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Sizing a System for Treating Effluents from the Mozambique Sugar Cane Company

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Abstract: The sugar industry must be managed in a manner that encourages innovation with regard to the waste generated throughout the process. The organic load of sugar mill waste is high, as is its potential to pollute water bodies at various stages of the production process, including cooling bearings, mills, sugar cane washing, bagasse waste and cleaning products. It is therefore necessary to identify treatment mechanisms that not only reduce this waste but also return purer water to the environment, combining the reuse of water in various applications. The objective of this study was to analyze the results of the physical and chemical properties of the effluents generated and the principal treatment technologies employed for the remediation of industrial wastewater from sugar factories. The wastewater from Mozambique's sugar mills has high levels of dissolved or suspended solids, organic matter, pressed mud, bagasse and atmospheric pollutants. The BOD/COD ratio is low (<2.5), indicating the need for secondary treatment or, more specifically, biological treatment. This can be achieved through humid systems built from stabilization ponds, with the resulting water suitable for reuse in agricultural irrigation. In this work, an educational proposal has been developed for engineering students where they learn to calculate and optimize, among other parameters, the natural wastewater treatment and compare it with a conventional wastewater treatment.

Keywords: environmental management; sugar industries; wastewater; treatment systems

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1. Introduction

Industrialization is a crucial factor in a country's economic and social development. However, the environmental impact of industrial activities represents a significant global concern. The reduction and control of water consumption in industrialized countries is linked to the optimization of industrial and domestic wastewater treatment processes. At the present time, there is a global interest in avoiding or reducing the effects of pollution on the environment. However, despite this interest, contamination continues to occur on a large scale, particularly given that a significant proportion of the effluents generated in industrial production processes are difficult to remedy through conventional treatments. Furthermore, the food sector is one of the fields that consume the most water and produce the most effluents per unit of production.

The process of transforming sugar cane is a highly complex one, resulting in the generation of considerable quantities of wastewater. This wastewater comprises both liquid and solid discharges, originating from the processing, handling and transformation of the sugar cane itself.

The aforementioned discharges are the result of a number of processes, including cooling, heating, extraction and reaction, as well as the washing of products and the control of other rejected by-products. The quantities and qualities of these discharges are highly variable. As the water progresses through the chambers and tanks, from the stage of extraction to sugar crystallization, its pollutant load in terms of organic matter and a range of pollutants increases significantly (3). However, this production route results in the generation of considerable quantities of solid waste, including cane straw, bagasse, molasses and pressing sludge. Bagasse is the residual material obtained after the sugar cane stalks have been pressed (crushed) in order to extract the juice. The processing of one ton of sugar cane results in the generation of between 0.25 and 0.30 tons of bagasse. In 39 factories in Brazil, the average yield of bagasse is 0.28 tons per ton of processed sugar cane [1–3]. Other studies have indicated that 0.14 tons of bagasse (dry mass) and 0.14 tons of straw (stalks) are obtained from one ton of sugar cane. Figure 1 below illustrates the flow of the sugar production process, delineating the type of effluent removed from the process at each stage and its characterization at the subsequent point.

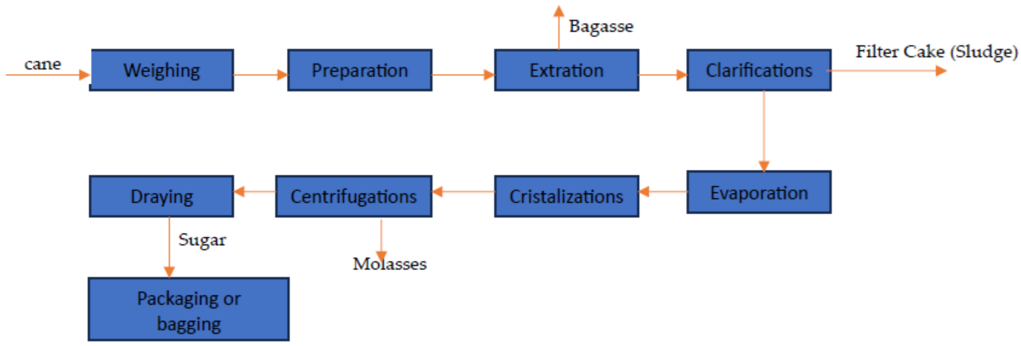

Figure 1. Sugar production flowchart, Source: Tongaat Hulett, 2023.

The objective of this study was to analyze the results of the physical and chemical properties of the effluents generated and the principal treatment technologies employed for the remediation of industrial wastewater from sugar factories. The wastewater from Mozambique's sugar mills has high levels of dissolved or suspended solids, organic matter, pressed mud, bagasse and atmospheric pollutants.

Moreover, an educational proposal has been developed for engineering students where they learn to calculate and optimize, among other parameters, the natural wastewater treatment and compare it with a conventional wastewater treatment.

2. Materials and Methods

2.1. Description of Sugar Industry Effluents

In all areas of the food industry, food production is undertaken with considerable energy consumption, and substantial quantities of waste are generated as a consequence of technological processes. Consequently, the principal challenges confronting food technology are associated with the management of energy and industrial effluents. These effluents are of a solid, semi-solid and liquid nature and can be classified into two categories. The first category comprises waste from the harvesting operation, which includes cane leaves and tips. The second category consists of waste from the cane processing flow, which encompasses bagasse, bagasse ash from incineration, pressing sludge (sludge from juice sedimentation and residual cake from juice filtration), and bearing lubricants in mills [4]. Normally, crushing one ton of sugar cane yields around 280–300 kg of bagasse with 50% moisture, 30 kg of pressed mud and 41 kg of molasses. The energy from sugar cane is distributed according to the three main components extracted from the stalks: juice (sugar or ethanol), fibers (bagasse) and leaves (LT) have the same level of energy content, so currently only two thirds of the total energy potential is used. The energy content of one ton of sugar cane is 6560 MJ, distributed as follows: 140 kg of sugar for 2340 MJ; 280 kg of bagasse (50% moisture) for 2110 MJ; and 280 kg of LT (50% moisture) for 2.11 MJ [5].

2.2. Sample Collection and Analysis

The sugarcane transformation process is highly complex, generating significant quantities of wastewater comprising liquid and solid discharges from the processing, handling and transformation of sugarcane. These discharges result from cooling, heating, extraction and reaction processes, as well as the washing of by-products and the control of other rejected by-products [6]. After collecting and analyzing the effluents at the three points of the factory, namely boilers, workshops and pumps, the analytical results for TSS show that the workshop unit had the highest TSS of 22 mg/L, a value which is low in relation to the values established by Mozambican legislation of 50 mg/L. As for TDS, the values at all the collection points were as high [1137–1392] (mg/L) in relation to the value of the legislation and in comparison with other sugar industries [6]. These TDS values are due to the industry's high crushing rate which as a result generates a greater amount of fly ash and heavy ash. The bagasse stacking plant is also nearby, so the coarse bagasse particles are mixing with the final effluent. In the mills, particularly in the bearings, there is a lot of spillage of lubricants due to the long use of these vises, which have been in use since national independence (1975 independence of Mozambique, post-colonial era) and have several leaks which are the main contributors to TDS. BOD is the biochemical oxygen demand (BOD); it represents the amount of oxygen consumed by bacteria and other microorganisms while they decompose organic matter under aerobic (oxygen is present) conditions at a specified temperature. The BOD and COD values were analyzed for each collection point from the entrance and exit of the sector in the factory, and in the end the average in each sector and in general in the total effluents of the factory was evaluated. All the BOD and COD values were found to be higher than the standard values of 50 mg/L and 250 mg/L, respectively, according to Mozambican legislation [6]. The raw effluent values at the outlet showed BOD and COD values of 731 mg/L and 1351 mg/L, respectively, a COD/BOD ratio of approximately 2:1, showing that the biodegradable fraction is high and biological treatment technology is the most suitable method. On the other hand, these high values can be increased by the spillage of molasses and sugar leaked onto the floors of the mills, which are swept and washed; the parameters of these effluents are tabulated in [6]. Among the physical-chemical parameters of the sugar industry's wastewater, pH and temperature were measured immediately on site, while the other physical-chemical parameters, such as total solids (ST), suspended solids (TSS), BOD, COD, chloride and sulphate tests, turbidity, alkalinity, density and conductivity, were analyzed in our laboratories here at Zambezi University (Table 1). To analyze these values, several items of equipment and reactors from the Panreac company of Barcelona (Spain) were used. Also, a spectrophotometer, conductivity meter, pH meter and turbidity meter from Hach of Bilbao (Spain) were employed.

