addition to the modernization of agricultural areas with the harvesting of sugarcane in green form, eliminating burning and unhealthy working conditions (Moraes et al., 2015; Monteiro et al., 2018).

The Brazilian sugar-energy sector is considered the most modern and competitive in the world (Fito et al., 2023) and ranks first in sugarcane production (37.6% of the total world harvest area in 2019), followed by India (18.9%), Thailand (6.9%), China (5.3%), Pakistan (3.9%), and Mexico (3.9%) (FAO, 2020). since there is an extensive area available for crop cultivation and a favorable climate condition for its development (Zheng et al., 2022). In the country, approximately 7.8 million hectares (0.9% of the national territory) are occupied by sugarcane plantations (Bordonal et al., 2018), located mainly in the Center-South and northeast areas (Zheng et al., 2022).

Spatially, sugarcane ethanol plants are evenly distributed in the interiors of most Brazilian states (IBGE, 2017). This generates positive economic and social impacts when compared, for example, to oil production, in which the location of oil industries results, for the most part, in centralized economic and social development, limited to cities in coastal regions (Pereira, 2009; Hernandes et al., 2014).

As much as Brazil has great water availability, agro-industrial managers must always seek increasingly restrictive water consumption and loss rates in order to preserve water resources, adapting their production to progressively more efficient and sustainable techniques (Freitas et al., 2019). According to the National Water and Sanitation Agency (*Agência Nacional de Águas e Saneamento Básico* – ANA, 2009), for decades, the mills used open circuits to cool the boilers, and the sugarcane used washing technique to remove solid residues carried during the crop cutting operation (Gonçalves Filho et al., 2015). However, the aforementioned consumption scenario has changed (ANA, 2019; Torquato and Jesus, 2019). In the last 40 years, the Brazilian sugar-energy sector has reduced water consumption in the industrial process by approximately 95%, mainly due to water reuse and the modernization of production plants. Despite these improvements, the sector still seeks to reduce water consumption and effluent generation. Currently, there are few contributions in the literature on the evolution of water use in the industrial processes of Brazilian sugarcane mills and how adopting new technologies has contributed to reducing water consumption. Given this setting, the objective of this study was to present and analyze the water consumption in the last ten years of a sugar-energy plant in the northwest of São Paulo, as well as to identify the technologies implemented in the industrial area in the same period. The results obtained from the study may contribute to the development and integrated management of water use in the sugar-energy sector.

Theoretical background

In Brazil, there are few crops of great relevance (Zheng et al., 2022), and among all those cultivated, five occupy 70% of the area planted in agriculture: rice, sugarcane, corn, beans, and soybeans (IBGE, 2017). The sugarcane is the third largest crop in the country. Ahead of it are only soybean (~36 million hectares) and corn (~13 million hectares) plantations. National sugarcane production was potentially established in the state of São Paulo, combining factors of economic, technological, and scientific development with the availability of areas for its plantation. This set of systems made São Paulo the major Brazilian producer of sugar and ethanol (Furtado et al., 2011; Alves et al., 2021). According to the National Agency of Petroleum, Natural Gas and Biofuels (*Agência Nacional do Petróleo, Gás Natural e Biocombustíveis* — ANP, 2020), the country has 360 sugar-energy plants in operation, with São Paulo alone having 151 plants installed.

Despite the high demand for water in the different production stages, the sugar-energy sector has a high reuse rate (Pacheco and Hoff, 2013; Fito et al., 2023). In industrial parks, reuse water must be applied according to the required water quality, which can be used directly or after specific treatments to avoid scaling and corrosion in the equipment. Cooling systems can operate with reused water. They are "open" when there is no water reuse; "semi-open" when the water used is directed to cooling ponds, towers, or sprays, where significant water loss occurs and replacement is necessary; and "closed" when there is no evaporation of water in cooling, resulting in minimal replacement. The open system has been widely used in Brazilian plants in the last decades (Torquato and Jesus, 2019). However, due to water use charges and water deficits in recent years, the sector has implemented improvements in plants with the use of closed water circuits.

