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► To cite this version:

Mary Ng, Sadou Dalhatou, Jessica Wilson, Boniface Pone Kamdem, Mercy Bankole Temitope, et al.. Characterization of Slaughterhouse Wastewater and Development of Treatment Techniques: A Review. *Processes*, 2022, 10 (7), pp.1300. 10.3390/pr10071300 . hal-03753701

HAL Id: hal-03753701

<https://hal.science/hal-03753701>

Submitted on 22 Sep 2022

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Review

Characterization of Slaughterhouse Wastewater and Development of Treatment Techniques: A Review

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Citation: Ng, M.; Dalhatou, S.; Wilson, J.; Kamdem, B.P.; Temitope, M.B.; Paumo, H.K.; Djelal, H.; Assadi, A.A.; Nguyen-Tri, P.; Kane, A. Characterization of Slaughterhouse Wastewater and Development of Treatment Techniques: A Review. *Processes* **2022**, *10*, 1300. <https://doi.org/10.3390/pr10071300>

Academic Editor: Ioannis Vyrides

Received: 31 May 2022

Accepted: 27 June 2022

Published: 30 June 2022

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Abstract: Commercialization in the meat-processing industry has emerged as one of the major agrobusiness challenges due to the large volume of wastewater produced during slaughtering and cleaning of slaughtering facilities. Slaughterhouse wastewater (SWW) contains proteins, fats, high organic contents, microbes, and other emerging pollutants (pharmaceutical and veterinary residues). It is important to first characterize the wastewater so that adequate treatment techniques can be employed so that discharge of this wastewater does not negatively impact the environment. Conventional characterization bulk parameters of slaughterhouse wastewater include pH, color, turbidity, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and coliform counts. Characterization studies conducted have revealed the effects of the pollutants on microbial activity of SWW through identification of toxicity of antibiotic-resistant strains of bacteria. Due to the high-strength characteristics and complex recalcitrant pollutants, treatment techniques through combined processes such as anaerobic digestion coupled with advanced oxidation process were found to be more effective than stand-alone methods. Hence, there is need to explore and evaluate innovative treatments and techniques to provide a comprehensive summary of processes that can reduce the toxicity of slaughterhouse wastewater to the environment. This work presents a review of recent studies on the characterization of SWW, innovative treatments and technologies, and critical assessment for future research.

Keywords: slaughterhouse wastewater (SWW); treatment; advanced oxidation processes; microbial activity; public health; environment

1. Introduction

Numbers “2” and “6” of the 17 Sustainable Development Goals (SDGs) outlined by the United Nations (UN) are “Zero Hunger” and “Clean Water and Sanitation,” respectively [1]. These two goals are directly related to the meat industry as a result of growth and commercialization. Along with population growth, urbanization, technological advances, and movements towards eradicating hunger, slaughterhouses and meat-processing plants have become increasingly centralized with significant increases in the usage of water for slaughtering and cleaning of slaughtering facilities [2]. The wastewater produced from slaughterhouses and meat processing plants has grown in volume and complexity of contaminants and includes emerging pollutants which are commonly discharged to waterbodies without treatment [3], leading to environmental and public health disruption.

According to Bustillo-Lecompte and Mehrvar (2015), the meat-processing industry is estimated to consume approximately 24% of total freshwater used in the food and beverage industry with respect to processing and cleaning of slaughtered meat and facilities to meet adequate levels of health and sanitation [4]. Slaughterhouse wastewater (SWW) contains organic loads which includes paunch, feces, urine, blood, lint, fat and lard, carcasses, undigested food, microbial pathogens, pharmaceuticals, disinfectants, loose meat, suspended material, and facility cleanings [4,5]. According to Liew et al. (2020), oil and grease, carbohydrates, proteins, and lignin are the main constituents of high-strength wastewaters [6]. When compared to medium strength municipal wastewater, average SWW characteristics can be 3.9 times higher for TOC, 6.3 times higher for BOD₅, 9.8 times higher for COD, 10.7 times higher for TN, 5.5 times higher for TSS, and 7.1 times higher for TP [4,7].

Conventional treatment techniques for slaughterhouse wastewater may not be sufficient due to the toxicity of SWW at post-treatment being above the permissible limit and invariably not safe for discharge. Examples of conventional methods used for SWW treatments are biological processes, chemical coagulation and flocculation, and clarification processes [8]. Alternative processes include electrocoagulation [9], electron beam irradiation [10], advanced oxidation, and cold plasma [11]. The objective of this review is to summarize the characterization parameters from recent SWW studies (2015—present), their associated toxicity, and to discuss the effective treatment techniques that can be employed to safely discharge slaughterhouse wastewater into the environment or for re-use. Finally, a critical assessment of these works and future direction for SWW research will be presented.

2. SWW: Characteristics and Environmental/Public Health Impacts

2.1. Characteristics of SWW—Physical, Chemical, Biological

2.1.1. Physical/Chemical Characteristics

A study conducted on 41 slaughterhouses in Serbia in terms of wastewater qualities and concentrations of pollutants revealed higher COD contents in 17 slaughterhouses, whilst 12 showed higher BOD contents. Six slaughterhouses showed TSS values exceeding the allowable limits, while five slaughterhouses showed FOG (fats, oil, and grease) exceeding the allowed limit values. These high effluent concentrations can lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment [12]. The standard levels and limit values of organic constituents (COD, BOD, TSS, and FOG) considered here were the ones prescribed by the World Bank Group, the Council of the European Communities, and the Republic of Serbia.

2.1.2. Biological Activity

Biological activity can be influenced by the presence of foreign pollutants such as veterinary pharmaceutical residues. In addition to being toxic to natural aquatic organisms, SWW also contributes to its own microbial contamination.

Many characterization studies have been conducted identifying strains that have evolved to adapt to the pollutants, such as antibiotic-resistant strains. Characterization studies have revealed a disproportionate population among species of microbes. For example, in Guwahati city, India, SWW in the river and receiving drainage system showed

E. coli as the most dominant at 81.99% of species, followed by *Staphylococcus* sp. at 54.86% and *Streptococcus* sp. at 11.11% [13].

Although nephro- and neurotoxic, colistin (polymyxin E) has been extensively used to prevent and treat gastrointestinal infections caused by bacteria in pigs and poultry and has also help to treat infections caused by multidrug-resistant *Acinetobacter baumannii* and *Pseudomonas aeruginosa* in humans [14]. Due to the high prevalence of colistin-resistant Enterobacteriaceae in poultry and pigs, process waters and wastewater from slaughterhouses were considered as a reservoir for isolates carrying plasmid-encoded, mobilizable colistin resistances (mcr genes) [15]. As slaughterhouses might represent a significant source of mcr genes into the food chain via possible contamination of carcasses and products [16], it becomes important to isolate and characterize these genes in in-house and municipal wastewater treatment plants to avoid their release into the environment. In this respect, Savin et al. (2020a) detected mcr genes producing *Klebsiella pneumoniae* and *Escherichia coli* in areas of German poultry and pig slaughterhouses as well as in their in-house wastewater treatment plants [15]. A total of 70.8% (46/65) of *E. coli* and 20.6% (7/34) of *K. pneumoniae* isolates carried mcr-1 gene on a variety of transferable plasmids with incompatibility groups IncI1, IncI2, IncHI2, IncF, and IncX4, ranging between 30 and 360 kb.

