water

MDPI

Article

Treatment of Slaughterhouse Wastewater through a Series System: Upflow Anaerobic Reactor and Artificial Wetland

Andrés A. Galindo Montero *, **Yeison M. Berrio Arrieta** and **Estefany V. Pimienta Serrano**

Grupo de Investigación GISA, Facultad de Ingeniería, Universidad de La Guajira, Riohacha 440001, Colombia; ymberrio@uniguajira.edu.co (Y.M.B.A.); evpimienta@uniguajira.edu.co (E.V.P.S.)
* Correspondence: agalindo@uniguajira.edu.co

Abstract: Slaughterhouse wastewater is characterized by high concentrations of organic matter. This creates a need to explore methods for its treatment before discharge. This study evaluated the efficiency of an integrated treatment process consisting of a laboratory-scale upflow anaerobic sludge blanket reactor and a pilot-scale horizontal subsurface flow wetland. This treatment was used for (i) the removal of organic matter through anaerobic–aerobic microbiological processes, (ii) the conversion of organic matter from hydraulic processes, and (iii) for bioremediation and phytoremediation. The treatment system was evaluated at hydraulic retention times (HRTs) of 7.5, 5.0, and 2.5 d; during the investigation, the influence of the HRTs on the removal efficiency of the system was evaluated. High efficiencies of 85% and 75% were obtained for COD_T and BOD, respectively, at an HRT of 7.5 d. The highest overall efficiency for the removal of total solids was observed at an HRT of 2.5 d. The results obtained confirm the feasibility of implementing the suggested system as an alternative for the adequate and sustainable treatment of slaughterhouse wastewater, and the system can be applied to slaughterhouses with similar conditions to those in this study.

Keywords: slaughterhouse wastewater; meat processing plant; wetlands; anaerobic treatment

check for updates

Citation: Galindo Montero, A.A.; Berrio Arrieta, Y.M.; Pimienta Serrano, E.V. Treatment of Slaughterhouse Wastewater through a Series System: Upflow Anaerobic Reactor and Artificial Wetland. *Water* **2024**, *16*, 700. https://doi.org/10.3390/w16050700

Academic Editor: Carlos Costa

Received: 7 July 2023
Revised: 20 September 2023
Accepted: 21 September 2023
Published: 27 February 2024

1. Introduction

The slaughtering, processing, and preservation activities used during meat production in municipal slaughterhouses produce large amounts of wastewater [1]. Wastewater discharge without proper treatment negatively impacts the environment [2]. The liquid effluents generated at municipal slaughterhouses cause severe pollution owing to their high organic load, showing a biochemical oxygen demand (BOD) ranging between 5000 and 10,000 mg/L. In addition, they have high contents of solids, nutrients, fats, and oils, which are pollutants with low biodegradability [3]. Therefore, if these wastewaters are not adequately treated, they may contribute to the degradation of the receiving environment, including water and soil [4,5]. In this regard, the implementation of specialized treatment systems is required for pollutant removal [2,6–8].

The safe and controlled disposal of slaughterhouse wastewater (SWW) has become increasingly important owing to the strict regulatory requirements of each country and the regulations imposed by environmental protection agencies on the quality of effluents from the meat processing industry [9]. Therefore, to increase the removal efficiency of contaminants, a treatment system aimed at decreasing the levels of contamination present in SWW is required to minimize the impact of the discharge on the environment [10]. According to Rittmann and McCarty [11], aerobic treatments are not an adequate option for SWW because aeration has high energy costs and limitations in the liquid-phase rates of oxygen transfer. In addition, the large volumes of sludge produced are a limitation. Therefore, for sustainable system development and utilization, anaerobic digestion has become a key technology for SWW treatment owing to its low cost and its generation of by-products (i.e., bioenergy, nutrients, and water for reuse) [5,10].

Anaerobic treatment systems (ATSs) have become increasingly consolidated and used, especially for medium- and high-load effluents [12]. Among the anaerobic processes, upflow anaerobic sludge blankets (UASBs) have been widely adapted for the treatment of high-load industrial wastewaters such as meat effluents [5,8,13,14]. A study conducted by Nair & Ahammed [15] demonstrated that UASB reactors have a removal efficiency range of 55% to 75% for this type of substrate, which varies depending on the composition of the treated SWW. Despite the high removal efficiencies achieved in anaerobic systems (e.g., UASB reactors), their effluents still contain residual nutrients, organic matter, and pathogenic microorganisms. Therefore, the effluents of ATSs that integrate UASBs often do not comply with the standards established by environmental legislation [8]. Among the main difficulties encountered during the treatment of SWW by ATSs are sludge washing as well as the inhibition of this process by operational factors such as volatile fatty acid concentrations, ammonium levels, and the buffer capacity of the system [7]; thus, post-treatment is required to ensure that the treated SWW meets the environmental standards of each country and to ensure the protection of the environments in which the effluents are discharged [4,16,17].

Wetlands are post-treatment systems used for the treatment of ATS effluents [9]. Wetlands have been used to treat different types of effluents because they have low costs, are environmentally friendly, and efficiently remove pollutants [18–20]. This bioremediation mechanism is widely used to treat wastewater [7,21,22]. For the treatment of slaughterhouse wastewater, mainly subsurface flow wetlands have been implemented, with high removals reported for both vertical and horizontal flow [7,21–23]. The removal processes occur through the action of aerobic bacteria attached to the filter medium (gravel) and plant roots, which provide optimal conditions for filtration, absorption, and nutrient consumption, favoring the development of symbiotic processes in the rhizosphere (i.e., between bacteria and roots) [23,24].

For wastewater treatment using wetlands, the genus *Typha* is one of the most widely used given its wide geographic distribution and tolerance to changes in temperature and contamination levels [9,25,26]. Specifically, *Typha domingensis* is characterized by an extensive root system and a spongy plant structure that favors fixation processes, the accumulation of heavy metals that cannot be removed [27], the absorption of nutrients from soil [28], and the release of compounds that reduce the growth of pathogenic microorganisms [29].

In this sense, starting with the complex chemical composition of SWW (i.e., high organic loads and presence of particulate matter, fats, colloids, cellulose, and inorganic matter) and the difficulty in obtaining high efficiencies from individual treatments [16,17], this present study aims to increase the treatment removal efficiency by integrating anaerobic digestion and aerobic processes in a series system that combines two alternatives (a UASB + a subsurface wetland with horizontal flow) that have been widely studied [7]. The load conversion processes are based on physical processes: sedimentation, coagulation, and filtration. Moreover, they are assisted by the following biological processes: the biochemical activity of microorganisms (anaerobic) present in the reactor substrate and the aerobic activity in the filter medium (gravel) and the rhizosphere of the wetland plants; these conditions allow the system to reach higher efficiencies in pollutant removal. Compared with other treatments, the integrated system used in this study has the following advantages in terms of the experimental unit and operational conditions: (i) regulation of the buffer capacity of the reactor, (ii) better distribution of the influent with stable upward velocities, (iii) filtration processes by the granular media and by the plant roots for the elimination of solids and particulate material, (iv) facilitate of nutrient removal through nitrification and denitrification owing to oxygenation and the contribution of the carbon source present in the proteins and fats of the SWW, and (v) phytoaccumulation or immobilization of complex substances that are difficult to degrade [10,17,30,31].