Regarding industrial effluents, sugarcane mills discharge approximately half of the water used in their production processes into water courses in wastewater form with different ranges of pollutants (Table 1). In the current world scenario, about 2 m^3 of water is used to process 1 ton of sugarcane, resulting in the discharge of approximately 1 m^3 of effluent (Prakash and Capoor, 2018). According to ANA (2009), a mill that processes 1 million tons of sugarcane per year and produces sugar and alcohol has a potential organic pollutant load at harvest equivalent, on average, to a city of 1.5 million inhabitants. The wastewater generated in the sugar-energy industries is made up of effluents from the industrial process (sugarcane washing systems, floors, cooling circuits, purges from the chimney gas scrubber system, and leftover condensed water). The most common treatment system consist of decantation, flotation, cooling, separation of water and oil, and sanitary sewage treatment in compact plants. The final disposal is usually carried out in soils through irrigation with vinasse (fertigation) (Martinelli et al., 2013; Bordonal et al., 2018).

Material and Methods

Characterization of the study area

The study was developed at Vale do Paraná S/A Álcool e Açúcar, which has its administrative headquarters in Suzanápolis, northwestern São Paulo (20°23'21.49" S; 51° 1'56.21" W) and was implemented in 2006. The plant produces sugar, ethanol, and electricity by burning sugarcane bagasse. The crop covers 27,000 hectares, including the municipalities of Pereira Barreto, Suzanápolis, Sud Mennucci, Santa Fé do Sul, Santana da Ponte Pensa, Três Fronteiras, Rubineia, Nova Canaã Paulista, Marinópolis, Ilha Solteira, and Aparecida D'Oeste. The cultivation areas are mostly rented out, except for the industrial park and a property of native vegetation acquired for registration as a legal reserve area. Sugarcane harvesting is 100% mechanized and does not use the burning technique. The plant has an operating license issued by the Environmental Company of São Paulo State (*Companhia Ambiental do Estado de São Paulo* — CETESB) for crushing up to 2.4 million tons of sugarcane per year.

Table 1 – Summary of industrial process effluents and physicochemical characteristics.

Effluent		Specific flow rate	pH	T (°C)	SW ($mL\ L^{-1}$)	COD ($mg\ L^{-1}$)	BOD ($mg\ L^{-1}$)	OG ($mg\ L^{-1}$)
Sugarcane washing		2–5 ($m^3\ t^{-1}$ sugarcane)	5–6	room	5–10	280–700	180–500	0
Cooling of equipment		0.7 ($m^3\ t^{-1}$ sugarcane)	7	<30	<0.5	0	0	-
Barometric columns and multijets		70–100 ($L\ kg^{-1}$ sugar)	6–7	45	<0.2	20–80	10–40	0
Cooling Distillery	Wort juice	30 ($L\ L^{-1}$ ethanol)	7	<45	0	0	0	0
	Tanks	60–80 ($L\ L^{-1}$ ethanol)	7	<35	0	0	0	0
	Condenser	80–120 ($L\ L^{-1}$ ethanol)	7	50–60	0	0	0	0
	Total	200 ($L\ L^{-1}$ ethanol)	7	50	0	0	0	0
Boiler gas flushing		2 ($L\ kg^{-1}$ vapor)	8	80	50–100	200–300	100–150	-
Condenser	Exhaust steam	40–50 ($L\ kg^{-1}$ sugar)	7	80	0	0	0	0
	Vegetable steam	50–60 ($L\ kg^{-1}$ sugar)	5–6	60–80	0	600 – 1,500	300–800	0
Cleaning of floors and equipment		50 ($m^3\ t^{-1}$ sugarcane)	5–6	room	<0.5	1,000–3,000	800 – 1,500	>20
Domestic sewage		70 ($L\ fun^{-1}\ day^{-1}$)	6–7	room	5–20	600	300	-
Vinasse and phlegm		12–18 ($L\ L^{-1}$ ethanol)	4–5	80	3–5	25,000–40,000	15,000 – 20,000	8

pH: potential hydrogen; T: temperature; SW: settleable waste; COD: chemical oxygen demand; BOD: biochemical oxygen demand; OG: oils and greases.
Source: Elia Neto e Shintaku (2009).