Recently, a study conducted by Meiramkulova et al. (2021) identified some pathogenic microbes (*Salmonella coliphages*, *Pseudomonas aeruginosa*, and *Staphylococcus aureus*, *Enterococcus* etc.) in wastewater samples collected from the Izhevsk PC poultry slaughterhouse located in Izhevsk village, Arshalinsky District, in the Akmola Region of the Republic of Kazakhstan [17]. Other characterization studies assessed potential for strains to be used as biomarkers for tracking indicators of contamination. Table 1 summarizes the microbial characterization studies conducted on SWW from 2015–2022.

Table 1. Microbial characterization studies in slaughterhouse wastewater from 2015–2022.

Microbe	Resistance	Author
<i>Escherichia coli</i>	Antibiotic-resistant	[15,18–22]
<i>Escherichia coli</i>	N/A	[13,23,24]
<i>Echinococcus multilocularis</i>	N/A	[25]
<i>Enterococcus faecium</i>	Vancomycin-resistant	[21]
<i>Klebsiella</i> spp.	Antibiotic-resistant	[15,21,26]
<i>Enterobacter cloacae</i>	Antibiotic-resistant	[21]
<i>Citrobacter</i> spp.	Antibiotic-resistant	[21]
<i>Acinetobacter calcoaceticus-baumannii</i>	N/A	[21]
<i>Campylobacter</i>	Antibiotic-resistant	[27]
<i>Sulfonamide bacteria</i>	Antibiotic-resistant	[28]
<i>Shiga toxin-producing Escherichia coli</i>	N/A	[23]
<i>Staphylococcus</i> sp.	N/A	[13,24]
<i>Staphylococcus</i> sp.	Methicillin-resistant	[21]
<i>Streptococcus</i> sp.	N/A	[13]
<i>Cryptosporidium oocyst</i>	N/A	[29]
<i>Giardia cyst</i>	N/A	[29]
<i>Listeria monocytogenes</i>	N/A	[30]
HEV RNA genotype 3	N/A	[31]

Table 1. Cont.

Microbe	Resistance	Author
<i>Hepatitis E virus (HEV)</i>	N/A	[24]
<i>Somatic coliphages</i>	N/A	[24]
<i>F-specific RNA bacteriophages</i>	N/A	[24]
<i>Bovine enterovirus (BEV)</i>	N/A	[24]
<i>Bacteroides</i>	N/A	[32]
<i>Salmonella coliphages</i>	N/A	[33]
<i>Pseudomonas aeruginosa</i>	N/A	[33]
<i>Staphylococcus aureus</i>	N/A	[33]
<i>Enterococcus</i> sp.	N/A	[33]

2.2. Environmental Health and Toxicity Impacts

2.2.1. Environmental Health

Direct discharge of SWW has been studied and at times this discharge has exceeded limits set by the World Health Organization and/or other national regulatory organizations. Akanni et al. (2019) sampled wastewater at discharge points of two slaughterhouses in the township of Osogbo, Nigeria and results did not meet World Health Organization guidelines of permissible color of 5–40 NFU, 2–6 mg/L dissolved oxygen, and zero total coliform detected in any 100 mL sample [34]. Aniebo et al. (2009) observed from a 6-week study that blood and stomach contents of meats from slaughterhouses were directly discharged into the New Calabar River [35]. Milanović et al. (2015) also characterized raw SWW and its effluent after tertiary treatment (denitrification and disinfection) in Serbia and found that the 24 physico-chemical parameters investigated were above regulatory permissible limits [36]. Yaakob et al. (2018) characterized chicken SWW using water quality parameters, BOD, COD, TSS, TN, TOC, orthophosphate, temperature, and pH and identified their potential for eutrophication [37]. Similarly, in Merauke, Indonesia, the characterization of SWW on water quality parameters BOD, COD, TSS, ammonia, and microbial contamination was carried out, and it was also observed that water quality parameter levels exceeded quality standards [38]. Likewise, Musa et al. (2018) characterized untreated and treated SWW in Malaysia and found that certain parameters exceeded safe discharge standards [39]. Finally, Olaniran et al. (2019) also found that effluent discharged in the Ogun River, Nigeria was not within the national regulatory limits [3].

Thus, recent characterization studies show that pollution from SWW remains a persistent issue. In addition to polluting drinking water sources, discharge above regulations and guidelines has potential for contributing to eutrophication, altering aquatic ecosystems, increasing microbial contaminants in waterbodies, and depleting oxygen levels in surface waters [40].

2.2.2. Environmental Diversity

Along with changes in water quality of waterbodies due to SWW effluent, concerns for aquatic toxicity and ecosystem disruption have been raised. Olaniran et al. (2019) conducted a comparative study of the Ogun River, Nigeria at the SWW effluent discharge point and a control point without SWW effluent [3]. In the course of the research study, it was observed that, at the effluent discharge point, the fish species diversity indices were lower than at the control point, which indicates lower species richness and diversity. Comparison of macrobenthic fauna were also made and results showed more organic-pollution tolerant and invasive species of microbenthic at the outfall and downstream than the control.

2.2.3. Toxicity

Toxicity is the degree to which a substance is poisonous to living organisms, while toxicology is the science of the study of poisons [41]. The toxicity depends on several factors, including dose, duration, route of exposure, shape, and structure of the chemical itself, as well as individual human factors [42]. The problems of industrial toxicology include those concerning not only humanity, but also water, air, soil, and indeed the whole biosphere [43]. Toxicity response is among the parameters that influence SWW treatment. In fact, there is a significant correlation between contaminant removal by a treatment process of SWW and toxicity reduction [44].

Many studies have shown that SWW comprises bioresistant, nonbiodegradable, recalcitrant, and toxic substances as reported in the literature [2]. According to Al-Mutairi (2006), it was found that chemical treatment can influence the toxicity of a system where toxic residual contaminants are still present in the final supernatant wastewater after post-treatment [8]. In general, there are many toxic aquatic organisms in SWW that originate from toxic compounds (such as detergents, disinfectants, and biocides) used for slaughterhouse facilities and tools cleanings. Examples include linear alkylbenzene sulfonates, hydrogen peroxide, formaldehyde, dieldrin, dichlorodiphenyltrichloroethane, borax hexachlorobenzene, dichlorobenzene, and permethrin. Olaniran et al. (2019) discovered that the diverse array of pollutants can cause stress and morphological change in aquatic ecosystems, leading to toxicity in the aquatic organisms [3]. Topal & Arslan Topal (2020) reported the ability of *Phragmites australis* as phytoremediator to eliminate lead and nickel from a stream receiving treated poultry slaughterhouse wastewater (PSW) [45]. They found that the uptake of Pb and Ni by this plant followed the order of root > leaf > stem and deduced that *P. australis* can be used for removal and phytoremediation of Pb and Ni metals from contaminated water. Kim et al. (2017) stated that toxicity of industrial wastewater is caused by heavy metals, chlorine, synthetic organic compounds, medicines, and insecticides, amongst others [44]. The researchers further presented statistical correlations between ecotoxicity and water quality parameters in slaughterhouse wastewater and used *Daphnia magna* to test acute toxicity. Furthermore, toxicity can also be caused by non-biodegradable organic matter, as reported previously [46]. Recent ecotoxicity was also studied using *Gammarus pulex* [9], luminescent bacteria *Vibrio fischeri*, and a freshwater microcrustacean *Daphnia similis* as surrogate organisms [10]. Pereira et al. (2016) conducted both acute (in *Daphnia similis*, *Escherichia coli*, and *Pseudomonas putida*) and chronic (in *Ceriodaphnia dubia*, *Ceriodaphnia silvestri*, *Pseudokirchneriella subcapitata*, *E. coli*, and *P. putida*) toxicity assessments [47].