Table 1. Values of the physico-chemical parameters of the Mozambique sugar plantation.

Parameters	Pump	Boilers	Workshops	Decree 18/2004
Temperature (°C)	45	50	40	≤24
PH	6.34	8.13	6.96	6–9
Hardness (mg/L)	240.63	490.20	177.13	
Alkalinity (mg/L)	187.00	215.00	138.33	
Chlorides (mL/g)	105.60	172.63	81.43	
TDS (mg/L)	1392.00	1174.67	1137.00	
TSS (mg/L)	17.33	25.67	22.00	50
Turbidity (NTU)	9.15	11.16	15.03	
BOD (m/L)	731.67	628.00	675.00	50
COD (m/L)	1048.67	991.33	1351.00	250

Table 1. *Cont.*

Parameters	Pump	Boilers	Workshops	Decree 18/2004
Conductivity (S/cm)	2.49	1.96	7.83	
Phosphate (mg/L)	11.91	16.22	16.23	2
Nitrogen (mg/L)	14.11	10.58	11.39	10

2.3. Effluent Treatment Techniques

In environmental engineering and more specifically in effluent treatment technologies, the concentration of organic matter in the effluent is measured using two main analytical parameters, biochemical oxygen demand (BOD) and chemical oxygen demand (COD). BOD shows the amount of oxygen required to stabilize carbonaceous organic matter through biochemical processes, indirectly indicating the amount of biodegradable organic carbon, while COD measures the consumption of oxygen due to the chemical oxidation of organic matter, indirectly measuring the content of organic matter present [7]. The choice of treatment technologies for any effluent depends on the COD/BOD ratio, according to a previous study [8]. The author of that study suggests the following: Low COD/BOD ratio (<2.5): the biodegradable fraction is high, and the use of biological treatment is recommended. Intermediate COD/BOD ratio (from 2.5 to 4.0): the biodegradable fraction is not high, and it is recommended to carry out treatability tests to validate the use of biological treatment. Biological treatment refers to secondary level treatment [9,10]. High COD/BOD ratio (>4.0): the inert (non-biodegradable) fraction present in the effluent is high, it is not recommended to use a biological system, and the potential for using a chemical treatment system should be assessed [11]. The processes used to treat industrial effluents can be categorized as physical, chemical and biological. Physical treatment includes processes in which there is no chemical or biological alteration of the substances. It is a primary treatment that aims to use physical phenomena to remove particles such as suspended solids and separate immiscible liquids. Examples of physical processes include filtration, flocculation and sedimentation [9]. Chemical treatment involves carrying out chemical reactions to improve the quality of the wastewater. In this type of treatment, neutralization is commonly used to adjust the pH of the effluent. Operations such as electrochemical processes and advanced oxidative processes are also classified as chemical treatment [12]. Most effluent treatment plants use biological processes to remove organic compounds from wastewater. Biological treatment aims to break down polluting substances into stable products through the biochemical reactions of microorganisms, mostly bacteria. The main biological processes used in this type of wastewater treatment are the following: aerobic, anaerobic, facultative, and a combination of the three types. In aerobic biological treatment, oxygen is present and used by microorganisms to degrade organic compounds into carbon dioxide and water. An example of an aerobic reactor widely used for effluent treatment is the conventional activated sludge reactor [10].

2.3.1. Activated Sludge

The purpose of wastewater treatment using the activated sludge process is to biochemically oxidize dissolved organic matter in colloidal suspension by microorganisms, clustered in flakes, which are kept in suspension, forming suspended biomass within a reactor. This can be inserted into the treatment line as a secondary treatment (when the objective is limited to reducing BOD, COD and TSS) and/or as a tertiary treatment (when the aim is to remove nutrients), and it is possible to combine secondary and tertiary treatments in a single reactor. The biomass (live and dead microorganisms) and non-biodegradable SS present in the biological reactor effluent must be separated from the liquid phase, generally in a decanter downstream of the biological reactor, because their concentration of organic matter and TSS presents values incompatible with discharge into a receiving environment [13]. It can even be said that this separation operation is an integral part of biological treatment.

The biodegradation process can be significantly intensified by increasing the concentration of biomass in the reactor. This increase is achieved by recirculating sedimented sludge from the decanter to the reactor, since the TSS content of the sludge is largely composed of biological flocs. The part of the sludge that is not recirculated to the biological reactor is called excess sludge and must be periodically removed by sludge purging.

The efficiency of the Activated Sludge process is affected by the electrical energy of the aeration system, which is essential to supply oxygen to the microorganisms that degrade organic matter and offers a very efficient treatment, but at a higher electrical cost due to the demand for continuous aeration. The COD/BOD ratio is an important indicator of the biodegradability of the effluents and the effectiveness of the treatment processes. Each range of this ratio suggests a specific type of treatment that may be more appropriate. Each type of treatment must be considered in the specific context of the effluent in question and the regulatory requirements for disposal.

2.3.2. UASB Reactor

The UASB anaerobic reactor is an upflow treatment unit that uses the anaerobic process to degrade matter in the form of sludge using colonies of anaerobic microorganisms, such as sewage. For our project, this technology would not be ideal because to maintain the upflow within the reactor we need electric pumps, which means consuming electrical energy. Considering the cost of energy, which has been increasing, the most ideal solution would be to build an economically viable and environmentally acceptable system which would have a higher efficiency in terms of removing the effluent load. It would be necessary to build a gas turbine to compensate for the production and consumption of electrical energy from the grid. If we look at the issue of HRT in these systems, it is greater than 60 days in relation to the operational lagoons, there is the possibility of generating bad odors and corrosion of the structure, and Sofala being in the coastal area, this phenomenon would occur more quickly; or, if we look at materials that are more efficient in terms of corrosion, their acquisition value would be higher.

2.3.3. Wetlands

Macrophyte beds (known in the literature as constructed wetlands) are nature-based systems that imitate and enhance the action of marshy areas in purifying the water that flows into them. The word "macrophytes" refers to tall plants, while "microphytes" are small plants commonly referred to as algae. These beds constitute secondary treatment units that must include a primary treatment stage upstream (septic tank or anaerobic lagoon) to retain solids that would otherwise end up clogging the bed and making treatment unfeasible. The purification mechanisms in a macrophyte bed include the following: (1) Physical mechanisms: sedimentation, filtration, adsorption. (2) Chemical mechanisms: precipitation (nitrogen and phosphorus), oxidation and reduction (heavy metals). (3) Biological mechanisms: bacterial metabolism (BOD, nitrogen), phytological metabolism (pathogenic microorganisms), phytological adsorption (nitrogen, phosphorus, heavy metals). (4) Natural decay: pathogenic microorganisms. The wetlands play an important role in the development of ecosystems. They are home to a wide variety of invertebrate and vertebrate animals whose activities significantly affect ecological processes, such as the disintegration and consumption of organic material by insects, insect larvae and earthworms. The development of the invertebrate community naturally stimulates the spread of predators, which include resident amphibians and birds that pass through the area.