This license contains technical requirements for environmental monitoring throughout the industrial and agricultural process chain, aiming to monitor the plant's activities to reduce and mitigate environmental impacts during its operation.

Water collection

Vale do Paraná S/A Álcool e Açúcar collects surface water (main source of supply ~95%) from the shores of the reservoir of the Ilha Solteira Hydroelectric Plant (SP), in the São José dos Dourados River watershed (Water Resources Management Unit [*Unidade de Gerenciamento de Recursos Hídricos*] — UGRHI-18).

The unit was granted a license to capture 1,000 m^3 h^{-1} of water by ANA (expiration date: July 2024). The system employed is floating, where a set of pumps sucks water from the Paraná River and recharges it, through a 17 km long pipe, to a reservoir inside the industry. The water stored is treated and sent to the industrial process. It should be emphasized that in the first years of the plant operation, all the water used in the industrial process came from eight wells (potential flow rate: 452.24 m^3 h^{-1}), with use grants issued by the Department of Water and Electric Power (*Departamento de Águas e Energia Elétrica* — DAEE) (expiration: January 2024). However, in 2015, the surface water collection system was implemented and, currently, the wells are used only in times of maintenance of the surface water collection system and for the supply of the administrative sector and restaurants, and one well specifically for toilets. The main factor that led the company's managers to switch to surface collection was the lowering of the water table between 2015 and 2016 which caused significant problems in water supply. In addition, groundwater in the region has a high silica and hardness content, which can cause, for example, fouling of pipes and pumps. The cost of treating water containing such substances is high, which is a key reason for using surface water.

Water collection limits

Resolution SMA 88 of the Secretariat of Infrastructure and Environment (*Secretaria de Infraestrutura e Meio Ambiente* — SMA) (Brasil, 2008) defines the technical guidelines for the licensing of projects in the sugar-alcohol sector in the state of São Paulo. The legislation established limits on the use of water resources in sugar-energy plants according to the areas in which they are located. In the case of Vale do Paraná S/A Álcool e Açúcar, classified as a "suitable area with limitations" and "suitable area with restrictions", the permitted water collection is up to 0.7 m^3 ton^{-1} of processed sugarcane.

Measurement and distribution of water in the industrial process

Automatic flow rate meters are important devices for recording and monitoring the water used during the industrial process. In the company under study, the flow rate of the surface collection is recorded at two locations: 1. at the pumping of the Paraná River and 2. at the arrival of the water in the reservoir tank. In the groundwater collection system for human consumption, there is also flow rate measurement at the outlet of the well pumping. All water intake information in the industry is recorded and stored in the industrial operations center (*Centro de Operações Industriais* — COI), which controls all data digitally and monitors and manages all industrial process operations.

Data collection

To carry out this work, secondary data from bibliographic research (water use rights grants, internal programs, and technical bulletins presenting the company's production information) were used. The survey made it possible to quantify the use of water in the plant under study between 2012 and 2021 and to evaluate the technologies implemented in order to reduce its use in the industrial process. A field survey was also conducted in all sectors of the company. It must be emphasized that all technical information was made available by Vale do Paraná S/A Álcool e Açúcar namely: harvest and production data; collection flow rate; technologies implemented to reduce water demand; process flowcharts; and water use grants.

Results and Discussion

Water balance

According to ANA (2009), preparing a water balance in the industrial process is important to enhance the reuse of water, provide a change of culture, and indicate technological means to reduce the collection of water resources. For its elaboration, it is necessary to have technical knowledge of the sectors and to map the water and effluent circuits. The water balance of Vale do Paraná S/A Álcool e Açúcar (Table 2) is based on the milling of 458 tons of sugarcane per hour (~11,000 tons of sugarcane per day), corresponding to the production of 17,005 bags of sugar and 419.5 m^3 of ethanol per day. As can be seen in Table 2, the total water collection at the mill is 344.7 m^3 h^{-1}, the largest consumers being the respective sectors in descending order: fermentation and distillery (41%); power generation (24%); juice concentration (20%); other uses (13%); juice treatment (2%); and extraction (diffuser) (0%).