2.2.4. Chemical Activities

Concomitant with evolving processes and technological advances, pollutants found downstream in slaughterhouse waste are often influenced by feedlot and meat-processing operations. Due to the evolution towards large-scale feedlots, non-veterinary pharmaceuticals are commonly used to treat and prevent diseases in animals to protect public health; however, it normally results in veterinary residues hidden and unused in the animal blood stream. Pharmaceutical residues and/or metabolites are usually detected in the environment at trace levels, but even low levels (e.g., ng/L or µg/L) have the potential to induce toxic effects. In a study conducted by Olaniran et al. (2019), elevated levels (0.85 µg/mL) of the antibiotic tetracycline were detected in Ogun River, Nigeria [3].

Internal operations during meat-processing, which include burning of bones and skin with wood and coal, can introduce polycyclic aromatic hydrocarbons (PAHs) into the waste stream of SWW [48]. According to Olaniran et al. (2019), the PAHs were found to accumulate in the sediment of waterbodies due to their hydrophobic and lipophilic characteristics [3]. Resuspension of these PAHs and antibiotics contributed by SWW into the environment has significant potential for biomagnification and accumulation in surface waters and aquatic species.

Increase in acidity for waterbodies can also be a potential consequence of improper discharge of SWW. In internal operation of slaughterhouses, lactic and acetic acids are

applied on carcasses to control microbial contamination, which also increases acidity of wastewater produced from slaughterhouses as a result of cleanings [49]. Externally, after discharge of high concentrated SWW, decay of undesired growth of algae may produce humic acid, also resulting in increase in acidity [3].

2.3. Public Health Impacts

Inappropriate handling of SWW can also have negative impacts on public health. As found in a study conducted by Bello and Oyedemi (2017), the authors interviewed residents within the radius of 100 m to slaughterhouses and collected water samples from wells in same vicinity [50].

The research study discovered pollution of water wells and air with a high number of cases of excessive coughing, typhoid fever, diarrhea, malaria, and muscle pains among the residents. Similarly, in a separate study conducted by Wiyarno and Widyastuti (2015), odorous chemicals containing SWW were found to contribute to air pollution [51]. Discharge of SWW above maximum permissible limits has the potential to pollute drinking water wells used for direct contact and consumption. According to Environment America (2020), slaughterhouses released 55 million pounds of toxic substances directly into rivers and streams across the United States in 2018, leading to water quality that was unsafe for both consumption and recreational use [52]. The report also cites meat and poultry as the largest industrial point source of nitrogen polluting drinking water wells and waterbodies and increasing the risk for “blue baby syndrome” due to the nitrates in the water. Further, the increase in nutrients contributes to eutrophication and algal outbreaks, which leads to unsafe drinking water when water treatment facilities are unequipped for filtration. Environment America (2020) also cites viruses and bacteria as a direct link to health concerns such as gastrointestinal disease, diarrhea, and liver damage, as well as contributing to unsafe by-products in drinking water sources [52].

3. Methods of Treatment

Depending on the internal operations of slaughterhouses and meat processing plants, facilities may have a pre-treatment process prior to releasing to treatment plants. Figure 1 depicts the common treatment train for slaughterhouse wastewater treatment. Secondary treatment methods include biological, physical, chemical, or advanced oxidation processes employed as either a stand-alone or in combination for SWW.

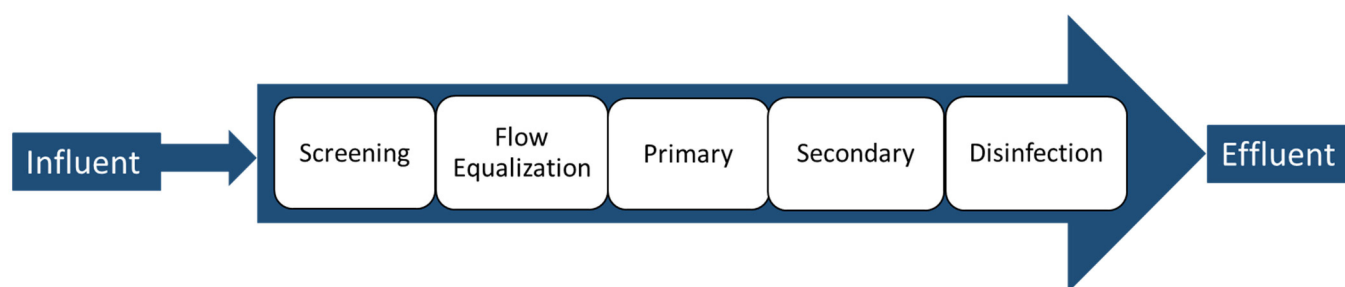


Figure 1. Common treatment train for slaughterhouse wastewater [53,54].

An example of a conventional combined process includes a poultry WWTP (wastewater treatment plant) that confirms the ability to remove COD, BOD, oil and grease, nitrogen, and phosphorus using a combination of dissolved air flotation, upflow anaerobic sludge blanket reactor, aerated-facultative pond, and a chemical DAF (dissolved air flotation) system [55].

3.1. Biological Treatment of SWW

In recent years (2015–2022), many studies have been conducted to improve the biological treatment of SWW. A significant focus for biological treatment of SWW studies has been on anaerobic digestion, followed by aerobic or combined aerobic/anaerobic treatments and

phyco-remediation. Table 2 summarizes significant results, advantages, and disadvantages of recent studies; these are discussed in detail below.

3.1.1. Anaerobic Processes

Research on optimizing anaerobic digestion is often based on performance evaluation with respect to BOD and COD removal [39,56,57]. Anaerobic digestion is advantageous for efficient treatment of high strength wastewater and producing biogas as a valuable by-product. In previous research, it has been shown that biogas production can be improved with pre-treatment of SWW influent through hydrolysis to remove the rate limiting step [6,58]. Alternatively, one study found that adjusting the SWW influent by co-digesting both sewage sludge and SWW in a full-scale digester improved biogas production [59].