The other macrophyte systems, submerged aquatic plants and subsurface flow, feature plants of different species, namely reed (*Phragmites australis*), bulrushes (*Schoenoplectus lacustris*, *Typha latifolia*) and rush (*Juncus effusus*), which can be planted in soil or in a gravel layer. The dimensions of a macrophyte bed for wastewater treatment are determined by the hydraulic retention time and simultaneously by the organic load, both quantified empirically, taking into account the natural factors mentioned above (temperature, wind speed and soil porosity). The level of pollutant removal is higher for a high retention time

(6 to 8 days) and low flow velocities (EU Guide, 2001). Subsurface flow beds can also be dimensioned for a certain reduction in influent BOD [7,11,14,15].

$$A = Q * Ln(BOD_a BO_e)/(KT * E * n) \quad (1)$$

where A is the surface area of the macrophyte [m^2], Q is the average influent flow rate [m^2/d], BOD_a and BOD_e are BOD concentrations in the influent and effluent, respectively [mg/L], KT is the BOD reduction rate [d$^{(-1)}$], at the design temperature, T [°C] determined by the following relationship:

$$KT = K20 \times 1.06^{T-20} \quad (2)$$

where $K20$ is the BOD reduction rate [d$^{(-1)}$] at 20 °C, E is the water height in the wetland [m] and n is the porosity of the support medium. Looking at these two systems and evaluating the effluents provided in Table 1, wetlands are more effective for removing effluents in which the focus would be phosphate and nitrogen but at temperatures above ≤24 °C, which can be a problem for wetlands because high temperatures can affect the effectiveness of plants and microorganisms for their treatment. In relation to lagoon systems, macrophyte beds require a larger installation area than a facultative pond, as well as more construction material. However, they can be used in combination with facultative ponds [16–18]. Below is a representation of a combination of facultative ponds and wetlands in Figure 2.

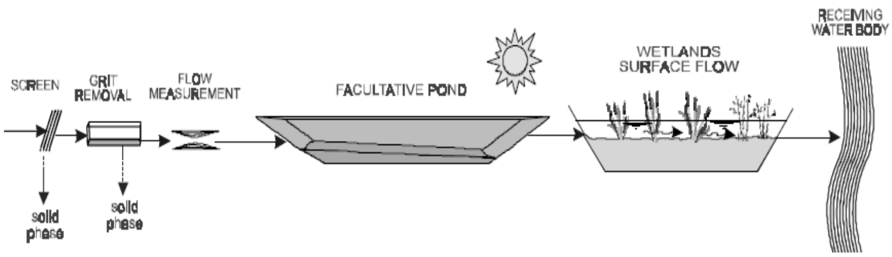

Figure 2. A combination system of facultative pond and wetlands.

Considering the data presented in reference [6], we have elected to utilize a combination of stabilization ponds as the optimal solution for this particular undertaking. Stabilization ponds are biological treatment systems that employ bacteriological oxidation (either aerobic or anaerobic fermentation) and/or photosynthetic reduction by algae to stabilize organic matter. The diagram below illustrates the sequence of treatment processes for these effluents, which will be conducted in the following order: physical, chemical, and finally biological. The latter will focus on the stabilization ponds and their sizing (Figure 3).

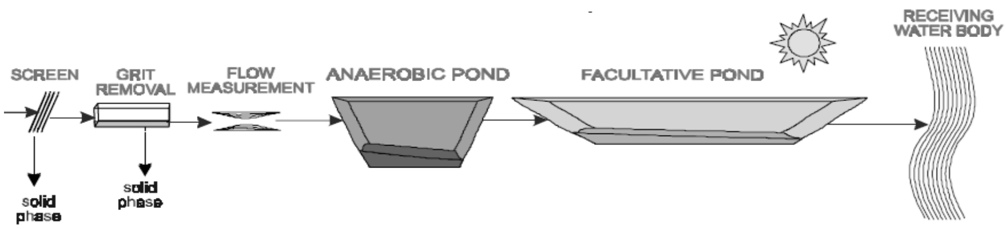

Figure 3. A combination system of anaerobic pond and wetlands.

3. Results

Firstly, preliminary treatment is carried out, where solid parts of the effluent are removed, such as silt and residual bagasse from extraction that may be in the effluent. This usually consists of the following stages: grating, desander and Parshall flume. The main purpose of this treatment is to remove coarse solids and sand through physical removal mechanisms, to protect the sewage transport equipment (pumps and pipes), to protect the subsequent treatment units, and to protect the body receiving the treated effluent. In addition to the physical removal mechanisms, this system has a flow measurement unit (e.g., Parshall flume) [13,19]. The grating is made of iron or steel grids, depending on the corrosive action of the effluent, and the spacing between the bars varies between 0.5 and 2 cm, which can be simple grids or mechanized grids depending on the volume of solids to be removed and to facilitate cleaning. The desander removes the coarse solids that may be present in the effluent, such as sand and earth, especially during rainy periods, which need to be separated. This is to prevent these particles from damaging the structures and causing blockages in the pipes and negative interference in biological processes. The Parshall flume is used to take flow measurements which, by means of throttling and bouncing, establish, for a given vertical section upstream, a relationship between the flow rate and the water table in that area. They have a low pressure drop and are very accurate at reading flow rates [19]. Figure 4 below shows the flume model and the flow calculation ratios.

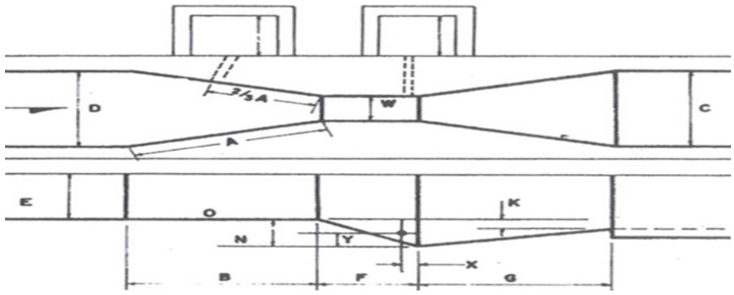

Figure 4. Parshall flume model for flow measures [19].

To calculate the flow rate, we use the following relationship:

$$Q = k \times h^n \tag{3}$$

where

Q—flow in m^3/s

k and n—coefficients as a function of throat width

h—water blade.

Typical values for calculating effluent flow in Parshall flumes are shown below in Table 2.

Table 2. Values of the constants k and n [13,19,20].

Throat (W)	W (m)	n	k
3″	0.076	1546	0.176
6″	0.152	1580	0.381
9″	0.229	1530	0.535
1″	0.305	1522	0.690
2″	0.610	1550	1.426
3″	0.915	1566	2.182
4″	1.220	1578	2.935
6″	1.830	1595	4.515
8″	2.440	1606	6.101

After passing through the previous stages, in particular the Parshall flume, the effluent goes to a stabilization tank, where it is completely homogenized. This is where some preliminary treatment processes take place, such as minimizing shocks caused by overloading the system, diluting substances in the effluent and stabilizing the pH, in order to improve the final quality of the treated effluent. In this way, the effluent becomes suitable for biological treatment. A detention time of between 3 and 6 days is used to calibrate the equalizer tank [21]. The established detention time is the most suitable for stabilization and the first biological treatment. A time of less than 3 days could cause the methanogenic bacteria in the effluent in the lagoon to exceed their own reproduction rate, which may be slow, depending on the temperature and the time of year. Times longer than 6 days can promote the emergence of an aerobic zone in the lagoon. Such a condition would be fatal to anaerobic bacteria. The detention times recommended in industry standards are shown in Table 3 below [20].

Table 3. Recommended retention times.