Sugarcane cleaning

The first stage of production in a sugar-energy plant is the cleaning of sugarcane to remove mineral and vegetable impurities (~10% of the weight of the raw material), usually carried out using water jets (sugarcane washing) before its crushing in the mill (Gonçalves Filho et al., 2020). Such impurities, coming from the crop, can wear out the machines and equipment used in the industrial process. Good quality raw material contributes to increasing the efficiency of the industry and saving financial resources (Brassolati et al., 2016).

Table 2 – Summary of the water balance for Vale do Paraná S/A Álcool e Açúcar.

Sector	Water use	Recirculated area ($m^3 h^{-1}$)	Water collected ($m^3 h^{-1}$)
Extraction (diffuser)	Soaking	278.1	0.0
Juice treatment	Preparation of milk from lime	0.0	1.5
	Polymer preparation	0.0	6.1
Juice concentration	Soaking of filter sludge	0.0	0.1
	Column of waters	6,930.0	70.0
Power Generation	Water for the boiler	162.0	33.1
	Soot retention	300.0	50.0
Fermentation and distillery	Preparation of yeast	0.0	65.0
	Wort preparation	0.0	0.0
	Tank flywheel	0.0	15.0
	Cooling	5,049.0	51.0
	Sealing	0.0	10.0
Other uses	Potable use	0.0	0.8
	Washing of filters of the Water Treatment Plant	0.0	12.2
	Other various uses	0.0	15.0
	Floor washing	0.0	7.5
	Washing of automotive equipment	0.0	7.5
Total		12,441.0	344.7

After washing sugarcane, the water used may have a high concentration of solids, which makes it necessary to treat it, often in boxes for decanting particulate matter, for later reuse (Brassolati et al., 2016; Nascimento et al., 2016). There is the option of cleaning sugarcane with air through blowers (dry cleaning), but in this case, the product must be harvested mechanically (Nascimento et al., 2016; Gonçalves Filho et al., 2020).

Vale do Paraná S/A Álcool e Açúcar used, until 2019, the sugarcane washing process to remove mineral and vegetable impurities and performed awareness-raising work for operators in the field to reduce the amount of impurities at the time of harvest, through training the harvester operators. The water used in the washing process flowed through a closed-circuit recirculation system, consisting of settling boxes, which allowed the solids to be deposited and the water to be reused. After drying the settling boxes, the solid material was taken to the field and incorporated into the soil in sugarcane reform areas.

Currently, the settling box system only works for the settling of effluents from the boiler gas flushing system. The installation of the dry-cleaning system began in 2019, and the first tests were carried out. In the following year, the system was partially implemented and operated, before being fully integrated in 2021. The system was designed with a grid to support the unloading of sugarcane onto the feeder table. In short, in a cascade effect, the sugarcane hits the grid and the solid material is separated by gravity. At the bottom of the grid, there is an air injection system, responsible for removing excess vegetable and mineral impurities. The solid material and straw are separated by a sieve. Subsequently, one belt carries the solid material, and another, the straw. The mineral impurities are transported to the plantation and the vegetable impurities are deposited in the bagasse yard for burning in the boiler.

Cooling and water circuits

At Vale do Paraná S/A Álcool e Açúcar all the cooling circuits (i.e., condensers, barometric columns, condensation generators, and bearing towers) are closed for reuse. There is also a closed-circuit recirculation system for the boiler gas scrubber, aimed at removing, with water, the particulate matter resulting from bagasse burning and complying with environmental legislation. After cleaning the gas scrubber system, the effluent with ashes is sent, using the action of gravity, to settling ponds. The treated water is then pumped out and returned to clean new streams. The decanted material is taken to the crop and distributed in the soil of the sugarcane fields. When necessary, water is replaced in the system. More information on the water balance can be found in Table 2.