In another study, a sample of chicken slaughterhouse wastewater was collected from a chicken processing plant (in Saraburi, Thailand) and treated with purple nonsulfur bacteria [60]. As a result, the soluble COD (sCOD) removal was predicted to be 85.3% at optimal conditions (inoculum size, 3.63% (roughly 106 cells/mL); pH, 6.9; and light intensity, 3731 lux). The values of tCOD (total COD, 217 mg/L), sCOD (147 mg/L), BOD (104 mg/L), TS (total solids, 934 mg/L), SS (suspended solids, 392 mg/L), and DS (dissolved solids, 552 mg/L) in digester effluent (after bacteria inoculation and incubation) were lower than those obtained from digester influent [60]. Recently, anaerobic digestion of SWW was carried out with fats, oil, and grease (FOG) at different percentages (1–10%). The optimal conditions were achieved at 5–10% of FOG, showing biodegradability of 66–70% tCOD removal and specific biomethane productions of 562 and 777 mL CH₄·g^{−1} sCOD removed, respectively. At 10% FOG, the values of tCOD, CODs, total solids (TS), total volatile solids (TVS), and volatile fatty acids (VFA) were 31.2, 28.6, 3.1, 19.6, 12.6, and 0.33 g/L, respectively. SWW and FOG afforded lower tCOD (8.9 and 14.9 g/L) and COD (2.03 and 2.4 g/L) values, whereas the FOG group yielded higher values for TS (143 g/L), TVS (125 g/L), and VFA (0.5 g/L). These results demonstrated the effect of anaerobic co-digestion of slaughterhouse wastewater with FOG. It is worth noting that the co-digestion of SWW with FOG (5–10%) enhanced biomethane production and biodegradability compared to anaerobic digestion of sole SWW (biomethane production: 230 mL CH₄·g^{−1} CODs removed; biodegradability 28.5%) [61].

Optimization of digester performance has been accomplished by changing the digester contents and by using poultry SWW as both the inoculum and substrate for the biological production of hydrogen as a more sustainable and cost-efficient method [62,63]. In addition, Almeida et al. (2019) studied the optimization conditions of upflow anaerobic sludge blanket using granular sludge for poultry SWW [64].

Rather than altering the contents of the digester, other researchers experimented with the configuration of the anaerobic digester reactor and studied a low-cost alternative for anaerobic digestion on a real scale, since cost is commonly a limitation to shift technology from lab scale to full scale [65]. The authors used a series of three tubular digesters and found that the tubular digesters are competitive with a performance of specific biogas production of 0.55 m³/kg SV (volatile solids) with a hydraulic retention rate of 9.7 days. Martí-Herrero et al. (2018)'s study showed 70% COD removal rate after 19 days [65]. Yousefi et al. (2018) looked at the configuration of anaerobic baffled reactors using the indicators of organic loading rate and hydraulic retention time (HRT) for optimal operations, as well [66]. The system consisted of influent fed into three parallel anaerobic baffled reactors followed by an anaerobic filter each. The study found that an optimal HRT in the anaerobic baffled reactor was 18 h with an optimum organic loading rate of 7 kg COD/m³/d with a COD removal of 83.29% and an increase to 36 h in the anaerobic filter further increased the COD removal.

In addition to SWW treatment, a study demonstrated the ability of microalgae *Chlorella vulgaris* to remove ammonium from unsterilized tofu wastewater (TWW) [67]. In fact, the co-culturing of diluted (at 25, 50, and 100% concentrations) unsterilized TWW with *C. vulgaris* increased the biomass production, inferring that this pathogen can grow in symbiosis with

other pathogens to remove ammonium and COD from TWW. However, the co-culturing of microalgae with undiluted TWW did not lead to biomass production, concluding that the removal of ammonium and COD by the symbiosis of *C. vulgaris* with others present in TWW is influenced by the dilution factor.

A study by Yazdani et al. (2019) showed improved biogas production using black tea based-iron nanoparticles as micronutrients supplements in anaerobic digestion of slaughterhouse wastewater (37.6% enhancement over the control reactor at 9 mg/mL of iron nanoparticle addition) [68]. Schmidt et al. (2018) researched into the addition of trace elements as Fe, Ni, Co, Mn, and Mo to provide methanogens with necessary growth elements [69].

Recently, the co-digestion of SWW with *Opuntia fucus-indica* (Indian prickly pear cactus) ameliorated the biogas production by bioreactors at mesophilic temperature (38 °C). The biodigester containing 75% SWW and 25% *Opuntia fucus-indica* showed the optimum biogas yield and methane content with 86 L and 57% (v/v), respectively. Moreover, the bioreacted SWW-*Opuntia fucus-indica* increased parameters such as COD (14.960 mg/L), volatile solids (84.59%), volatile fatty acids (2542.71 mg/L), and total solids (6.17%), compared to the values obtained with bio-reacted SWW (580 mg/L, 68.69%, 399.25 mg/L, 0.63% for COD, VS, VFS, and TS, respectively). The treatment with *Opuntia fucus-indica* also removed fecal coliforms, total coliforms, and *Escherichia coli*. These results also demonstrated the role of anaerobic digestion in the treatment of SWW [70].

3.1.2. Aerobic and Combined Anaerobic/Aerobic Processes

Less common in recent studies are advancements for aerobic treatment of SWW. This is due to the high concentration characteristics of SWW that would necessitate high energy demands. However, a new method proposed the use of an airlift membrane bioreactor to remove COD and total nitrogen from SWW [71]. In addition, adding biofilm process to the conventional activated sludge process enhanced biological degradation [72].

Rather than employing a purely aerobic process, studies have looked to combine aerobic and anaerobic processes. The combination of aerobic and anaerobic digestion methods often results in an improvement of contaminant removal from slaughterhouse wastewaters. Svierzoski et al. (2020) treated wastewater obtained from cattle slaughterhouses located in the state of Rondônia (north of Brazil) using a two-stage anoxic-aerobic biological system, followed by UV-C disinfection to remove nitrogen and organic matter [73]. Upon addition of external chemical oxygen demand (COD) as ethanol, total nitrogen removal reached up to 90% at the highest load ($0.28 \text{ kgN.m}^{-3}.\text{d}^{-1}$). After UV-C (ultraviolet C) treatment, 3-log reduction of total coliforms was attained. The 96 h ecotoxicity tests showed that all non-diluted samples tested (raw, biologically treated and UV-C irradiated wastewater) were toxic to microalgae. Nevertheless, these organisms were able to acclimate and grow under the imposed conditions, allowing nitrogen and phosphorous removal up to 99.1% and 43.0%, respectively.

Palomares-Rodríguez et al. (2017) provided economic and energy demand justification for leveraging a combination of aerobic and anaerobic treatment that would reduce energy requirement by 76% and environmental impact by 30% [54]. Sequencing batch reactors have also been studied to remove COD and nitrogen to operate between nitrification and denitrification, aerobic and anaerobic methods [74,75].