Finally, the aim of this study was to evaluate the performance of two biological systems combined at different HRTs. Very simple and low-cost technologies were used, and the specific objectives of this study were to (i) characterize the SWW, (ii) characterize the granular sludge, (iii) adapt and start-up the system, (iv) monitor and operate the system, and (v) analyze the system's removal efficiency. Based on the information collected, the viability of the system for the treatment of SWW was determined. The results could play an important role in the management of this type of wastewater as well as in the protection of the environment.

2. Materials and Methods

2.1. Design of the Experimental System

A UASB operating in series with a horizontal subsurface wetland was used for the experiment. The UASB was built using fiberglass and had a volume of 12 L and a biogas measurement system. Because of its dimensions, the UASB was considered to be at the laboratory scale.

To obtain retention times similar to those of operational wetland systems, the wetland was designed on a pilot scale in a rectangular shape. It was constructed using acrylic with a height, length, and width of 25 cm, 110 cm, and 40 cm, respectively, and it had a bottom slope of 0.4 cm. Baffles were used to divide it into four chambers to promote an upward and downward coil flow (i.e., to improve the system's micromixing). As support material, 27 L of gravel with diameters of 1/2″, 3/8″, 1/4″, and 1/8″ distributed upward was added, and 25 specimens of *T. domingensis* were planted over an area of 0.03 m^2 per plant unit. A 600 rpm peristaltic pump, which ensured a constant flow rate at each HRT assessed, was incorporated into the system. A diagram of the experimental system is shown in Figure 1. The system operated at sea-level environmental conditions (Riohacha, La Guajira, Colombia).

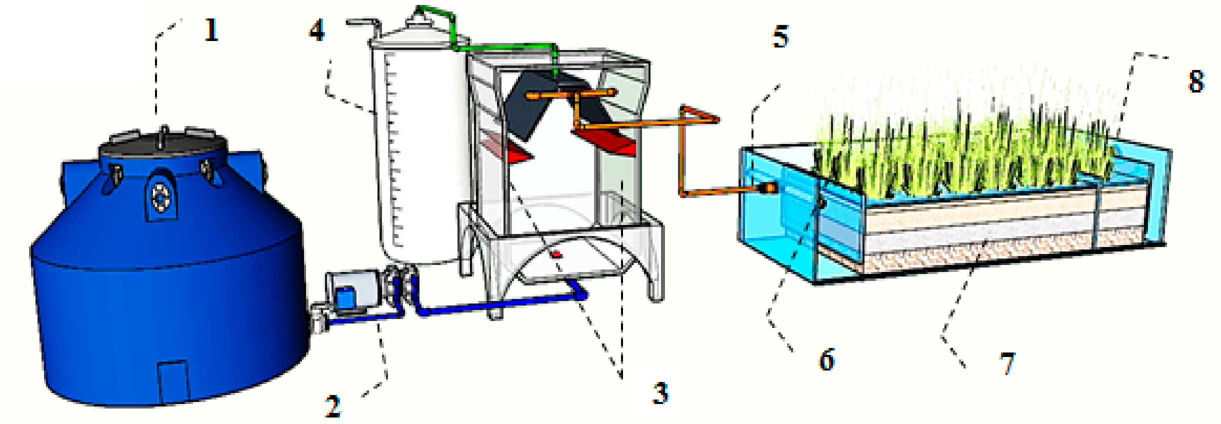

Figure 1. Diagram of the experimental system used. 1. Load tank, 2. peristaltic pump, 3. UASB, 4. biogas system, 5. wetland inlet, 6. *Typha domingensis*, 7. filter material, 8. wetland effluent.

2.2. Operation of the Experimental System

2.2.1. UASB Inoculation

The inoculum was characterized, and the granule size (500 granules), sedimentation velocity, relative density, total solids (TSs), and moisture content were determined [32,33]. The inoculated sludge was obtained from a brewery. The granular sludge had a contact area of 0.10 m^2, and 2.4 L of sludge was fed into the UASB. This corresponded to 20% of the reactor's used volume, a commonly used heuristic in this type of reactor [34].

2.2.2. System Start-Up

To ensure adequate sludge washing, the system was initially operated for 12 h at an upward rate of 13.33 mL/min, and the UASB was fed with SWW from the municipality of Riohacha (La Guajira, CA, USA). The UASB was progressively fed with increasing dilutions of SWW (40%, 60%, and 100%), and the reactor was operated for 20 d at each dilution level. A calcium carbonate solution ($CaCO_3$) was simultaneously prepared at a concentration of

500 g/L, of which approximately 5 mL was added to the system to increase the pH of the influent to 7.5 to avoid acidification of the system [35]. Regarding the adaptation of the sludge to the substrate, the reactor was operated in batches for 60 d at a 48 h HRT until constant biogas production was obtained. The start-up phase of the reactor was completed once the reactor stabilized with regard to pH and biogas production.

2.2.3. Wetland Setup

To set up the wetland, *Typha domingensis* specimens were obtained from a natural lagoon located in an urban area of the city of Riohacha (Laguna Salá). The selection was performed considering the criteria and/or characteristics of young and healthy specimens [28]. To acclimate the seedlings to the new substrate, they were kept in plastic containers containing SWW diluted at 50% for 10 d and at 70% for a further 20 d. During this time, their development was monitored until the specimens reached stem, leaf lamina, and root lengths of 5 cm, 30 cm, and 15 cm, respectively [25]. The specimens were then transferred to the experimental system. For the integrated system (UASB + Wetland), the preparation phase lasted six weeks.

2.2.4. System Operation

The experimental system was installed and monitored at the facilities of the Institute for Environmental Studies and Water Use of the University of La Guajira, located in the city of Riohacha. The system (UASB + Wetland) was operated for 36 weeks, divided into three phases with a duration of 12 weeks for HRT1 (7.5 d), 9 weeks for HRT2 (5 d), and 9 weeks for HRT3 (2.5 d).

2.2.5. Analytical Methods

To assess the system, HRTs of 1.5, 1, and 0.5 d for the UASB and 6.1, 4.1, and 2 d for the wetland were considered. The HRTs evaluated are considered relevant for systems studied in tropical zones, such as that in which this study was conducted. Once the system stabilized, 10 samples were taken at each HRT to evaluate the removal levels. The sampling points were the influent, the UASB effluent, and the wetland. In the UASB, the biogas production and methane percentage were also measured. The following operational parameters were measured daily: pH, total alkalinity, and temperature. To evaluate the removal efficiency of the system, the following were measured: chemical oxygen demand (COD_T), BOD, TSs, total volatile solids (TVSs), total fixed solids (TFSs), total suspended solids (TSSs), nitrate (NO_3^{+5}), nitrite (NO_2^{+3}), ammonium (NH_4^{-3}), and phosphate (PO_4^{-3}), following standard methods [36].

3. Results and Discussion

3.1. Sludge Characteristics

The characterization results showed large variability in the granule size, ranging between 0.02 mm and 4 mm; this large variability prevents instability in the sludge bed [33]. The sedimentation velocity of the sludge was 37.4 m/h, which is within the recommended range (29 to 42 m/h) for the formation of a suitable granular sludge [33]. The relative density of the sludge was slightly higher than that of water (1.02). It ranged between 1 and 1.07, consistent with that previously reported for this type of sludge [32].

3.2. Operational Parameters

Table 1 shows the operational parameters of the reactor. The mean, maximum, and minimum pH values, temperature (T), and alkalinity for the reactor influent and effluent during the system operation time are shown.