Average Temperature of the Lagoon in the Coldest Month (°C)	Detention Time (d)	
	Start of Plan	End of Plan
≤20	≥4	≤6
>20	≥3	≤5

When the effluent leaves the factory, its temperature plays an important role in the degradation process in the lagoon. If it coincides with a time when the ambient temperature is warm, then there will be greater degradation of the effluent in terms of BOD removal; but if it is cold, the degradation time will be longer [8]. This means that the temperature of the effluent at the outlet may not require a longer detention time for anaerobic processes. However, the values measured at the plant ranged from 40 °C to 50 °C, and taking into account that the area where the plant is located has high ambient temperatures ranging from 29 °C to 38 °C [22], this could lead to a shorter detention time and greater efficiency in removing the load from the effluent. Stabilization pond systems comprise units specially designed and built for the purpose of treating effluents, and are the simplest form of wastewater treatment [23], due to their low operating cost, but also due to the good efficiencies in removing organic matter, which can exceed 90% BOD removal [24] and pathogenic microorganisms, with 99.9% removal of fecal coliforms in the case of maturation ponds [19] that can be achieved in these systems. Among stabilization pond systems, the facultative pond process is the simplest, depending solely on natural phenomena, according to [20]. To calculate the volume of stabilization ponds, we need the hydraulic retention time (HRT), which is the time required for the effluent to remain in the pond for proper treatment. The typical HRT for stabilization ponds varies from 20 to 50 days, depending on the organic load and the temperature of the environment [13]. According to our data, the temperatures of the effluent leaving the factory ranged from 400 °C to 50 °C, so we can consider the lowest HRT to be between 15 and 20 days, depending on whether the season is cold or hot, which is why we found the highest value to be 20 days [25–29].

$$V_{eql} = Q_{ind} * T_{RH} \tag{4}$$

where

V_{eql}—volume of effluent in m^3/day

Q_{ind}—effluent flow rate

Tdetention—Hydraulic Retention Time (HRT) in days

As the plant pumps 900 to 1000 m^3/h, this must be converted to m^3/day: Q = 900 × 24 h *a* 1000 × 24 h for the flow range, which gives 21,600 m^3 /day to 24,000 m^3/day. With this flow data, we can estimate the volume of effluent in the lagoon and estimate its occupied area; bearing in mind that according to [30] the typical depth of anaerobic lagoons varies from 3 to 5 m, for our work we consider a depth of 4 m. From here, we calculate the volume of the lagoon considering a HRT of 20 days (an average value):

$$\begin{array}{lll} V = 21600\ \mathrm{m}^3/\mathrm{day} \times 20\ \mathrm{days} & or & 24000\ \mathrm{m}^3/\mathrm{day} \times 20\ \mathrm{days} \\ V = 432000\ \mathrm{m}^3 & or & V = 480000\ \mathrm{m}^3 \end{array} \tag{5}$$

With this volume of effluent and adopting a minimum depth of 4 m [19], we can find the area of our stabilization pond.

$$Area = \frac{V}{Deep} = \frac{432000 \text{ m}^3}{4 \text{ m}} \quad or \quad \frac{480000 \text{ m}^3}{4 \text{ m}} \tag{6}$$

$$Area = 108000 \text{ m}^2 \quad a \quad 120000 \text{ m}^2$$

When the temperature of the effluent is higher, the microbial activity in the anaerobic and facultative treatment process tends to be even more efficient, potentially allowing the hydraulic retention time (HRT) to be reduced [31–35]. By analyzing the data in the table, we can analyze the load of the effluent contaminated using the following equation:

$$C_{DBO} = \frac{S_0 \times Q_{max}}{1000} \tag{7}$$

In which
C_{BOD}—BOD load in kg BOD/day
S_0—BOD concentration (S_0 = 731.67 mg/L)
Q_{max}—maximum effluent flow (Q_{max} = 24,000 m^3/day)
With this data we can estimate the load, as follows:

$$C_{DBO} = \frac{S_0 x Q_{max}}{1000} = \frac{731.67 \text{ mg/L} \frac{1 \text{ kg}}{1000000} \times 24000 \text{ m}^3/\text{dia}}{1000} = 17.560 \text{ kg/day} \tag{8}$$

Next, we need to determine the surface application rate (LS). According to [19], there are several empirical equations available internationally that correlate the surface application rate (LS) and the local temperature. This work will use the equation proposed by [14], which is stated to be applicable worldwide.

$$L_s = 350 \times \left[1.107 - \left(0.002 \times T^0_{min}\right)\right]^{T^0_{min} - 25} \tag{9}$$

In which
L_s—surface application rate, in kgBOD/ha·day
T^0_{min}—average air temperature in the coldest month of the year (T° min = 20 °C).

$$L_s = 350 \times [1.107 - (0.002 \times 20)]^{20-25} = 338.83 \text{ kgBOD/ha·day} \tag{10}$$

Next, we calculate the area required (A_{lagf}) for the implementation of the lagoons. According to [20], the area required for the implementation of the facultative lagoon is calculated based on the following equation:

$$A_{lagf} = \frac{C_{BOD}}{L_s} = \frac{17.560 \text{ ka/day}}{338.83 \text{ kgBOD/ha·day}} = 0.0518 \text{ ha} \tag{11}$$

Therefore, 0.0518 hectares, or 51.8 m^2, will be needed to set up the ponds. Comparing the values in (4) and (9) leads us to make series connections for each type of stabilization pond, i.e., anaerobic, aerobic and facultative ponds, and further on we will show how many of each type will be needed. Facultative ponds are made up of three treatment zones: aerobic, anaerobic and facultative (Figure 5). Formed by algae and aerobic bacteria, the aerobic zone is responsible for decomposing organic matter by means of oxidative processes on the surface of the pond. In contrast, the anaerobic zone is characterized by the absence of oxygen and anaerobic bacterial activity, which is found at the bottom of the lagoon. The facultative zone is found in the middle of the two aforementioned zones and is formed by the combination of the two types of microorganisms (aerobic and anaerobic), which eliminate the organic material still present in the liquid medium [36–38].

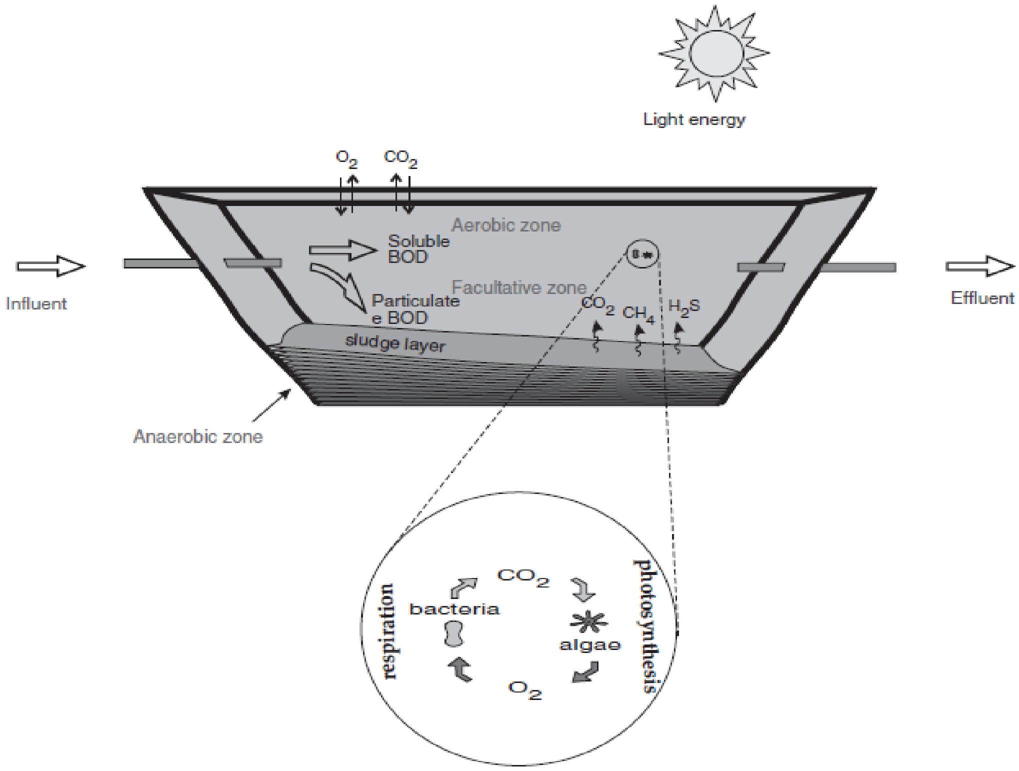

Figure 5. Drawing of a facultative lagoon representing the different zones of microbiological activity, aerobic, facultative and anaerobic, and the exchange of gases with the atmosphere [36].