3.1.3. Phytoremediation/Constructed Wetlands Processes

Since some of the treatment methods of SWW are cost-prohibitive, phyco-remediation treatment has recently been explored as an alternative to anaerobic and aerobic processes [76,77]. Other studies highlighted the sustainable advantage of phytoremediation for SWW treatment over other treatment strategies, showing the creation of microalgae biomass as fish feed or as biodiesel [37,78]. Though several reports have shown varying effectiveness of the phytoremediation process, they highlight that algal culture performance for SWW treatment is still above the safe discharge limits [79].

Other studies explored COD removal by looking on enhancing the biological process using bioremediation and leveraging marine protist, *Thraustochytrium kinney* VAL-B1, for treatment [80].

Low-cost designs such as constructed wetlands for SWW have also been explored [81,82]. Treatment of SWW using wetlands have varying degrees of removal. A study revealed that treatment of SWW using wetlands did not afford a final effluent that met Mexican environmental regulations [83]. However, other studies showed the great potential of wetland system for SWW treatment [84]. Anaerobic lagoons were also studied as a low-cost design for areas with more available land [69].

Table 2. Biological treatment methods/biomethane production for SWW. Abbreviations for common terms in table footnotes.

Process: Anaerobic Digestion	Significant Results	Advantages	Disadvantages	Reference
Two down-flow high-rate anaerobic bioreactors: Down-flow expanded granular bed reactor (DEGBR) and static granular bed reactor (SGBR)	95% removal of BOD ₅ , COD, and FOG during peak performance days for both reactors	DEGBR displayed a more consistent and significant production of biogas than the SGBR	SGBR took more than 50 days to reach a 95% removal of FOG as opposed to the DEGBR (14 days)	[56]
Anerobic mono-digestion	COD, sCOD, and BOD removal efficiency of 49.93, 65.85, and 82.22%, respectively	Stable reactor with VFA/TA ratio < 0.4	Organic matter residual requires post-treatment to meet effluent standards	[57]
Anaerobic co-digestion of SWW with hydrolyzed grease	75% SWW and 25% hydrolyzed grease led to biogas yield of 0.6 L/g COD introduced	Optimum digester conditions observed at 25% hydrolyzed grease	Increasing the OLR from 2.0 to 2.5 g COD/L-d led to a decrease in the biogas production	[58]
Co-digestion of SWW with WMS (waste mixed sludge)	Higher values of BMP of 735 NLCH ₄ /kg were obtained vs. with an SWW: WMS = 40% and TS = 4%	The maximum biomethane generation of 550 NLCH ₄ /kg VS was achieved for an OLR = 1.5 kgVS/m ³ -day	SWW:WMS = 40% appears as a limiting value above which system will start to have a significant decrease in efficiency	[59]
Addition of purple non-sulfur bacteria (PNSB) to treat SWW	Treatment of wastewater with PNSB simultaneously produces effluent containing plant growth promoting bacteria	Can reduce sCOD in SWW by 85–90% and release sufficient amounts of 5-aminolevulinic acid for use in agriculture	Indigenous PNSB were not able to compete with other heterotrophs in the SWW	[60]
FOG co-digestion with SWW	Optimal conditions were 10% of FOG, resulting in 66% COD _{tremoval} biodegradability and specific BMP of 562 and 777 mLCH ₄ -g ⁻¹ COD _{sremoved}	At 5–10% FOG, HABs (Hydrolytic acidogenic bacteria) were highly active leading to an increase in methanogenic activity	Sedimentation time and temperature must be controlled in order to achieve adequate sedimentation capacity	[61]
Laboratory scale upflow anaerobic sludge blanket (UASB)	COD removal was approximately 90% at OLR 0.4 g/L d ⁻¹ ; 5 L/d of biogas was obtained.	Concentration of VFAs was low; HRT of 1 day was sufficient to remove greater than 70% of COD	COD removal dropped to below 50% when the loading rate increased to 15 g/L d ⁻¹	[39]
Poultry SWW as both the inoculum and substrate for the biological production of hydrogen	SWW inoculum has potential for bio-H ₂ production, as it produced CH ₄ -free biogas containing 50–60% H ₂	The inoculum is adaptable to the use of glycerine as a substrate	Requires a longer acclimatization period when using glycerine as a substrate than sucrose	[63]

Table 2. Cont.

Process: Anaerobic Digestion	Significant Results	Advantages	Disadvantages	Reference
Granular sludge from UASB	SWW presented higher proportions of organic substrate molecules for the methanogenesis than sanitary sewage sludge thus facilitating the production of the highest biogas	Methane generation was directly proportional to the acetate concentrations used; biogas production highest when using only SWW or a mix of SWW and sewage sludge	High organic load may destabilize the metabolic process of methane generation	[64]
Low-cost tubular digesters producing biogas from SWW	Low-cost tubular digesters with biofilm carriers are effective for $OLR < 0.5 \text{ kg COD/m}^3\text{-d}$ of biogas production, and for $0.25 \text{ kg COD/m}^3\text{-d}$	COD removal achieves values above 70% from $HRT > 19 \text{ d}$	Low-cost biofilm carriers might not be scalable to full-scale digesters	[65]
Combined anaerobic system consisting of three pilot-scale anaerobic baffled reactors (ABRs) in the first stage and three anaerobic filters (AFs)	Optimum HRT and OLR were 24 h and $7 \text{ kg COD/m}^3\text{/d}$ and 36 h and $1 \text{ kg COD/m}^3\text{/d}$ in ABR and AF reactor, respectively	Removal efficiencies for COD ranged from 83% to 86% for ABR and 63% to 79% for AF reactors	Removal efficiency decreased at a considerably lower HRT (12 h) and a high OLR ($10 \text{ kg/m}^3\text{/d}$)	[66]
CO ₂ Capture of Biogas Using <i>Chlorella vulgaris</i>	AD able to remove 63% of COD. Biogas composition of slaughterhouse wastewater after incubation for 15 days was 52.70% air, 46.85% CH ₄ , and 0.45% of CO ₂	<i>C. vulgaris</i> enhanced CO ₂ removal from biogas up to 7%.	Growth of microalgae can be inhibited by the low percentage of CO ₂ ; percentage of CO ₂ provides sufficient support to microalgae growth if the concentration was above 15%	[67]
Biosynthesized iron nanoparticles (NPs) from water treatment sludge in anaerobic digestion	Addition of iron NPs improved the biogas production and shortened the lag phase	Highest biogas yield was obtained from 9 mg L^{-1} of additive, which corresponds to improved COD removal efficiency to 42%	Application of NPs would be very costly; further research needed for scale-up and process optimization	[68]
Anaerobic digestion with addition of trace elements	Addition of Fe, Ni, Co, Mn, and Mo resulted in enhanced degradation of SWW, higher biogas production, and improved process stability	Higher OLRs and lower HRTs were achieved in comparison to control digesters	Large-scale operators need to manage waste streams to minimize solid loadings	[69]
Airlift membrane bioreactor (AL-MBR) for on-site treatment of SWW	Removal efficiencies of COD and TN were $95 \pm 1.9\%$ and $70 \pm 3.3\%$, respectively, at a hydraulic retention time (HRT) of 2.5 days	AL-MBR provided a consistent flux of 18 LMH/bar at low pressures (0.8 bar) without regular membrane cleaning; energy consumption was 14% lower than an average cross flow MBR	A higher recycle flow could inhibit denitrification; at lower recycle flow, NO ₃ -N was not transferred adequately to the anoxic tank	[71]

Table 2. Cont.