Table 1. Operational parameters of the influent and effluent at the UASB.

Hydraulic Retention Time: 7.5 Days					
HRT (h)	Component	(°C) $\bar{x} \pm \sigma$	pH $\bar{x} \pm \sigma$	Alk P (mg/L) $\bar{x} \pm \sigma$	Alk T (mg/L) $\bar{x} \pm \sigma$
36	Influent	28.1 ± 2	8.54 ± 0.22	347 ± 144	520 ± 203
	Effluent UASB	31.1 ± 1.36	7.43 ± 0.88	766 ± 492	933 ± 499
Hydraulic Retention Time: 5.0 days					
HRT (h)	Component	T (°C) $\bar{x} \pm \sigma$	pH $\bar{x} \pm \sigma$	Alk P (mg/L) $\bar{x} \pm \sigma$	Alk T (mg/L) $\bar{x} \pm \sigma$
24	Influent	28.8 ± 1.31	8.49 ± 0.36	557 ± 154	799 ± 157
	Effluent UASB	30.5 ± 0.96	7.79 ± 0.22	1700 ± 319	2006 ± 346
Hydraulic Retention Time: 2.5 days					
HRT (h)	Component	T (°C) $\bar{x} \pm \sigma$	pH $\bar{x} \pm \sigma$	Alk P (mg/L) $\bar{x} \pm \sigma$	Alk T (mg/L) $\bar{x} \pm \sigma$
12	Influent	27.9 ± 1.57	8.65 ± 0.20	538 ± 190	756 ± 226
	Effluent UASB	31.1 ± 0.87	8.01 ± 0.17	1462 ± 430	1736 ± 448

Notes: pH: potential of hydrogen. Alk P: partial alkalinity. Alk T: total alkalinity. T: slaughterhouse residual water temperature. $\bar{x} \pm \sigma$: average values ± standard deviation.

The temperature of the SWW in the influent and effluent of the UASB reactor at the different HRTs evaluated showed values within the expected range for the type of climate studied (tropical, between 20 and 40 °C); in this range, adequate anaerobic digestion is achieved through bacterial metabolism. The temperature values for the influent were between 24 and 29 °C, and those for the reactor effluent were between 30 and 31 °C, indicating that they were within the mesophilic range [6]. A suitable temperature during anaerobic processes, specifically those of the UASBs, is fundamental for ensuring the efficiency of treatment, considering that this variable affects the speed of biological reactions, gas transfer, and sedimentation [37].

The overall pH value for the influent was 8.5, which is higher than that of the effluent (7.7), given that $CaCO_3$ was added during start-up to neutralize the pH. The pH plays a fundamental role in organic-matter-removal processes [35]. The pH values of the reactor inlet showed an overall mean of 7.33 ± 0.33 once stabilized with the $CaCO_3$ solution, whereas the overall mean pH for the system effluent was 8.54 ± 0.27. This increase in pH may have been due to biomethanization [35]. The neutralization of the pH through the addition of $CaCO_3$ mitigated the acidification of the system, and the variations between the influent and effluent inhibited competition between the bacterial consortia characteristic of ATSs. Therefore, the bacteria would optimize the separation of the phases of anaerobic digestion and would reach adequate levels for the effective operation of the system [38]. The optimal pH varies with the substrate and digestion technique [35]; therefore, it was reported that the best performance occurs at an HRT of 7.5 d, where a pH of 7.48 is observed [39]. In this study, although the pH at the other two HRTs considered was higher than this, the system performed adequately.

The pH of the wetland technology had an overall mean of 7.88 ± 0.20 and a range of 7.23–8.38. Vymazal [20] reported that the optimum pH for nitrification processes by nitrifying bacteria (Nitrosomonas and Nitrobacter) lies in the range 7.5–8.6. With respect to this range, the pH observed in the operational phase of the wetland system during the denaturation of nutrients by aerobic microorganisms to convert the nutrients into substances assimilable by *T. domingensis* plants was in the optimal range for the operation of the system and plant development [22,35].

In this phase of project, the alkalinity was measured only in the UASB reactor because the alkalinity ratio is a fundamental control parameter for anaerobic processes [14,40]. In contrast, for aerobic systems (i.e., wetlands), these parameters may be considered secondary because the fluctuation of alkalinity data does not imply substantial negative impacts, as with anaerobic technologies [22]. As shown in Table 1, higher values were found for the effluent of the UASB reactor compared with those for the influent. The variations in the alkalinity results were attributed to the by-products generated at the methanogenic stage of the anaerobic digestion process, mainly the residual methane dissolved in the effluent. This produced chemical conditions that favored an increase in the alkalinity of the UASB effluent [7,41]. Achieving the appropriate metabolic conditions within the treatment system was favorable because it allowed the methanogenic bacteria to use the intermediary acids as soon as these were formed, preventing their accumulation and ensuring that the alkalinity and pH remained in a suitable range [38]. The HRT that most closely matched these requirements was 7.5 d; hence, biogas production was highest at this point [35] (Figure 2).

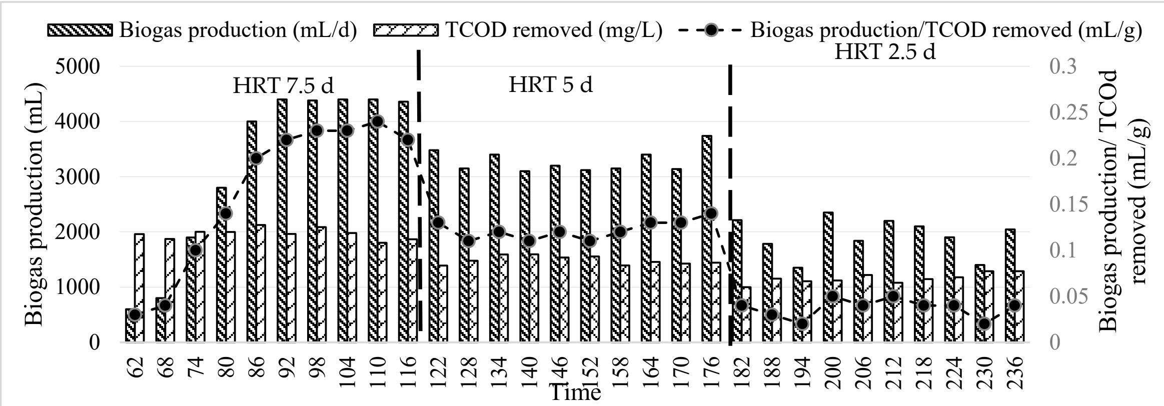

Figure 2. Production of biogas vs. COD removed in the UASB during the treatment of the SWW.

The average biogas production was approximately 2500 mL/day, with higher generation at a 36 h HRT in the UASB. This biogas production was the result of the high organic load applied and a favorable performance of the UASB, as it indicates the partial conversion of the organic compounds entering the system (Figure 2). These results were consistent with the highest removal rate and efficiency of the system, indicating that biogas production is closely related to organic matter removal [42].

The behavior of COD_T and BOD in the system at the assessed HRTs is shown in Figures 3 and 4. The BOD/COD_T ratio was 0.64, indicating the potential for biological treatment of these wastewaters through conventional systems such as the integrated UASB + Wetland, wherein high removal efficiencies were achieved [43,44].