Given that in anaerobic lagoons the degradation efficiency of BOD removal is around 50% (for temperatures less than or equal to 20 °C) to 60%, this alone is not enough to make the effluent suitable. This is why it is not implemented as the only treatment, and is more commonly followed by a facultative lagoon for an organic matter removal efficiency of 82% on average [20]. However, a disadvantage of the anaerobic process is the generation of bad odors due to the production of methane and the reduction of sulfur which produces hydrogen sulfide gas:

$$BOD_{Remaining} = 731.67\ \text{mg/L} \times (1 - 0.60) = 292.67\ \text{mg/L} \quad (12)$$

To determine the removal of the BOD/COD effluent load, this is determined as a function of the average temperature. The higher the temperature, the higher the rate applied, reducing the total volume of the pond to be dimensioned. Next, we will analyze the concentration of BOD and COD and their removal expectations according to the type of stabilization pond [17,39–42].

Determine the total contaminant load in terms of BOD and COD.

Maximum flow: 24,000 m^3/day
Maximum BOD concentration: 731.67 mg/L
Maximum COD concentration: 1351 mg/L

$$DBO = Q_{maxim} \times Concentration\ of\ DBO$$

$$Charge\quad BOD = \frac{24000\ \text{m}^3}{\text{day}} \times \frac{731.67\ \text{mg}}{\text{l}} \times \frac{1\ \text{kg}}{1000000\ \text{mg}} = 17.560\ \text{kg/day} \quad (13)$$

$$Carga\ de\ DQO = Q_{maxim} \times Concentracao\ DQO$$

$$Charge\ COD = 24000\ \text{m}^3/\text{day} \times 1351\ \text{mg/L} \times \frac{1\ \text{kg}}{1000000\ \text{mg}} = 32.424\ \text{kg/day} \quad (14)$$

3.1. Removal Efficiency by Lagoon Type

In the anaerobic lagoon: 50–70% BOD and COD removal.

$$Charge\ BOD\ remaining : 17.560\ \text{kg/day} \times (1 - 0.6) = 7.024\ \text{kg/day} \tag{15}$$

$$Charge\ COD\ remaining : 32.424\ \text{kg/day} \times (1 - 0.6) = 12.970\ \text{kg/day} \tag{16}$$

In the facultative lagoon: 60–80% BOD and COD removal (after the anaerobic lagoon).

$$Charge\ BOD\ remaining : 7.024\ \text{kg/day} \times (1 - 0.7) = 2.107\ \text{kg/day} \tag{17}$$

$$Charge\ DQO\ remanescence : 12.970\ \text{kg/day} \times (1 - 0.7) = 3.891\ \text{kg/day} \tag{18}$$

In the aerobic lagoon: 80–90% BOD and COD removal (after the facultative lagoon).

$$Charge\ BOD\ remaining : 2.107\ \text{kg/day} \times (1 - 0.85) = 0.3160\ \text{kg/day} \tag{19}$$

$$Charge\ COD\ remaining : 3.891\ \text{kg/day} \times (1 - 0.85) = 0.584\ \text{kg/day} \tag{20}$$

The rate of application of the parameters for sizing anaerobic lagoons depends on the temperature, where warmer locations allow for a higher rate and consequently a smaller volume. In Table 4, there is an estimate of BOD removal in an anaerobic lagoon with a minimum depth of 4 m depending on the temperatures in the coldest months of the year [43–47].

Table 4. Estimated BOD removal in anaerobic lagoon [24].

Average Temperature in Lagoon in a Cold Month (°C)	BOD Removal Efficiency %
≤20	≤50
>20	≤60

3.2. Lagoon Numbers Calculation

To determine the number of ponds, we must consider the load removal capacity of each pond. Sizing based on load:

In anaerobic lagoons: Average BOD removal efficiency of 60%, with removal capacity per typical lagoon: Let us assume 5.000 kg of BOD/day.

$$\begin{aligned} &Number\ of\ Anaerobic\ Lagoons = \frac{Charge\ of\ BOD\ removal}{Capacity\ of\ Remotion\ per\ lagoon} = \frac{17.560\ \text{kg/day} \times 0.6}{5.000\ \text{kg/days}} \\ &Number\ of\ Anaerobic\ Lagoons = 2.11 \end{aligned} \tag{21}$$

Rounding the value up will give us 3 anaerobic ponds.

Facultative ponds with a BOD removal efficiency of 70% after anaerobic ponds, which have a typical removal capacity of 2000 kg of BOD/da

$$\begin{aligned} &Number\ of\ Facultative\ lagoons = \frac{Charge\ of\ BOD\ removal}{Capacity\ \ of\ Remotion\ per\ lagoon} = \frac{7.024\ \text{kg/dia} \times 0.7}{2.000\ \text{kg/dia}} \\ &Number\ of\ Facultative\ lagoons = 2.46 \end{aligned} \tag{22}$$

Rounding the value up will give us three facultative ponds.

For aerobic lagoons, the average removal efficiency is 85% of BOD after the facultative lagoons. The removal capacity per typical lagoon: approximately 1.000 kg of BOD/day.

$$\begin{aligned} &Number\ of\ Aerobic\ lagoons = \frac{Charge\ of\ BOD\ removal}{Capacity\ of\ Remotion\ per\ lagoon} = \frac{2.107\ \text{kg/day} \times 0.85}{1.000\ \text{kg/day}} \\ &Number\ of\ Aerobic\ lagoons = 1.79 \end{aligned} \tag{23}$$

Rounding the value up will give us two aerobic ponds. In summary, Table 5 shows the calculations, and below there is a more detailed explanation of the results in the context of the study objective.

Table 5. Lagoon number results.

Lagoon Number Calculations	
Number of Anaerobic lagoons	2.11
Number of Facultative lagoons	2.46
Number of Aerobic lagoons	1.79

A quantitative analysis of the calculations for the system in question reveals that the number of lagoons required based on the contaminant load will consist of the following: the system will require three anaerobic lagoons, three facultative lagoons, and two aerobic lagoons, for a total of eight lagoons. It is important to note that the pumping system must be designed in a way that allows for gravity-fed flow, as this will help to minimize energy consumption. It is essential that the connections between the lagoons be designed in a manner that allows for the continuous flow of effluent, with the preference being for this to occur by gravity. However, the use of pumps is an acceptable alternative in instances where gravity is not feasible. It is essential to install flow control to guarantee sufficient flow at each stage and to maintain load balance. It is crucial to monitor the contaminant load in each lagoon and to make any necessary adjustments to the process [48–50].