Process: Anaerobic Digestion	Significant Results	Advantages	Disadvantages	Reference
Batch bioreactors with purple phototrophic bacteria	91.9% removal of sCOD, 70.1% removal of sTN, 90.9% removal of PO ₄ under phototrophic conditions	Phototrophic conditions produced valuable carbohydrate and protein byproducts	sCOD and PO ₄ removal rate constants were five-fold lower in chemotrophic conditions	[85]
Static granular bed reactor (SGBR) coupled with single-stage nitrification-denitrification (SND) bioreactor and ultrafiltration membrane module (ufMM) system	Average COD, ortho-phosphate, TSS, and TDS removal efficiencies of 91%, 51%, 97% and 52%, respectively, achieved over 52 days	ufMMs operated in dead-end filtration mode were able to further reduce the COD and TSS by an average of 65% and 54%, respectively	Final effluent not compliant with the industrial wastewater discharge standards for PO ₄ ^{3−} and NH ₄ ⁺ -N	[86]
Process: Combined Anaerobic/Aerobic	Significant Results	Advantages	Disadvantages	Reference
Sequencing Batch Reactor (SBR) in aerobic/anaerobic sequential mode	Average percent removals of 85 to 90% of sCOD, N, and P	Excellent sludge settling (SVI ₃₀ < 100 mL/g)	Operational strategy and temperature variability have a significant impact on microbial community dynamics and granule growth	[74]
Intermittently Aerated Sequencing Batch Reactors	Optimum aeration rates were 0.6, 0.8, and 1.2 L air/min at the average OLRs of 0.61, 0.82, and 1.02 gCOD/L-d	Partial nitrification-denitrification efficiencies were between 61 and 70% at the optimum aeration rates	Highest N ₂ O generation in the non-aeration period was observed at the optimum aeration rates	[75]
Novel acrylic fiber carrier with conventional activated sludge (AS + BF (biofilm reactor))	The combined attached and suspended growth system supports aerobic and anaerobic conditions and efficiently removed BOD and COD	COD and BOD ₅ removal were 97.5% and 99.1%, respectively, using the AS + BF system	AS only showed removal of COD and BOD ₅ of 84.3%, 98.8% (only marginally lower than AS + BF)	[72]
Anoxic-aerobic biological reactors followed by UV disinfection	Total ammoniacal nitrogen (TAN) removal ranged within 83–99%, TN removal up to 90%	3-log reduction of fecal coliforms possible after UV disinfection	Non-diluted samples were toxic to microalgae	[73]
Batch and anaerobic sequential batch reactors	87.8% COD removal at OLR of 1.16 to 2.16 kg/m ³ -day	BMP of 0.23 LCH ₄ /L _{digester} -day	Faster OLR leads to bioreactor destabilization	[87]
Process: Physico-Remediation	Significant Results	Advantages	Disadvantages	Reference
Use of mixed algal species from SWW to remove OM and nutrients	Removal of TOC, TN, and TP of 89.6, 70.2, and 96.2%, respectively	Optimal removal achieved with undiluted SWW and mixed algal (eukaryotic and cyanobacterial culture) photo-bioreactors	Cyanobacterial species played a more effective role than the eukaryotic species in the treatment of SWW	[76]
SWW used for algal biomass production for pollutant removal	Sufficient nutrient removal efficiencies (23–42%, 18–48%) and pollutant load efficiencies (17–31%, 7–29%)	Optimal algal growth observed at 50% SWW	Use of photobioreactor is costly and energy-intensive; more research needed for scale-up	[78]

Table 2. Cont.

Process: Physico-Remediation	Significant Results	Advantages	Disadvantages	Reference
Phycoremediation using eleven algal cultures for SWW	Removal percentages 73, 89, 90, and 85% for sCOD, NO ₃ -N, NH ₄ ⁺ -N, and PO ₄ ³⁻ , respectively	Most cultures showed good performance for biomass production (0.78–1.16 g/L)	Most of the contaminants were above the discharge limit in treated SWW	[79]
Marine protist (Chilean Thraustochytrid (TH) strain) used for SWW treatment	COD reduced by 56.29%, O&G reduced by 99%, and TN, TP, and total iron decreased by 63%, 98%, and 60%, respectively	Nutrients and trace metals are beneficially usable by THs for their growth and biomass production	Biomass production significantly affected by media composition (e.g., trace metals); omitting trace metals negatively impacts growth	[80]
Process: Constructed Wetlands	Significant Results	Advantages	Disadvantages	Reference
Constructed wetlands for removal of COD, TSS, TDS, BOD ₅ , nitrate, and phosphate from SWW	Removal percentages of phosphate, COD, BOD ₅ , nitrate, TDS, and TSS were 77.5%, 93.3%, 68%, 71.3%, and 88.7% respectively	Significant reductions in pollutants observed after 9 days retention time	Average effluent concentrations of certain parameters did not meet maximum permissible limit standards for safe discharge of industrial wastewater to the inland water surface	[81]
Constructed wetlands for COD and ammonia removal from SWW	Percent removal COD and ammonia were 85% and 80%, respectively	All plant stages (early, optimum, and harvest) show similar removal of pollutants	Difficult to determine optimal plant for removing pollutants due to competing physical, chemical, and biological processes occurring	[82]

SWW = slaughterhouse wastewater; BOD₅ = 5-day biochemical oxygen demand; COD = chemical oxygen demand; FOG = fats, oils, and grease; sCOD = soluble chemical oxygen demand; VFA = volatile fatty acids; TA = total acids; BMP = biomethane potential; OLR = organic loading rate; vs. = volatile solids; AD = anaerobic digestion; HRT = hydraulic retention time; TN = total nitrogen; TP = total phosphorus; SRT = solids retention time; SVI = sludge volume index; TSS = total suspended solids; TDS = total dissolved solids. NLCH₄.kgVS⁻¹ = an average specific methane (CH₄) generation per kg of vs. (Volatile Solid), expressed in liters (L) at normal (N) conditions (T = 273.15 K, P = 101,325 Pa).

3.2. Physical Treatment of SWW

Physical wastewater treatment includes processes such as sedimentation (suspension of insoluble particles), aeration (water oxygen supply), and filtration (contaminant filtering), among others [88]. Table 3 summarizes the significant results, advantages, and disadvantages of different physical treatment techniques for SWW.

Physical treatments including the use of membrane processes (reverse osmosis, nanofiltration, ultrafiltration, and microfiltration) have been explored as an alternative to the conventional biological treatment [89–91]. While using an ultrafiltration membrane module (UfMM) system initiated by a bioreactor, Rinquest et al. (2019) achieved rejection efficiencies of 59, 61, and 88% for COD, TSS, and turbidity, respectively, with an average effluent TDS (total dissolved solids) concentration of 1198 mg/L in the membrane permeate stream; when the bioreactor was operated in down-flow configuration without aeration and under aerated conditions, the UfMMs afforded rejection efficiencies of 78, 50, and 92% for COD, TSS, and turbidity, respectively, with a membrane permeate for effluent TDS of 785 mg/L [86].