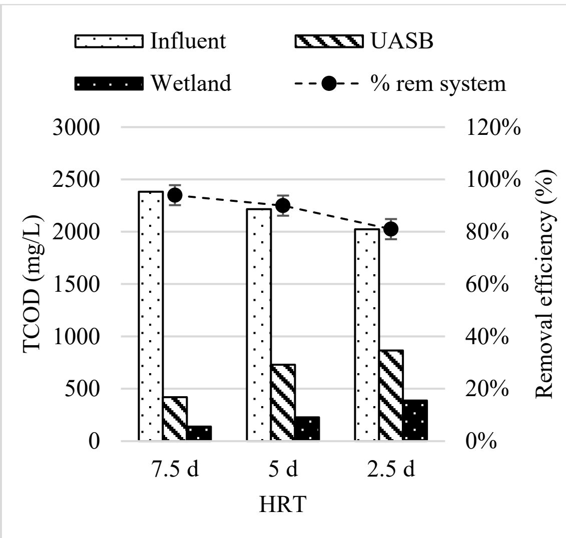

Figure 3. Evolution of the COD_T in each of the component system.

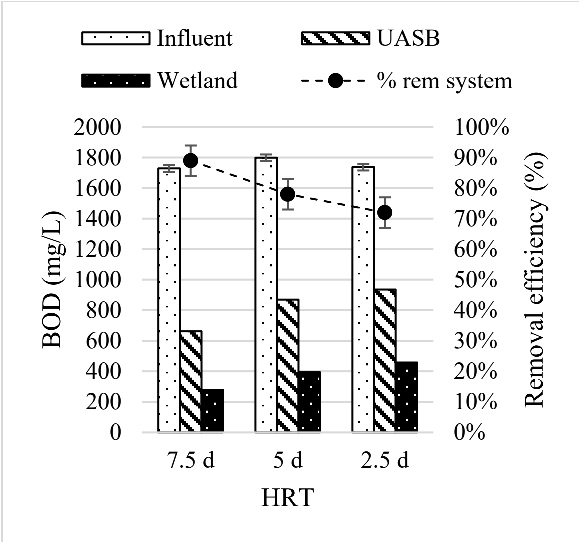

Figure 4. Evolution of the BOD in each of the component systems.

The COD_T values for the influent ranged from 2467 mg/L to 1952 mg/L for the different HRTs. These values are suitable for treatment via anaerobic organisms [45]. The highest COD_T removal efficiency was found at an HRT of 7.5 d (Figure 5). HRT1 (7.5 d) reported an average COD_T removal efficiency of 94% for the UASB + Wetland system, with an average volumetric organic load (VOL) of 2.4 kg/m^3. Subsequently, at an HRT of 5 d, with a mean VOL of 2.2 Kg/m^3, the mean efficiency of the system was 90%. Finally, at an HRT of 2.5 d, a mean efficiency of 81% for COD_T removal was obtained with a mean VOL of 2 Kg/m^3. Values similar to those achieved in this study for HRT1 were reported by [2] and [14] when treating meat effluents through biological purification at different HRTs, achieving efficiencies between 85 and 97% for COD_T removal.

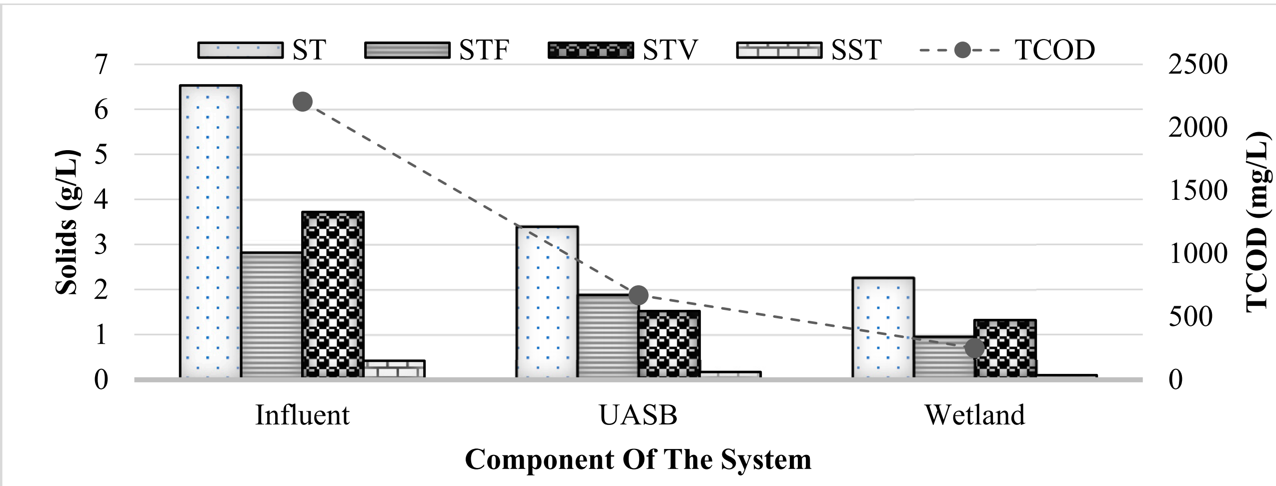

Figure 5. Evolution of the solids in each component of the system during SWW treatment.

The results obtained in this study coincide with those reported by Lopez-Lopez et al. [6], who indicated that the COD removal efficiency is directly dependent on the HRT, which they observed upon treating SWWs at different HRTs. The authors of [10] treated meat effluent under mesophilic conditions at six different HRTs and confirmed this statement. Both studies found that the higher the HRT, the higher the efficiency, which is because the microorganisms have greater contact with the substrate, which under optimal operating conditions favors a greater potential to degrade the pollutants in the wastewater. However, the authors emphasized that a suitable VOL concentration of the system is essential for obtaining higher efficiencies, based on the design of the system and considering that there are concentrations that inhibit anaerobic processes and prevent the removal of pollutants, which is consistent with the results reported in this study.

The BOD showed a trend similar to that of the COD_T. The efficiency for BOD removal was affected by changes in the HRT: the shorter the contact time, the lower the removal rate. The values of BOD input into the system varied between 1.96 kg/m^3 and 1.66 kg/m^3 (Figure 4), with the mean being 1.74 kg/m^3. These values, according to Lopez-Lopez et al. [6], are within the concentration range for slaughterhouse effluent water (1.5–2.5 kg/m^3). The highest removal performance was achieved at an HRT of 7.5 d, with a mean of 84% (Figure 6). These results are similar to those obtained by De la Varga et al. [46], who explored the same system (UASB + Wetland) and reported a BOD removal efficiency of up to 88% at an HRT of 2.7 d.