Maintenance and access must be monitored for each lagoon, and it must be ensured that all environmental and safety regulations are complied with in the construction and operation of the lagoons. Expected efficiency in our system of anaerobic lagoons: 50–70% BOD/COD removal; facultative lagoons: 60–80% additional removal after anaerobic; aerobic lagoons: 80–90% additional removal after facultative. After the preliminary treatment, where most of the processes are physical, we move on to the biological treatment phase, which takes place in the stabilization ponds for primary treatment [51–53]. We have already analyzed the detention time, depth and BOD removal rate of the incoming effluent, and we will now focus on primary treatment, which involves anaerobic reactions carried out by microorganisms in the presence of sunlight, which take place in the ponds over a period of 3 to 6 days.

These results align with the objective of this study, which was to analyze the results of the physical and chemical properties of the effluents generated and the principal treatment technologies employed for the remediation of industrial wastewater from sugar factories. This can be achieved through humid systems built from stabilization ponds, with the resulting water suitable for reuse in agricultural irrigation.

3.3. Biological Treatment in Stabilisation Ponds

In stabilization ponds, bacteria such as Achromobacter, Proteus, Alcaligenes, Pseudomonas, Thiospirillum and Rhodothecae predominate, and are responsible for degrading organic matter by oxidation [10]. The predominance of sunlight and the CO_2 synthesized by bacteria further facilitates the process of algae growth and thus increases photosynthesis in lakes, subsequently increasing the oxygen concentration. The most common algae are Chlorella, Euglena, Scenedermus and Microcistis [9]. As more and more algae grow inside the lake, the oxygen produced by the algae with the help of sunlight and the photosynthetic process increases, allowing the bacteria to break down more waste and achieve a reduction in the organic level [12]. The most common redox reactions are the following:

Oxidation:

$$\text{Organic matter} + O_2 + \text{bacteria} \rightarrow CO_2 + NH_3 + NO_3 \quad (24)$$

Reduction:

$$\text{Algae} + \text{Solar Energy} + CO_2 + NH_3 + NO_3 \rightarrow O_2 + H_2O \quad (25)$$

During the night, the upwelling process is weak and the organic solids and sludge settle to the bottom of the WSP and in the absence of oxygen, the anaerobic bacteria convert the insoluble inorganic waste into soluble organics such as ethanol and others which are broken down by anaerobic bacteria to form H_2S, NH_3, CH_4, CO_2. The sludge deposited at the bottom of the tank can be removed by dredging [12]. Below, Figure 6 shows the biological cycle that takes place in the stabilization ponds mentioned above, which is the final process for removing the contaminant load from the effluent in its entirety.

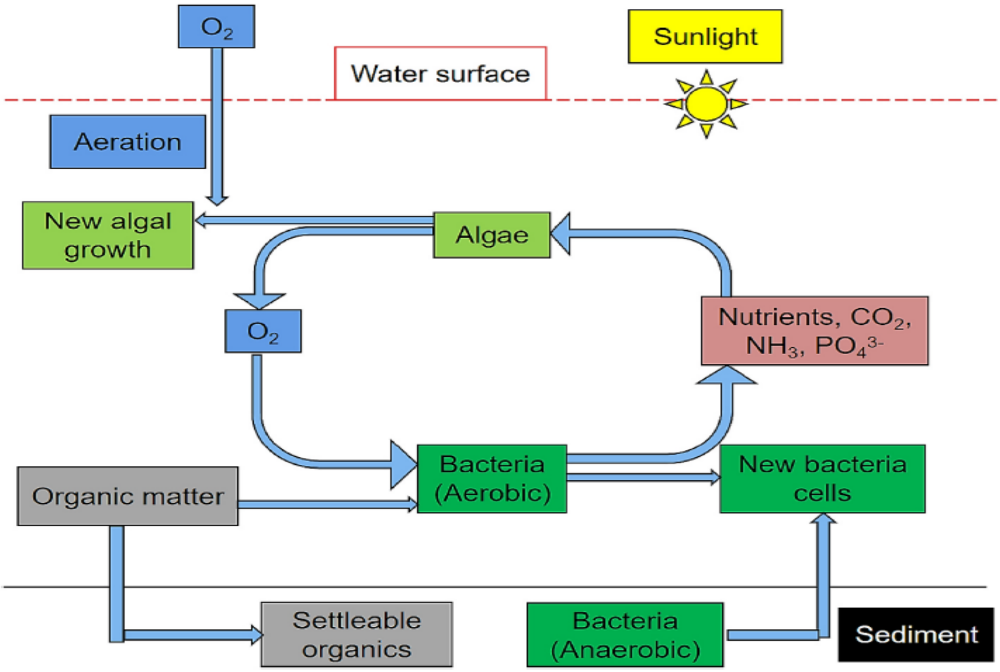

Figure 6. Load removal cycle by biological processes.

3.4. Alternative Technologies Evaluated

Other alternative technologies were evaluated but no in-depth studies were carried out because we have a low COD/BOD ratio (<2.5); the biodegradable fraction is high, and the use of biological treatment is recommended. Other technologies, such as anaerobic reactors (UASB), activated sludge systems and aerobic biofilm reactors, require longer periods such as 120 days to start the degradation process and are not economically viable.

3.5. Advantages and Disadvantages

3.5.1. Advantages of Using Stabilization Pond Systems

The use of different types of lagoons has a number of advantages: high BOD and coliform removal efficiency; reduced operating and maintenance costs; and simple operation.

3.5.2. Disadvantages of Using This Type of Stabilization Pond System

The main disadvantages are that large areas are required to implement these systems; biological activity is affected by temperature; if they are in cold regions the process is slow; and they generate bad odors.

4. Conclusions

The treatment of industrial effluents is of immeasurable importance and the consequences of improper disposal can be seen in various spheres of society. In environmental terms, the improper disposal of wastewater causes eutrophication of water bodies, death of aquatic life, contamination of soil and groundwater, since these systems use huge quantities of water for their production activities. For the first time, based on the parameters obtained from the effluents from this factory, we were able to design a system for treating these effluents using anaerobic, aerobic and facultative ponds. The lagoon system represents a reliable and dependable solution for basic sanitation, and is widely implemented in several countries. In Mozambique, due mainly to its tropical climate, lagoons represent a reliable and dependable solution for basic sanitation. In general, lagoons are easy to operate, have relatively low maintenance and construction costs and consume little energy. In terms of BOD removal efficiency, the typical range is between 75 and 85 per cent. With regard to coliform removal, up to 99.9 per cent efficiency can be achieved. This serial scheme, with three anaerobic, three facultative and two aerobic lagoons, maximizes contaminant removal efficiency and ensures that the treated effluent meets regulatory parameters before being released into the environment. We now need approval for the proposal from the sugar factory and support from the government of Mozambique to introduce our solution all across the country.