Industrial effluents

Although evaluating industrial effluent management is not the main objective of this paper, it is as important as water use planning in sugarcane mills. At the beginning of the century, several water resources researchers believed that the main threat from the sugarcane industry was industrial effluent (Berndes, 2002). The industrial processing of sugarcane presents a production chain in which several of its stages, if not properly managed, can cause unwanted environmental impacts on soil and water (ANA, 2009; Rebelato et al., 2016). Until the 1980s, most of the industrial effluents (e.g., vinasse) produced in mills were discharged untreated into rivers and streams (Goldemberg et al., 2008). In 2013, there were already strict laws regulating the use of such effluents in Brazil to prevent their uncontrolled input into bodies of water (Martinelli et al., 2013). Rebelato et al. (2016) and Fito et al. (2023) pointed out that although it is already governed by a large set of laws aimed at regulating its activities to preserve and minimize the environmental impacts of its operations, the sector has been constantly presenting more modern attitudes in the management of its activities.

There are countless ways to value and treat vinasse in sugar-energy plants, such as reverse osmosis, evaporation, incineration, industrial recycling, aerobic hyacinth ponds, stabilization ponds, biological filters, production of fungal or unicellular protein biomass, and anaerobic digestion. The most widely used technique is fertigation, which consists of mixing the vinasse produced with other effluents from the sugarcane industry and using the product as fertilizer. The use of these effluents in plantations has reduced the pressure on aquatic ecosystems in recent decades (Martinelli et al., 2013). However, pollution problems have not been fully solved, as the direct application of vinasse to the soil, without guidance and in an uncontrolled manner, can cause some impacts, such as: leaching of metals present in the soil to groundwater; salinization; nutrient imbalance; reduced alkalinity; crop losses; increased phytotoxicity; and unpleasant odor. In addition, flow of vinasse through pipes, trucks, and irrigation canals increases the chances of accidental spills and can maximize negative impacts on soil and groundwater.

Table 3 shows, according to the plant's water balance, the volumes of effluent generated in the industrial process of the plant under study, highlighting the generation of vinasse.

All vinasse generated in the industry leaves the distillation column and passes through a flow rate meter (Figure 1A). Then, the vinasse is sent to cooling towers (Figure 1B) through a pressurization process.

Table 3 – Flow rate and destination of effluents produced at the industrial plant.

Effluents	Flow rate (m^3 h^{-1})
Floor washing	7.5 (2.5%)
Automotive equipment washing	7.5 (2.5%)
Various other uses	15.0 (5.0%)
Domestic wastewater after treatment	0.8 (0.3%)
Washing of filter of the Water Treatment Plant	12.2 (4.0%)
Vinasse	256.4 (86.0%)
Total for the crop	299.4

After cooling, the vinasse goes to a waterproofed lung tank for storage (Figure 1C) and subsequent transportation to the crop. Both the vinasse and the wastewater are dumped into tanks on the plant's several rural properties by trucks (Figure 1D). All tanks are covered with a blanket and have a system of sight drains to check for any type of leakage (Figure 1D). After being discharged into the ponds, vinasse and wastewater are pumped through pipes coupled to a system of self-propelled trucks, responsible for distribution in the sugarcane field in the form of fertigation (Figure 1E). The areas that receive vinasse and wastewater are controlled and the applications are conducted according to the Vinasse Application Plan submitted to CETESB.

Water consumption in the plant studied

As mentioned above, sugarcane industries have largelly reduced water consumption in the production process in recent years due to the factors presented in the previous topics, among other reasons. Data on water consumption in the plant production process between 2012 and 2021 was obtained through technical bulletins that record information on inputs and products in the production chain (Figure 2).

Figure 1 – (A) Automatic flow rate meter at the outlet of the distillation column, (B) Vinasse cooling towers, (C) Vinasse reservoir inside the industrial park, (D) Waterproofed reservoir in the agricultural area with unloading of vinasse transported by truck, and (E) Application of vinasse to the crop with a self-propelled irrigation system.