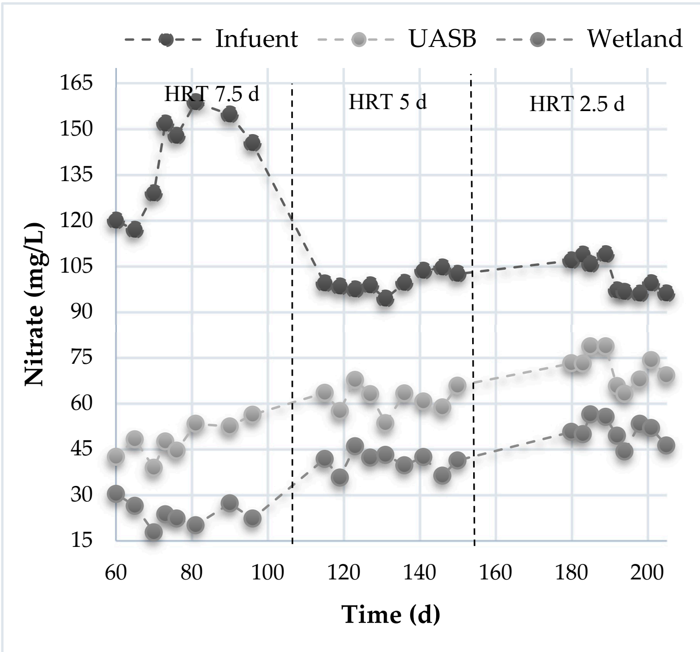

Figure 6. Evolution of NO_3^{+5} in each component of the system.

The values obtained for TSs reached a mean of 11.01 ± 1.62 g/L and 4.81 ± 0.53 g/L for the influent and effluent, respectively (Figure 5). Unstable behavior was observed during the experiment, and the maximum values were recorded at HRT3 (2.5 d). The highest removal efficiency was reached at HRT3, with a mean of 85%, whereas at HRT1 and HRT2, the mean removal efficiencies were 83% and 69%, respectively. Notably, in the slaughterhouse of the municipality of Riohacha, the sieving and screening system was not operational; therefore, the water had to be passed through a traditional strainer to retain the solids and remains of larger viscera.

The TFSs and TVSs trended as expected after treatment (anaerobic and aerobic). This may have been associated with the filtration processes that occurred in the wetland caused by the granular material and the rhizofiltration by the plant specimens. Furthermore, the presence of oxygen during photosynthesis favors the degradation of particulate material, including fats and proteins, which are major components of SWW [7]. The overall removal efficiencies for TFSs were 81%, 71%, and 60% for HRT1, 2, and 3, respectively (Figure 5), whereas the mean removal efficiencies for TVSs reached 84%, 67%, and 53% for HRT1, 2, and 3, respectively (Figure 5). Bandera [40] reported a lower mean efficiency (no higher than 50%) for these solids upon treating wastewater from the same slaughterhouse with a

UASB pilot reactor at an HRT of 1.5 d. This demonstrates that using a combination of the systems (UASB + Wetland) improves the removal of solids.

The overall mean TSS values for the influent were 0.44 ± 0.04 g/L, 0.39 ± 0.02 g/L, and 0.44 ± 0.03 g/L for HRTs 1, 2, and 3, respectively (Figure 5). These values coincide with the standard range, 0.3–0.9 g/L, proposed by Rajakumar et al. [14] for SWW composition. For the series system, the highest removal percentage of 79% was achieved at an HRT of 7.5 d, highlighting the influence of a system in which the UASB showed higher TFS removal efficiency. However, according to Vymazal [20], a wetland performed well in removing solids. In wetlands, the residence time of wastewater is longer, and the wastewater displays laminar flow behavior that allows for the settling of solids, whereby such solids and other substances are trapped in the gravels and the roots of the plants.

The trend for NO_3^{+5} is shown in Figure 6. The mean values for the system effluents were 0.02 mg/L, 0.04 mg/L, and 0.05 mg/L for HRTs 1, 2, and 3, respectively. For NO_2^{+3}, the values for the effluents for HRTs 1, 2, and 3 (0.01 mg/L, 0.03 mg/L, and 0.04 mg/L, respectively) were consistent with those reported by Carrasquero et al. [47]. The mean removal efficiencies for NO_3^{+5} for HRTs 1, 2, and 3 were 82%, 59%, and 50%, whereas for NO_2^{+3}, the mean efficiencies were 82%, 66%, and 56%, respectively, for each HRT assessed. These removal efficiencies were higher than those obtained by Bandera [40] and Mazunder et al. [48], which were no higher than 60% when treating SWWs for these nutrients. The UASB reactor showed good nitrification by transforming nitrites into nitrates and performed adequate denitrification (Figures 6 and 7). The high levels of protein present in the SWW favored increases in the fatty acid and nitrogen compound concentrations, inhibiting methanogenesis [3]. Therefore, it is evident that the UASB alone would not have achieved high removal efficiencies and that the combination of this treatment with an aerobic technology increased these efficiencies.

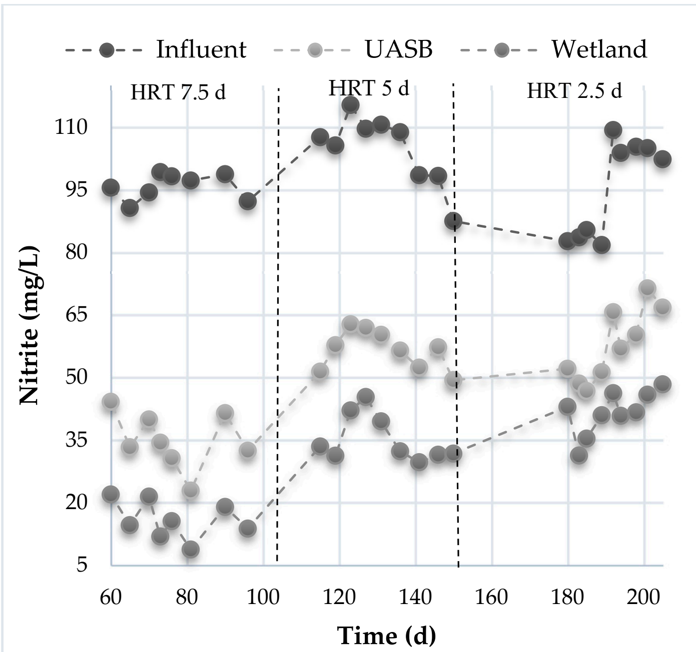

Figure 7. Evolution of NO_2^{+3} in each component of the system.

The trend for nitrogen in its ammonium form (NH_4^{-3}) is illustrated in Figure 8. It showed a mean of 0.63 ± 0.01 mg/L for the influent, and for the effluent, the mean values were 0.1 mg/L, 0.23 mg/L, and 0.25 mg/L for HRTs 1, 2, and 3, respectively. HRT1 showed a higher efficiency, reaching mean values of 86% and a maximum removal of 92%, a value similar to that found by Wu et al. [49] in their study on the treatment of meat effluents.

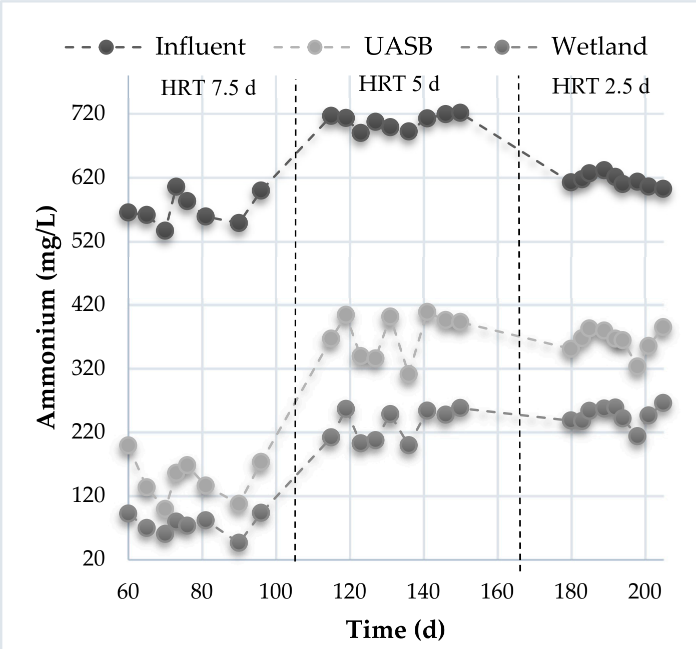

Figure 8. Evolution of NH_4^{+3} in each component of the system.