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References

1. Almeida, J.S.; Sousa, L.V.; Silva, E.P. Sistema de Tratamento de Águas Residuárias de Laticínios. In *Anais do 3° Simpósio de TCC*; Faculdades FINOM e Tecsoma: Paracatu, Brazil, 2020; pp. 617–630.
2. Pereira, F.J. A Concepção e Eficiência do Sistema de Esgotamento Sanitário de João Pessoa–PB com ênfase na estação de tratamento do baixo paraíba, outubro de 2018. Universidade Federal Da Paraíba—Ufpb Centro De Tecnologia—Ct Curso De Engenharia Ambiental Trabalho De Conclusão De Curso. 2024. Available online: https://repositorio.ufpb.br/jspui/bitstream/123456789/24457/1/TCC%20Felipe%20Juli%C3%A3o%20Pereira.pdf (accessed on 15 August 2024).
3. Meghana, M.; Shastri, Y. Sustainable valorization of sugar industry waste: Status, opportunities, and challenges. *Bioresour. Technol.* **2020**, *303*, 122. [CrossRef] [PubMed]
4. Ungureanu, N.; Vladut, V.; Biris, S.-S. Sustainable Valorization of Waste and By-Products from Sugarcane Processing. *Sustainability* **2022**, *14*, 11089. [CrossRef]
5. Pierossi, M.; Bernhardt, H.W. Sugarcane Leaves and Tops: Their Current use For Energy and Hurdles to be Overcome, Particularly in South Africa, for Greater Utilisation. *Proc. S. Afr. Sug. Technol. Ass.* **2016**, *89*, 350–360.
6. Muguirrima Vasco Mariano, P.; Rafael Penicela, N.C.; León Zerpa, F.A.; Mendieta Pino, C.A. Avaliação das Proriedades Fisico-Quimicas dos Efluentes da Companhia Açucareira de Moçambique. 2024. Available online: https://accedacris.ulpgc.es/handle/10553/130860 (accessed on 15 August 2024).
7. Matos, M.P. Effect of Binomial Time-Temperature of Sample Incubation on Biochemical Oxygen Demand Diffusion of Wastewater. Master's Dissertation, Federal University of Viçosa, Minas Gerais, Brazil, 2012.
8. Matos, M.P. Efeito de Binomio Tempo-Temperatura de Incubação da Amostra na Demanda Bioquimica de Oxigenio Difusão de Águas Residuárias. Disertação de Mestrado, Universidade Fedareal de Viçosa, Minas Gerais, Brazil, 2012.

9. Batista, N.B.S.; Aguiar, A. Estudo de Parâmetros Fisico-Químicos e suas correlações para efluentes de Laticínios do estado de Minas Gerais. In Proceedings of the XXII Encontro Latino Americano de Iniciação Científica, XVIII Encontro Latino Americano de Pós-Graduação e VIII Encontro de Iniciação à Docência-Universidade do Vale do Paraíba, São José dos Campos, Brazil, 25–26 October 2018.
10. Muguirrima, P.V.M.; Chirinza, N.P.; Grande, S.C.; Mendieta Pino, C.A.; León Zerpa, F.; Pérez Báez, S.O.; Martín, A.R. Tratamiento de efluentes domésticos mediante métodos bioflitro sostenibles. In Proceedings of the X Jornadas Iberoamericanas de Innovación Educativa en el ámbito de las TIC y las TAC, Las Palmas de Gran Canaria, Spain, 16–17 November 2023.
11. Alprol, A.E.; Mansour, A.T.; Ibrahim, M.E.E.D.; Ashour, M. Artificial Intelligence Technologies Revolutionising Wastewater Treatment: Current Trends and Future Prospective. *Water* **2024**, *16*, 314. [CrossRef]
12. Apoorva, D.; Chandrashekar, B. Treatment of Sugar Industry Wastewater by Adsorption method. *Int. Res. J. Mod. Eng. Technol. Sci.* **2022**, *4*, 1693–1699.
13. Von Sperling, M. Introdução à qualidade das águas e ao tratamento de esgotos. In *Princípios do Tratamento Biológico de Águas Residuárias*, 3rd ed.; Departamento de Engenharia Sanitária e Ambiental-DESA, Universidade Federal de Minas Gerais: Belo Horizonte, Brazil, 2005; Volume 1, 452p.
14. Batista, N.B.S.; Aguiar, A. Study of physicochemical parameters and their correlations for dairy effluents in the state of Minas Gerais. In Proceedings of the XXII Latin American Scientific Initiation Meeting, XVIII Latin American Postgraduate Meeting and VIII Teaching Initiation Meeting-University of Vale do Paraíba, São José dos Campos, Brazil, 12–14 December 2018.
15. Marzec, M.; Listosz, A.; Malik, A.; Kulik, M.; Jóźwiakowski, K. Organic Pollutants Removal in a Hybrid Constructed Wetland Wastewater Treatment Plant with an Aeration System. *Water* **2024**, *16*, 947. [CrossRef]
16. Naz, I.; Ahmad, I.; Aslam, R.W.; Quddoos, A.; Yaseen, A. Integrated Assessment and Geostatistical Evaluation of Groundwater Quality through Water Quality Indices. *Water* **2023**, *16*, 63. [CrossRef]
17. de Campos, S.X.; Soto, M. The Use of Constructed Wetlands to Treat Effluents for Water Reuse. *Environments* **2024**, *11*, 35. [CrossRef]
18. Younas, F.; Mustafa, A.; Farooqi, Z.U.R.; Wang, X.; Younas, S.; Mohy-Ud-Din, W.; Hameed, M.A.; Abrar, M.M.; Maitlo, A.A.; Noreen, S.; et al. Current and emerging adsorbent technologies for wastewater treatment: Trends, limitations, and environmental implications. *Water* **2021**, *13*, 215. [CrossRef]
19. Von Sperling, M. Lagoas de estabilização. In *Princípios do Tratamento Biológico de Águas Residuárias*, 2nd ed.; Departamento de Engenharia Sanitária e Ambiental-DESA, Universidade Federal de Minas Gerais: Belo Horizonte, Brazil, 2002; Volume 3, 196p.
20. Von Sperling, M. Lodos ativados. In *Princípios do Tratamento Biológico de Águas Residuárias*, 1st ed.; Departamento de Engenharia Sanitária e Ambiental-DESA, Universidade Federal de Minas Gerais: Belo Horizonte, Brazil, 1997; Volume 4, 428p.
21. Panhwar, A.; Kandhro, A.; Bhutto, S.; Brohi, N.; Naz, S. Chemical Treatment Options of Wastewater from Sugarcane Industry and its Priority Parameters Comparison as Per Smart Rules of Sindh Environmental Protection Agency. *Pak. J. Sci.* **2021**, *73*. [CrossRef]
22. Tolêdo, C.S.S. Tratameto de Efluentes Industriais: Uma Revisão de Fundamentos e Aplicações. In Proceedings of the XVI CNEG_Congresso Nacional de Excelência em Gestão; INOVARSE_Simpósio de Inovação e Responsabilidade Social, Rio de Janeiro, Brasil, 14–16 July 2022.
23. Chernicharo, C.A.L.; Van Lier, J.B.; Noyola, A.; Bressani Ribeiro, T. Anaerobic sewage treatment: State of the art, constraints and challenges. *Rev. Environ. Sci. Biotechnol.* **2015**, *14*, 649–679. [CrossRef]
24. *IMPACTOS na Saúde e no Sistema Único de Saúde Decorrentes de Agravos Relacionados a um Saneamento Ambiental Inadequado*; Fundação Nacional de Saúde: Brasília, Brazil, 2010; 246p.
25. Zaharia, C.; Musteret, C.-P.; Afrasinei, M.-A. The Use of Coagulation-Flocculation for Industrial Coloured Wastewater Treatment-(I) The Application of Hybrid Materials. *Appl. Sci.* **2024**, *14*, 2184. [CrossRef]
26. Montero, A.A.G.; Arrieta, Y.M.B.; Serrano, E.V.P. Treatment of Slaughterhouse Wastewater through a Series System: Upflow Anaerobic Reactor and Artificial Wetland. *Water* **2024**, *16*, 700. [CrossRef]
27. Maria, M.P.; Torres, N.H.; Nascimento, V.R.S.; Chagas, T.S.A.; Saratale, G.D.; Mulla, S.I.; Bharagava, R.N.; Cavalcanti, E.B.; Ferreira, L.F.R. Current advances in the brewery wastewater treatment from anaerobic digestion for biogas production: A systematic review. *Environ. Adv.* **2023**, *13*, 100394. [CrossRef]
28. Bao, Y.; Koutavarapu, R.; Lee, T.G. Derivation of Optimal Operation Factors of Anaerobic Digesters through Artificial Neural Network Technology. *Systems* **2023**, *11*, 375. [CrossRef]
29. Mendieta-Pino, C.A.; Garcia-Ramirez, T.; Ramos-Martin, A.; Perez-Baez, S.O. Experience of Application of Natural Treatment Systems for Wastewater (NTSW) in Livestock Farms in Canary Islands. *Water* **2022**, *14*, 2279. [CrossRef]
30. das Neves, A.P.N.; Ferreira, D.d.S.; Castro, D.A.; Cavallini, G.S. Avaliação da eficiência de remoção de matéria orgânica em efluente sanitário em função da idade do lodo de reator UASB: Um estudo de caso. *J. Biotechnol. Biodivers.* **2019**, *7*, 449–456. Available online: https://sistemas.uft.edu.br/periodicos/index.php/JBB/article/view/7832 (accessed on 26 May 2023). [CrossRef]
31. Mendoza-Tinoco, T.P.; Sánchez-Vázquez, V.; del Carmen Fajardo-Ortiz, M.; González, I.; Beristain-Cardoso, R. How does a low-magnitude electric field influence anaerobic digestion in wastewater treatment? A review. *Chemosphere* **2023**, *325*, 138402. [CrossRef] [PubMed]
32. Khumalo, S.M.; Bakare, B.F.; Rathilal, S.; Tetteh, E.K. Characterisation of South African Brewery Wastewater: Oxidation-Reduction Potential Variation. *Water* **2022**, *14*, 1604. [CrossRef]