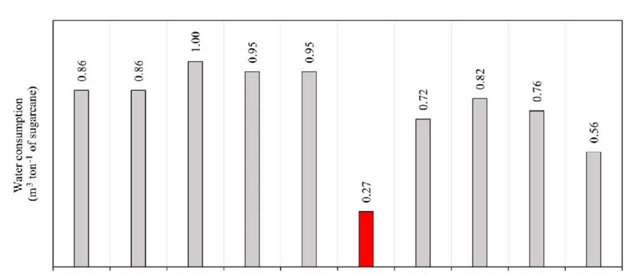

Figure 2 – Water consumption between 2012 and 2021 in Vale do Paraná S/A Álcool e Açúcar industrial process.

Over the last decade, the sugar-energy plant under study had an annual water consumption that did not exceed 1 m^3 ton^{-1} of processed sugarcane. It is worth mentioning that from 2012 to 2016, the information was not extracted from automatic flow rate measurement systems, but from averages obtained from the plant's water balance. In this period, data were collected and stored in the industrial laboratory sector along with the production data. In 2016, the company received a requirement — met in 2017 — from CETESB to install automatic flow rate meters in the plant water intake. However, in the 2017 harvest, the data recorded were not in line with expectations. The discrepant value of the others (0.27 m^3 ton^{-1} of processed sugarcane) can be justified by the fact that, in the period, the system was in the implementation phase and, according to information obtained from the technical area, it presented failures, not accounting for the measurement of all the water that entered the industry. There was a need for constant stops for system maintenance throughout the year. From 2018 on, the system started operating without technical problems.

Consolidated water consumption in 2018, 2019, 2020, and 2021 was 0.72, 0.82, 0.76, and 0.56 m^3 ton^{-1} of sugarcane, respectively, representing a reduction of 34.88% from 2012 to 2021.

In their study on water use by the sugar-energy industry in São Paulo, Elia Neto (2005) identified that water withdrawals decreased from approximately 15 m^3 ton^{-1} of processed sugarcane in the 1970s to 5 m^3 ton^{-1} in the 1990s. Martinelli et al. (2013), based on the total amount of sugarcane harvested by 96 mills in the 2007–2008 crop and the total volume of water collected by these mills in the same period, estimated that water consumption was approximately 1.53 m^3 ton^{-1} of processed sugarcane. The water collection per amount of sugarcane harvested found in the present work for the year 2021 (0.56 m^3 ton^{-1}) was 2,580% lower than in the 1970s (15 m^3 ton^{-1}). However, the sugar-energy sector must continue to work on solutions to minimize water use (Goldemberg et al., 2008; Leite et al., 2009; Zheng et al., 2022). Gaining efficiency in water use is especially important because most of the water used in the production process is withdrawn by the sugar-energy industry from low-order streams (Martinelli et al., 2013), which are often already demanded by inputs of untreated domestic sewage (Bega et al., 2021; Bega et al., 2022; Ribeiro et al., 2022) and nonpoint sources of pollution from agriculture (Cunha et al., 2020).

A chronological overview of the technologies implemented at the mill (2008–2021) and water consumption in m^3 ton^{-1} of processed sugarcane is presented in Table 4.

The 2008 harvest corresponded to the first year of operation of the mill under study, which reflects the greater number of technologies implemented compared with later harvests. It should also be not-

Table 4 – Chronological overview of technologies implemented at Vale do Paraná S/A Álcool e Açúcar between 2008 and 2021, water consumption, and source(s) of collection.

Year	Water consumption (m^3 ton^{-1} of sugarcane)	Collection	Technology implemented
2008	-	Groundwater	(i) Closed circuit: washing gases from the boiler and cooling towers and from vats, barometric columns, and bearings; (ii) Condensate recovery in juice treatment.
2012	0.86	Groundwater	None
2013	0.86	Groundwater	None
2014	1.00	Groundwater	(i) Closed circuit: ethanol cooling towers; (ii) Implementation of the water treatment system for washing boiler gases.
2015	0.95	Groundwater / superficial	None
2016	0.95	Groundwater / superficial	None
2017	0.27	Superficial	Condensate recovery and closed circuit: cooling towers in the sugar industry
2018	0.72	Superficial	Automatic flow rate measurement
2019	0.82	Superficial	Condensate recovery at the thermoelectric plant
2020	0.76	Superficial	Closed circuit: cooling towers at the thermoelectric plant
2021	0.56	Superficial	Dry cleaning of sugarcane

ed that with the establishment of Resolution SMA 88 in December of 2008 (Brasil, 2008), Vale do Paraná S/A Álcool e Açúcar (holder of the Agri-Environmental Protocol) should comply with the abstraction of 0.7 m^3 of water per ton of sugarcane processed, until 2024 (as it is in an area classified as suitable with environmental restrictions). However, before the deadline, already in 2021, the sugar-energy plant was below the limit established by the resolution and had a water intake of 0.56 m^3 ton^{-1} of processed sugarcane.