The influent nutrient PO_4^{-3} (Figure 9) had a low mean concentration of 0.66 ± 0.05 mg/L, consistent with that reported by Bustillo-Lecompte & Mehrvar [8]; this value is in the range of physicochemical characteristics of SWWs. PO_4^{-3} can be removed by biological treatment, and *T. domingensis* can sequester nutrients and assimilate them into their metabolic structures, particularly PO_4^{-3} [26]. This is verified by the mean values observed for the effluents in this study, which were 0.11 mg/L, 0.23 mg/L, and 0.34 mg/L for HRTs 1, 2, and 3, respectively. The highest removal efficiency of 83% was achieved at an HRT of 7.5 d.

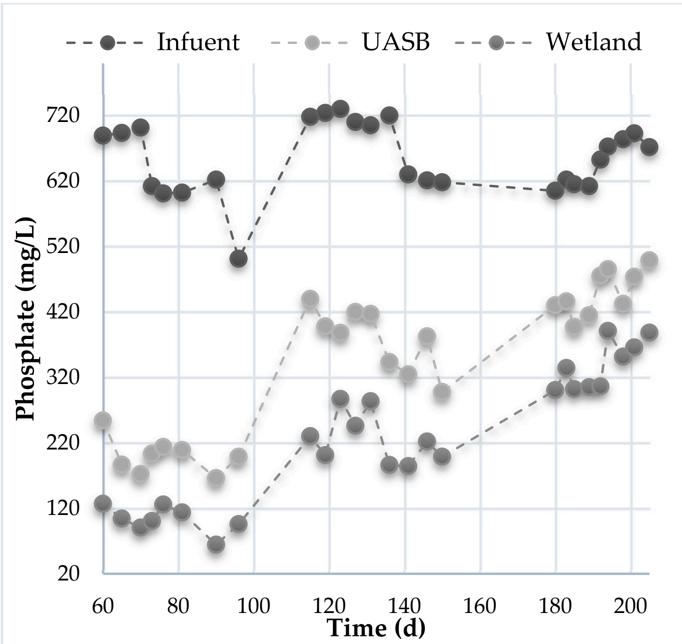

Figure 9. Evolution of PO_4^{-3} in each component of the system.

In addition to the water temperature, the artificial swamp with its oxygen supply favored nutrient removal, especially for N and P. The passage of water through this treatment unit allowed nitrification and converted NO_2^{+3} to NO_3^{+5}, which is why, after the combined treatment, the values for NO_3^{+5} were higher. For PO_4^{-3}, this allowed assimilation by plants, thus reducing its final concentration [44]. Studies conducted by Bustillo & Mehrvar [8] and El Khateeb et al. [23] found that the secondary treatment of wastewater using wetlands is efficient for N and P removal. Other authors, such as Wang et al. [50], treated wastewater using an artificial wetland and obtained removal efficiencies of 45% and 46% for N and P, respectively.

The results obtained in the present study demonstrate the effectiveness of the proposed system for the treatment of SWW. Compared with previously conducted similar studies, this study optimized the removal efficiency for the following parameters evaluated: total solids, ammonium [1], suspended solids [5,51], and phosphates [7]. However, it is important to note that the removal efficiencies for each system vary according to the composition of the SWW to be treated and the environmental and operational conditions of the treatment. Finally, based on the analysis of the results, the proposed system is efficient, economical, and easy to install and has a lower surface area requirement compared with other combined treatments.

Table 2 shows the parameters of international and Colombian regulations for SWW discharge. It is evident that the assessed system (UASB + Wetland) meets the minimum requirements for Colombian regulations; however, at the international level, the system would only comply in some cases. Several advantages of the UASB + Wetland treatment system can be highlighted, such as specialization of the bacterial consortium toward the anaerobic digestion phases, higher removal efficiency, alternative options for pollutant metabolization (anaerobic/aerobic), adaptation of the system to the high volumetric loads observed, and inhibition of factors such as increases in oil and fat concentrations. Therefore, the feasibility of this integrated system is evident, demonstrating improvements in the elimination of nutrients, solids, and sediments. The results obtained, when compared with values set by Colombian regulations, confirm the feasibility of implementing the UASB in series with a wetland to treat wastewater produced in municipal slaughterhouses, which could be replicable on a real scale under similar conditions.

Table 2. Comparative analysis of Colombian and international regulations in relation to the results of this study.

Parameter	EPA, USA	EU	India	China	Canada	Australia	Colombia		UASB–Wetland HRT 7.5 d, Riohacha
							A	B	
pH	6–9	-	6.5–8.5	6–9	6–9	5–9	6.00–9.00	5.00–9.00	7.23–8.38
COD (mg/l)	-	125	250	100–300	-	40	900	1350	340
BOD (mg/l)	16–26	25	30	20–100	5–30	5–20	450	675	375
NT (mg/l)	4–8	10–15	-	15–20	1.25	10–20	-	-	0.4
PT (mg/l)	-	1–2	-	0.1–1	1	2	-	-	0.23
F&O (mg/L)	-	-	10	-	-	-	50	75	50
TSSs (mg/L)	20–30	35–60	50	20–30	5–30	5–20	200	300	75

Notes: F&O: fat and oil, A: dumping in surface water, B: dumping in sewer. [7], Colombian normative (MAVD, 2015).

4. Conclusions

According to the results, the sludge formed in the UASB reactor for the treatment of SWW created favorable conditions for the treatment of this type of substrate at the operating conditions evaluated. The removal efficiencies (for BOD, COD, TSs, TSSs, etc.) obtained in the evaluated system (UASB + Wetland) meet the standards established in the local regulations (Colombia). Considering that the evaluated system is based on biological processes, which require low implementation and operation costs, it is both sustainable and efficient; it reached removal efficiencies of 88% (COD_T) and 84% (BOD) at an HRT of 7.5 d. The combined system proposed in this study achieves SWW treatment not only via biological action but also via the sedimentation that occurs in the wetland system, making it a viable and feasible tool for the treatment of SWW.