33. Ribeiro, T.; Janz, F.J.L.; Vizibelli, D.; Borges, J.C.Â.; Borssoi, J.A.; Fukumoto, A.A.F.; Bergamasco, R.; Yamaguchi, N.U.; Pereira, E.R. Magnetic Natural Coagulants for Plastic Recycling Industry Wastewater Treatability. *Water* **2023**, *15*, 1276. [CrossRef]
34. Ramírez, L.E.F.; Zamora-Castro, S.A.; Sandoval-Herazo, L.C.; Herrera-May, A.L.; Salgado-Estrada, R.; De La Cruz-Dessavre, D.A. Technological Innovations in the Application of Constructed Wetlands: A Review. *Processes* **2023**, *11*, 3334. [CrossRef]
35. García-Valero, A.; Acosta, J.A.; Faz, Á.; Gómez-López, M.D.; Carmona, D.M.; Terrero, M.A.; El Bied, O.; Martínez-Martínez, S. Swine Wastewater Treatment System Using Constructed Wetlands Connected in Series. *Agronomy* **2024**, *14*, 143. [CrossRef]
36. Gehling, G. *Lagoas de Estabilização*; Universidade Federal do Rio Grande do Sul: Farroupilha, Brazil, 2017.
37. Brasil Ministério do Desenvolvimento Regional; Agência Nacional de Águas E Saneamento Básico. *Atlas Esgoto/Ministério do Desenvolvimento Regional, ANA*; Ministério do Desenvolvimento Regional: Brasília, Brazil, 2020.
38. Mara, D.D. *Design Manual for Waste Stabilisation Ponds in INDIA*; Lagoon Tecnology International Ltd.: Leeds, UK, 1997.
39. Korniłłowicz-Kowalska, T.; Bohacz, J.; Rybczyńska-Tkaczyk, K.; Jóźwiakowski, K. Evaluation of the Richness, Species Diversity, and Biosafety of Saprotrophic Fungal Communities in Constructed Wetlands and Biological Wastewater Ponds. *Water* **2023**, *15*, 31. [CrossRef]
40. Wilkinson, S.R.; Naeth, M.A.; Dhar, A. Potential of Macrophytes for Wastewater Remediation with Constructed Floating Wetlands in Cold Climates. *Water* **2023**, *15*, 2479. [CrossRef]
41. Bachi, O.E.; Halilat, M.T.; Bissati, S.; Al-Ansari, N.; Saggai, S.; Kouadri, S.; Najm, H.M. Wastewater Treatment Performance of Aerated Lagoons, Activated Sludge and Constructed Wetlands under an Arid Algerian Climate. *Sustainability* **2022**, *14*, 6503. [CrossRef]
42. de Almeida, P.R.C.; da Costa, M.R.; de Souza Coutinho, R.D.; Méndez-Vicente, A.; Castro, J.P.; Monteiro-Neto, C.; de Almeida Tubino, R.; Correia, A.T. Use of otolith microchemistry signatures to assess the habitat use of Centropomus undecimalis in lagoon systems of the southwest Atlantic. *Reg. Stud. Mar. Sci.* **2024**, *73*, 103470. [CrossRef]
43. Jeon, W.H.; Lee, S.H.; Moon, H.S.; Kim, Y.; Chang, S.W.; Hwang, S. Impacts of pumping on the spatiotemporal dynamics of a fresh-saline water mixing zone in a coastal lagoon-aquifer system. *J. Hydrol. Reg. Stud.* **2024**, *51*, 101657. [CrossRef]
44. Gebru, S.B.; Werkneh, A.A. Applications of constructed wetlands in removing emerging micropollutants from wastewater: Occurrence, public health concerns, and removal performances—A review. *S. Afr. J. Chem. Eng.* **2024**, *48*, 395–416. [CrossRef]
45. Filho, F.J.C.M.; de Souza Filho, J.C.M.; Paulo, P.L. Multistage constructed wetland in the treatment of greywater under tropical conditions: Performance, operation, and maintenance. *Recycling* **2021**, *6*, 63. [CrossRef]
46. Su, H.; Wang, K.; Lian, J.; Wang, L.; He, Y.; Li, M.; Han, D.; Hu, Q. Advanced treatment and Resource recovery of brewery wastewater by Co- cultivation of filamentous microalga Tribonema aequale and autochthonous Bacteria. *J. Environ. Manag.* **2023**, *348*, 119285. [CrossRef]
47. Menció, A.; Madaula, E.; Meredith, W.; Casamitjana, X.; Quintana, X.D. Dataset for analysing and modelling the eutrophication processes in groundwater-coastal lagoon systems: The La Pletera lagoons case study (NE Spain). *Data Brief* **2023**, *48*, 109197. [CrossRef] [PubMed]
48. Vymazal, J. Constructed wetlands for wastewater treatment. *Water* **2010**, *2*, 530–549. [CrossRef]
49. Kochi, L.Y.; Freitas, P.L.; Maranho, L.T.; Juneau, P.; Gomes, M.P. Aquatic macrophytes in constructed wetlands: A fight against water pollution. *Sustainability* **2020**, *12*, 9202. [CrossRef]
50. Macário, M.; Saraiva, A.; Ferreira, E.; Ferreira, L.F.; Oliveira, M. O Bambu Como Alternativa aos Sistemas de Tratamento de Águas Residuais Convencionais. Vol. 8 N.º 3. Edição Temática: Ciências Naturais e do Ambiente. 2020. Available online: https://revistas.rcaap.pt/uiips/article/view/21341 (accessed on 15 August 2024).
51. Zheng, Y.; Song, Y.; Zhang, R.; Zhang, N.; Salah, M.; Cheng, S.; Li, Y.; Wang, Q.; Li, C.; Li, F. A feasible method for the composition analysis and chemical remediation of clogging matter in subsurface flow constructed wetland. *Water Cycle* **2024**, *5*, 131–136. [CrossRef]
52. Zhu, X.; Qie, R.; Luo, C.; Zhang, W. Assessment and Driving Factors of Wetland Ecosystem Service Function in Northeast China Based on InVEST-PLUS Model. *Water* **2024**, *16*, 2153. [CrossRef]
53. Lemenkova, P. Artificial Intelligence for Computational Remote Sensing: Quantifying Patterns of Land Cover Types Around Cheetham Wetlands, Port Phillip Bay, Australia. *J. Mar. Sci. Eng.* **2024**, *12*, 1279. [CrossRef]