Recently, fly-ash-based tubular membranes (75% fly ash, 20% quartz, and 5% calcium carbonate) were fabricated through an extrusion process to remove or dispose of the fly ash generated by thermal power plants and to treat poultry slaughterhouse wastewater. The fabricated membrane (pore size, 0.133 µm; porosity, 40.17%) successfully separated the

organic matter present in the wastewater, achieving complete removal of COD, TSS, and turbidity from the raw wastewater [92].

Table 3. Physical treatment methods for slaughterhouse wastewater. Abbreviations for common terms in table footnotes.

Process	Significant Results	Advantage	Disadvantage	Reference
UF, NF, and RO membrane processes for COD and conductivity removal	COD removal efficiencies were 90% for NF and 97.4% for RO, and conductivities decreased by 51.7% for NF and 96.6% for RO	Best alternative was the RO process; UF + RO is most cost-effective	RO and NF without pre-treatment were not effective	[89]
Composite ceramic membranes (CM) from natural aluminosilicates	Bacterial removal and COD rejection were 99.4% and 91%, respectively	CM developed also shows high hydraulic permeability	Pre-treatment needed to remove solids and fats (addition of chemical flocculants and secondary biological treatment)	[90]
Ultrasonic membrane anaerobic system	The removal efficiency of COD was 94.8–96.5% with hydraulic retention times of 308.6–8.7 days	Methane gas production rate was 0.24–0.56 L/g COD/d	Methane content generally declined with increasing OLR	[91]

UF = ultrafiltration; NF = nanofiltration; RO = reverse osmosis.

3.3. Chemical/Physicochemical Treatment of SWW

Combined chemical and physicochemical treatments have recently been explored for improvement of SWW treatment. Table 4 summarizes the recent studies on chemical/physicochemical treatments for SWW and effectiveness of different types of chemical and physicochemical treatment methods.

3.3.1. Coagulation Processes

Coagulation is a chemical process that primarily targets the removal of colloids and suspended solids, as well as organics (COD/BOD). While this is primarily accomplished through adsorption, the chemicals added in coagulation also form metal–organic complexes which are removed during precipitation. Coagulation of organics from SWW have been well-studied [93–97]. One such study used *Moringa oleifera* as a natural coagulant for adsorption of organic pollutants for COD removal [93]. Other studies explored different coagulants including lime, alum, ferrous sulphate, and anionic polyelectrolyte [98]. Electrocoagulation techniques have also been explored [99,100]. Biological flocculation and coagulation processes also have been studied to remove suspended solids, lipids, and proteins during dissolved air flotation rather than settling [101].

Garduño-Pineda et al. (2019) conducted studies using calcium acetate to remove metal, COD, and total coliform, turbidity, color, phosphates, and sulfates from SWW. Prazeres et al. (2019) used sulfuric acid, hydrochloric acid, and nitric acid for precipitation to reduce the hydroxide and bicarbonate species which would compete for oxidants to target pollutants. In addition, they proceeded to use an oxidation method by calcium hypochlorite, hydrogen peroxide, and calcium peroxide for removal of COD, TS, TVS (total volatile solids), TSS, ammonia, nitrogen, nitrates, and BOD [95].

3.3.2. Electrochemical Processes

Recently, Meiramkulova et al. (2020a) reported the beneficial effects of an electrochemical pre-treatment of wastewater to enhance its efficacy towards filtration of poultry slaughterhouse wastewater during the water purification process [33]. In a production cooperative located in Kazakhstan, the electrochemical pre-treatment of poultry slaughterhouse wastewater led to highly effective removal (71–85%) of physicochemical parameters,

including color, total suspended solids, turbidity, aluminum, total iron, chemical, and biochemical oxygen demands. In addition to the performance of the membrane, the electrochemical treatment also increased the removal of suspended and dissolved solids, which decreased the rate of cake formation on the membrane filters. Thus, proper selection and pre-treatment of the membrane filtration is paramount for slaughterhouse wastewater treatment [33].

In a study by Da Silva et al. (2020), effluents from a pig slaughterhouse and packing plant wastewater were treated by electrocoagulation (metallic electrodes immersed in the effluent and connected to a source of electrical energy) using a bench reactor. Turbidity, color, and COD removal were found to be 98.96, 97.96, and 67.44%, respectively. Ultimately, the color removal reached a maximum of 97.12%, affording a reduced electrolysis cost of US \$1.70 m⁻³; after 20 min, 5.45 cm between the electrodes and an electrical current density of 0.019 A cm⁻² [96].

Reátegui-Romero et al. (2020) treated the wastewater from a meat plant in (Lima Peru) by electrocoagulation (with aluminum and iron electrodes) using a batch bioreactor, and the removal efficiencies for turbidity and COD in meat industry and slaughterhouse wastewaters were 99% and 53–59%, for aluminum electrodes, and 81.5–88.5% and 59–60% for iron electrodes, respectively [102].

Meiramkulova et al. (2020b) also evaluated treatment of poultry slaughterhouse wastewater from de-feathering, cooling, and evisceration processes using lab-scale electrochemical process with three different electrode combinations, including iron–iron (Fe–Fe), aluminum–graphite (Al–Gr), and iron–graphite (Fe–Gr) [103]. The water quality index (WQI) was used to evaluate the effectiveness of different electrode combinations. Based on the developed WQIs, the quality of treated water obtained from each of the three-electrode combinations was classified from “excellent” status (WQI < 50) to the “unsuitable for drinking (irrigation)” status (WQI > 300), with drinking water (50 < WQI < 100) as a reference. The Al–Gr electrode combination was the most effective (WQI: 13–34), followed by Fe–Gr (WQI: 43–79). The Fe–Fe electrode combination was not as effective as the Al–Gr or Fe–Gr electrode (WQI: 59–119).

Recently, an electrochemical treatment of a poultry slaughterhouse wastewater from the Akmola Region of the Republic of Kazakhstan showed removal of several microorganisms, including *Salmonella coliphages*, spores of sulfite-reducing *Clostridia*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Enterococcus* sp. with efficiency ranging from 63.95% to 99.83%. An average 100% removal efficiency was achieved when a combined treatment was applied (electrochemical, ultrafiltration, and UV treatments) at an average current of 5.5 A and 40 min retention from the electrochemical treatment unit, as well as 60 mJ/cm² radiation dose and 24 min retention time from the UV treatment unit, with the exception of *Pseudomonas aeruginosa*, which was still detected in the final effluent [33].

Table 4. Chemical/Physiochemical treatment methods for SWW. Abbreviations for common terms in table footnotes.