Author Contributions: Conceptualization, A.A.G.M., E.V.P.S. and Y.M.B.A.; methodology, A.A.G.M. and E.V.P.S.; software, Y.M.B.A.; formal analysis, A.A.G.M., E.V.P.S. and Y.M.B.A.; writing—original draft preparation, A.A.G.M., E.V.P.S. and Y.M.B.A..; writing—review and editing, Andres and E.V.P.S.; supervision, A.A.G.M.; project administration, A.A.G.M.; funding acquisition, Universidad de La Guajira and Colciencias. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Saghir, A.; Hajjar, S. Biological treatment of slaughterhouse wastewater using Up Flow Anaerobic Sludge Blanket (UASB)—Anoxic-aerobic system. *Sci. Afr.* **2022**, *16*, e01236. [CrossRef]
2. Rahomi, A.; Razman, M.; Sohaili, J.; Nur, A.; Krishna, S. Performance of integrated anaerobic / aerobic sequencing batch reactor treating poultry slaughterhouse wastewater. *Chem. Eng. J.* **2017**, *313*, 967–974. [CrossRef]
3. Dalantai, T.; Rhee, C.; Kim, D.W.; Yu, S.I.; Shin, J.; Triolo, J.M.; Shin, S.G. Complex network analysis of slaughterhouse waste anaerobic digestion: From failure to success of long-term operation. *Bioresour. Technol.* **2022**, *361*, 127673. [CrossRef] [PubMed]
4. Caldera, Y.; Gutiérrez, E.; Luengo, M.; Chávez, J.; Ruesga, L. Wastewater treatment system evaluation of a poultry industry. *Rev. Científica* **2010**, *20*, 409–416.
5. Ratanatamskul, C.; Siritiewsri, T. A compact on-site UASB-EGSB system for organic and suspended solid digestion and biogas recovery from department store wastewater. *Int. Biodeterior. Biodegrad.* **2015**, *102*, 2–430. [CrossRef]
6. López-López, A.; Vallejo-Rodriguez, R.; Méndez-Romero, D.C. Evaluation of a combined anaerobic and aerobic system for the treatment of slaughterhouse wastewater. *Environ. Technol.* **2010**, *31*, 319–326. [CrossRef]
7. Aziz, A.; Basheer, F.; Sengar, A.; Khan, S.U.; Farooqi, I.H. Biological wastewater treatment (anaerobic-aerobic) technologies for safe discharge of treated slaughterhouse and meat processing wastewater. *Sci. Total Environ.* **2019**, *686*, 681–708. [CrossRef]
8. Bustillo-Lecompte, C.F.; Mehrvar, M. Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances. *J. Environ. Manag.* **2015**, *161*, 287–302. [CrossRef]
9. Tong, S.; Wang, S.; Zhao, Y.; Feng, C.; Xu, B.; Zhu, M. Enhanced alure-type biological system (E-ATBS) for carbon, nitrogen and phosphorus removal from slaughterhouse wastewater: A case study. *Bioresour. Technol.* **2019**, *274*, 244–251. [CrossRef]
10. Vidal, J.; Carvajal, A.; Huiliñir, C.; Salazar, R. Slaughterhouse wastewater treatment by a combined anaerobic digestion/solar photoelectro-Fenton process performed in semicontinuous operation. *Chem. Eng. J.* **2019**, *378*, 122097. [CrossRef]
11. Rittmann, B.E.; McCarty, P.L. *Environmental Biotechnology: Principles and Applications*; Tata McGraw: New Delhi, India, 2012. Available online: https://www.worldcat.org/title/environmental-biotechnology-principles-and-applications/oclc/847108341?referer=di&ht=edition#.YuKxITRoaJw.mendeley (accessed on 28 July 2022).
12. Moukazis, I.; Pellera, F.M.; Gidarakos, E. Slaughterhouse by-products treatment using anaerobic digestion. *Waste Manag.* **2018**, *71*, 652–662. [CrossRef] [PubMed]
13. Loganath, R.; Mazumder, D. Performance study on organic carbon, total nitrogen, suspended solids removal and biogas production in hybrid UASB reactor treating real slaughterhouse wastewater. *J. Environ. Chem. Eng.* **2018**, *6*, 3474–3484. [CrossRef]
14. Rajakumar, R.; Meenambal, T.; Saravanan, P.M.; Ananthanarayanan, P. Treatment of poultry slaughterhouse wastewater in hybrid upflow anaerobic sludge blanket reactor packed with pleated poly vinyl chloride rings. *Bioresour. Technol.* **2012**, *103*, 116–122. [CrossRef]
15. Nair, A.T.; Ahammed, M.M. Water treatment sludge for phosphate removal from the effluent of UASB reactor treating municipal wastewater. *Process Saf. Environ. Prot.* **2015**, *94*, 105–112. [CrossRef]
16. Travieso, L.; Benítez, F.; Sánchez, E.; Borja, R.; León, M.; Raposo, F.; Rincón, B. Evaluation of UASB effluent post-treatment in pilot-scale by microalgae HRP and macrophytes pond for nutrient recovery. *J. Clean. Prod.* **2022**, *357*, 985–992. [CrossRef]
17. Rodrigues-Silva, F.; Masceno, G.P.; Panicio, P.P.; Imoski, R.; Prola, L.D.T.; Vidal, C.B.; Xavier, C.R.; Ramsdorf, W.A.; Passig, F.H.; de Liz, M.V. Removal of micropollutants by UASB reactor and post-treatment by Fenton and photo-Fenton: Matrix effect and toxicity responses. *Environ. Res.* **2022**, *212*, 113396. [CrossRef]
18. Khan, A.A.; Gaur, R.Z.; Tyagi, V.K.; Khursheed, A.; Lew, B.; Mehrotra, I.; Kazmi, A.A. Sustainable options of post treatment of UASB effluent treating sewage: A. review. *Resour. Conserv. Recycl.* **2011**, *55*, 1232–1251. [CrossRef]
19. Liu, R.; Zhao, Y.; Doherty, L.; Hu, Y.; Hao, X. A review of incorporation of constructed wetland with other treatment processes. *Chem. Eng. J.* **2015**, *279*, 220–230. [CrossRef]
20. Vymazal, J. *Constructed Wetlands for Wastewater Treatment*, 2nd ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2018. [CrossRef]
21. Rengers, E.E.; da Silva, J.B.; Paulo, P.L.; Janzen, J.G. Hydraulic performance of a modified constructed wetland system through a CFD-based approach. *J. Hydro-Environ. Res.* **2016**, *12*, 91–104. [CrossRef]
22. Vymazal, J. Constructed wetlands for treatment of industrial wastewaters: A review. *Ecol. Eng.* **2014**, *73*, 724–751. [CrossRef]