Sustainable impacts of reducing water consumption in the sugar-energy industry

The sugar-energy sector, in recent decades, has shown commitment to sustainable development in its production chain, which demonstrates a strong foundation in sustainability indicators, and tools that play important roles in the economic and socio-environmental development of companies (Pereira, 2021). In Brazil, the sector has sought to implement clean and eco-innovative processes in sugar-energy plants. In recent years, for example, there has been an increase in the adoption of technologies aimed at reducing carbon dioxide, preserving biodiversity, safe working conditions, and reducing materials, energy and water — innovations in industrial plants are important factors for evolution in the globalized world, since new technologies can ensure that companies remain in the competitive market (Santos et al., 2015). In addition, charging for the use of water resources has been used to increase users' awareness of the scarcity, and is also a source of financial resources to fund projects connected to the preservation of river basins. Payment should be made by all users of groundwater and surface abstractions and by all consumers who use and discharge effluents into water courses. Finally, it is understood that charging decreases utilization and avoids waste, reducing the environmental impact on the receiving water course. Vale do Paraná S/A Álcool e Açúcar, for example, started paying for the use of water resources in 2020, with the amounts being collected in 2021. The charge was established by a state decree, which approved and set the amounts for the use of water resources owned by the state of São Paulo, urban users, and industries in UGRHI 18.

In light of the above, it is observed that the sugar-energy sector, specifically Vale do Paraná S/A Álcool e Açúcar, has adopted a more sustainable production in recent years. It includes dry cleaning of sugarcane, the use of closed circuits, water reuse, and the adoption of technological solutions, aimed at reducing the consumption of water resources in its production plants. In short, the modification of the sugarcane washing system between 2019 and 2020 contributed significantly to the integrated management of water resources at the plant. Other relevant factors observed in this study were the operation of 100% of the plant with closed circuits and the automated flow rate measurement that allows verification and decision-making at the plant.

Conclusions

Vale do Paraná S/A Álcool e Açúcar has significantly reduced water consumption in industrial processes over the last decade. Several technologies have contributed to this reduction, including: dry cleaning of sugarcane; use of closed circuits; recovery of condensates; water reuse; and implementation of a flow rate measurement system. In addition to the qualitative aspects of the receiving water courses, this reduction can be particularly important during intense periods of drought, such as those experienced in recent years, which have even led to the replacement of the water supply system. The company has achieved lower consumption than required for the year 2024, but there is no limit to reduction. Managers should always seek improvements in the industrial production process and, where possible, implement new technologies. In the case of the plant under study, it was observed that special attention should be paid to industrial effluents, especially vinasse, with the possible implementation of more treatment steps before application in the field as fertigation.

Although the research has presented significant data for managers of sugar and ethanol plants and environmental managers, as well as countless other classes of professionals and researchers interested in the subject, future studies are recommended. Some guidances are presented: (i) to continue monitoring water consumption in the mill in order to obtain a database and assist in understanding the evolution of the process evaluated; (ii) to compare the results obtained in Vale do Paraná S/A Álcool e Açúcar with other sugar-energy mills in the state of São Paulo and other Brazilian states; and (iii) to propose technologies that can reduce water consumption per ton of sugarcane in Brazilian enterprises, based on international experiences, through a bibliographic survey.

Contribution of authors:

BARROQUELA, W.B.: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft. BEGA, J.M.M.: formal analysis, writing – original draft, writing – review & editing. ANÍCIO, S.O.: writing – review & editing. OLIVEIRA, J.N.: conceptualization, methodology, project administration, resources, supervision, visualization.

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