23. El-Khateeb, M.A.; Al-Herrawy, A.Z.; Kamel, M.M.; El-Gohary, F.A. Use of wetlands as post-treatment of anaerobically treated effluent. *Desalination* **2009**, *245*, 50–59. [CrossRef]
24. Shehzadi, M.; Afzal, M.; Khan, M.U.; Islam, E.; Mobin, A.; Anwar, S.; Khan, Q.M. Enhanced degradation of textile effluent in constructed wetland system using Typha domingensis and textile effluent-degrading endophytic bacteria. *Water Res.* **2014**, *58*, 152–159. [CrossRef] [PubMed]
25. Li, S.; Lissner, J.; Mendelssohn, I.A.; Brix, H.; Lorenzen, B.; McKee, K.L.; Miao, S. Nutrient and growth responses of cattail (*Typha domingensis*) to redox intensity and phosphate availability. *Ann. Bot.* **2010**, *105*, 175–184. [CrossRef] [PubMed]
26. Di Luca, G.A.; Mufarrege, M.M.M.; Hadad, H.R.; Maine, M.A. Nitrogen and phosphorus removal and *Typha domingensis* tolerance in a floating treatment wetland. *Sci. Total Environ.* **2019**, *650*, 233–240. [CrossRef] [PubMed]
27. Vinícius, M.; Gomes, T.; Rodrigues, R.; Souza, D.; Silva, V.; Araújo, É. Chemosphere Phytoremediation of water contaminated with mercury using *Typha domingensis* in constructed wetland. *Chemosphere* **2014**, *103*, 228–233. [CrossRef]
28. Mojiri, A.; Ziyang, L.; Tajuddin, R.M.; Farraji, H.; Alifar, N. Co-treatment of landfill leachate and municipal wastewater using the ZELIAC/zeolite constructed wetland system. *J. Environ. Manag.* **2016**, *166*, 124–130. [CrossRef]
29. Alufasi, R.; Gere, J.; Chakauya, E.; Lebea, P.; Chingwaru, W. Mechanisms of pathogen removal by macrophytes in constructed wetlands. *Environ. Technol. Rev.* **2017**, *2515*, 135–144. [CrossRef]
30. Tong, S.; Zhao, Y.; Zhu, M.; Wei, J.; Zhang, S.; Li, S.; Sun, S. Effect of the supernatant reflux position and ratio on the nitrogen removal performance of anaerobic-aerobic slaughterhouse wastewater treatment process. *Environ. Eng. Res.* **2020**, *25*, 309–315. [CrossRef]
31. Abyar, H.; Younesi, H.; Bahramifar, N.; Zinatizadeh, A.A. Biological CNP removal from meat-processing wastewater in an innovative high rate up-flow A2O bioreactor. *Chemosphere* **2018**, *213*, 197–204. [CrossRef]
32. Ghangrekar, M.M.; Asolekar, S.R.; Joshi, S.G. Characteristics of sludge developed under different loading conditions during UASB reactor start-up and granulation. *Water Res.* **2005**, *39*, 1123–1133. [CrossRef]
33. Luo, J.; Zhou, J.; Qian, G.; Liu, J. Effective anaerobic biodegradation of municipal solid waste fresh leachate using a novel pilot-scale reactor: Comparison under different seeding granular sludge. *Bioresour. Technol.* **2014**, *165*, 152–157. [CrossRef]
34. Bohdziewicza, J.; Kwarciakb, A. The application of hybrid system UASB reactor-RO in landfill leachate treatment. *Desalination* **2009**, *248*, 123–130. [CrossRef]
35. Yan, L.; Ye, J.; Zhang, P.; Xu, D.; Wu, Y.; Liu, J.; Zhang, H.; Fang, W.; Wang, B.; Zeng, G. Bioresource Technology Hydrogen sulfide formation control and microbial competition in batch anaerobic digestion of slaughterhouse wastewater sludge: Effect of initial sludge pH. *Bioresour. Technol.* **2018**, *259*, 67–74. [CrossRef] [PubMed]
36. Apha. *APHA (2012) Standard Methods for the Examination of Water and Waste Water*, 22nd ed.; American Public Health Association, American Water Works Association, Water Environment Federation, American Journal of Public Health and the Nations Health: Washington, DC, USA, 2012. Available online: http://www.sciepub.com/reference/226577 (accessed on 28 July 2022).
37. Sanchez Sanchez, A. Combining Submerged Membrane Technology with Anaerobic and Aerobic Wastewater Treatment. 2013. Available online: https://dialnet.unirioja.es/servlet/tesis?codigo=113296&info=resumen&idioma=ENG (accessed on 19 October 2022).
38. Zhang, X.; Qiu, W.; Chen, H. Enhancing the hydrolysis and acidification of steam-exploded cornstalks by intermittent pH adjustment with an enriched microbial community. *Bioresour. Technol.* **2012**, *123*, 30–35. [CrossRef]
39. Si, B.; Li, J.; Zhu, Z.; Shen, M.; Lu, J.; Duan, N.; Zhang, Y.; Liao, Q.; Huang, Y.; Liu, Z. Science of the Total Environment Inhibitors degradation and microbial response during continuous anaerobic conversion of hydrothermal liquefaction wastewater. *Sci. Total Environ.* **2018**, *630*, 1124–1132. [CrossRef] [PubMed]
40. Bandera, L. *Treatment of Wastewater from the Municipal Slaughterhouse of Riohacha using a Pilot Scale UASB Reactor*; Research project; Faculty of Engineering, University of La Guajira and University of Zulia: La Guajira, Colombia, 2016; 171p.
41. Sarioglu, M.; Begüm, Ö. Investigation of the treatability of molasses and industrial oily wastewater mixture by an anaerobic membrane hybrid system. *J. Environ. Manag.* **2018**, *224*, 298–309. [CrossRef]
42. Xu, S.; Zhang, L.; Huang, S.; Zeeman, G.; Rijnaarts, H.; Liu, Y. Improving the energy efficiency of a pilot-scale UASB-digester for low temperature domestic wastewater treatment. *Biochem. Eng. J.* **2018**, *135*, 71–78. [CrossRef]
43. Ruiz, I.; Díaz, M.A.; Crujeiras, B.; García, J.; Soto, M. Solids hydrolysis and accumulation in a hybrid anaerobic digester-constructed wetlands system. *Ecol. Eng.* **2010**, *36*, 1007–1016. [CrossRef]
44. Cao, W.; Mehrvar, M. Slaughterhouse wastewater treatment by combined anaerobic baffled reactor and UV/H_2O_2 processes. *Chem. Eng. Res. Des.* **2011**, *89*, 1136–1143. [CrossRef]
45. Schmidt, T.; Mccabe, B.K.; Harris, P.W.; Lee, S. Bioresource Technology Effect of trace element addition and increasing organic loading rates on the anaerobic digestion of cattle slaughterhouse wastewater. *Bioresour. Technol.* **2018**, *264*, 51–57. [CrossRef]
46. De la Varga, D.; Díaz, M.A.; Ruiz, I.; Soto, M. Heavy metal removal in an UASB-CW system treating municipal wastewater. *Chemosphere* **2013**, *93*, 1317–1323. [CrossRef] [PubMed]
47. Carrasquero Ferrer, S.J.; Marquina Gelvez, D.C.; Soto López, J.G.; Viloria Rincón, S.; Pire Sierra, M.C.P.; Diaz Montiel, A.R.D. Nutrient removal in wastewater from a beef slaughterhouse using a sequential biological reactor. *Cienc. Ing. Neogranadina* **2015**, *25*, 43. [CrossRef]
48. Mazumder, D. Simultaneous COD and Ammonium Nitrogen Removal from a High-strength Wastewater in a Shaft-type Aerobic Hybrid Bioreactor. *Int. J. Environ. Sci. Dev.* **2010**, *1*, 327–332. [CrossRef]

49. Wu, H.; Zhang, J.; Li, P.; Zhang, J.; Xie, H.; Zhang, B. Nutrient removal in constructed microcosm wetlands for treating polluted river water in northern China. *Ecol. Eng.* **2011**, *4*, 560–568. [CrossRef]
50. Wang, M.; Zhang, D.Q.; Dong, J.W.; Tan, S.K. Constructed wetlands for wastewater treatment in cold climate—A review. *J. Environ. Sci.* **2017**, *57*, 293–311. [CrossRef]
51. Bustillo-Lecompte, C.F.; Mehrvar, M. Treatment of actual slaughterhouse wastewater by combined anaerobic-aerobic processes for biogas generation and removal of organics and nutrients: An optimization study towards a cleaner production in the meat processing industry. *J. Clean. Prod.* **2017**, *141*, 278–289. [CrossRef]