Process	Significant Results	Advantage	Disadvantage	Reference
EO and EO-related processes for removal of COD, SS, and color	EO/H ₂ O ₂ and EO/UVC reduced COD and SS below effluent limits	Pre-ozonation combined with UV processes improved organics removal	Pretreatment (grit removal, degreasing, biological treatment, and settling) necessary	[104]
Acid precipitation and oxidation for removal of pollutants	Effective removal of COD, turbidity, TP, solids, BOD ₅ with both acid precipitation (41 to 99%) and oxidation (71 to 100%)	Oxidation processes more effective than acid precipitation at removing turbidity and TP	Despite high removal efficiencies, post-treatment required to meet standards	[95]

Table 4. Cont.

Process	Significant Results	Advantage	Disadvantage	Reference
EO processes for removal of COD, TOC, TN, TSS, and color	At optimum conditions, TSS, TOC, COD, TN, and color removal efficiencies were 99.5%, 88.0%, 92.2%, 93.5%, and 99.9%, respectively	Most effective treatment was 0.025 M NaCl, 25 °C, pH = 7.03, 4.73 mA/cm ² current density, and 4 h reaction time	Full mineralization of organics takes 4 h; large volumes of effluent will result in impractical treatment time	[105]
Removal of inorganic chemical species and organic matter via calcium acetate	Removal efficiencies for TSS, turbidity, color, Fe, Cu, and Na were 82%, 76%, 81%, 54%, 70%, and 15%, respectively	Treatment also removed 99% fecal and total coliforms, 26% COD, and 74% TOC	High pH needed for removal of certain contaminants (e.g., phosphates), low pH needed for removal of others (e.g., Fe)	[94]
Cold plasma pathogen deactivation and removal of inorganic and organic pollutants	COD, TN, and TP removal efficiencies were 78–93, 51–92, and 35–83%, respectively. Bacteria could be removed by as much as 98% in all the operating conditions tested and toxicity unit dramatically decreased to less than 1 (96% removal)	Effective organic oxidation is possible even under high OLR	Proper residence time (>4 days) needed for sufficient reduction of toxicity unit	[11]
Catalytic supercritical water oxidation (CSCWO).	COD removal of 86% at t = 9 min, T = 430 °C, oxidation coefficient = 0.8, COD _{initial} = 3000 mg/L	Adding Na ₂ CO ₃ catalyst improved COD removal to 99.8%	Addition of catalyst requires higher temperature (500 °C)	[106]
Electrocoagulation in continuous flow mode with and without adding hydrogen peroxide	COD removal was 95.48%; optimal conditions are a current density of 50 mA cm ⁻² , an initial pH of 3, a flow rate of 0.027 L min ⁻¹ , and the presence of 0.2 M H ₂ O ₂ , and 0.5 g L ⁻¹ polyelectrolyte	Most efficient pH was original pH of the wastewater (approximately 7), which eliminates the chemical adjustment of pH if only using electrocoagulation method	pH adjustment required to increase COD removal efficiency from an electrocoagulation process to peroxi-electrocoagulation process	[107]
Electrochemical oxidation	Results showed that raising the applied current density to 3.83 mA/cm ² has a 100% COD removal, 90% color removal, and 80% turbidity removal	COD removal percentage of 100% was obtained after an electrolysis time of 200 min; improved and more economical method than results reported in other literature	pH adjustment required for optimal treatment	[108]
Preliminary settling tank followed by chemical coagulation followed by electrocoagulation	Supplemental process as electrocoagulation is essential for enhanced effluent quality to meet standards	Adopting the electrocoagulation process is economical	Removal efficiencies increased by increasing coagulant dose and electrical potential, which requires more chemical usage and electricity	[99]
Electrochemical (pre-treatment) followed by integrated membrane filtration treatment system (UF and RO)	Highly effective for the removal of some turbidity, color, TSS, total iron, aluminum, COD, and BOD; with removal efficiency ranging from 71 to 85%	High removal efficiency of total iron and aluminum reduces scaling of mineral salts onto the membrane surface, maintaining the design flux	Lower removal efficiencies of nitrate, nitrite, ammonium; EC pre-treatment unit necessary to achieve nickel removal efficiency of approximately 52.06%	[33]

Table 4. Cont.

Process	Significant Results	Advantage	Disadvantage	Reference
Electrochemical (aluminium–graphite and aluminium–titanium electrodes)	Both electrodes achieved high removal efficiency from turbidity, color, nitrite, phosphates, and COD, with removal efficiency 88% to 100% after 40 min.	Inert character of graphite electrode led to lower operating cost	Although aluminum–titanium outperformed aluminum–graphite, it is more costly than graphite due to inert character of graphite	[103]
Microbial fuel cells	COD removal in SWW was 67.9% and pH increased from 5.9 to 7.5 due to treatment process.	Considered green technology since electricity is a by-product and rumen microbes used as biocatalyst; pH also increased from 5.9 to 7.5 due to fast consumption of protons to cathodes than generation of protons in anodes	Microbial system must be optimized; microbes need sufficient food for growth whereas excessive substrate may not be beneficial for the process and lowers power density generation	[109]
Electrochemical (pre-treatment) followed by membrane filtration and UV treatments (UF and UV)	Combined treatment led to the removal of almost all the microorganisms in the wastewater with 99.86% to 100% efficiency	High-efficiency microbial elimination	Combined treatment required for optimal removal	[33]
Electrochemical method using stainless steel and copper electrodes	85% to 92% removal efficiency of TSS, color, turbidity, BOD, COD, and TOC after 60 min of contact time	Lower operating cost than aluminum electrodes (\$0.49/m ³ compared to \$3.85/m ³)	Low removal of ammonia (60%) even at longest contact time	[110]
Zeolite-based ion-exchange and sulfur oxidizing denitrification	NO ₃ –N removal efficiency of 100%	Meets effluent requirements for NH ₄ ⁺ –N and lower SO ₄ ^{2–} accumulation	Conventional secondary pre-treatment is needed	[111]

SWW = slaughterhouse wastewater; EO = electro-oxidation; COD = chemical oxygen demand; SS = suspended solids; UVC = ultraviolet C light; UV = ultraviolet; TP = total phosphorus; BOD₅ = 5-day biochemical oxygen demand; TOC = total organic carbon; TN = total nitrogen; TSS = total suspended solids; OLR = organic loading rate; UF = ultrafiltration; RO = reverse osmosis.

3.4. Advanced Oxidation Processes (AOP) of SWW

SWW commonly contains non-biodegradable pollutants and trace pollutants requiring further treatment beyond biological methods. Advanced oxidation processes (AOPs) have been explored as both an alternative and a complement to optimize treatment of SWW in order to improve biodegradability, remove recalcitrant and non-biodegradable pollutants, and possibly reach the level of treatment for water reuse. Studies from AOPs have shown that highest removal comes from using AOPs as either a pre-treatment or post-treatment with other combined technologies such as biological treatment. AOPs are effective due to their ability for mineralization rather than just degradation [64]. Table 5 summarizes recent AOP and combined processes studies for SWW treatment.

3.4.1. Fenton Processes

Proof-of-concept studies have been conducted for heterogeneous electro-Fenton (HEF) process as an alternative to conventional electro-Fenton (EF) process to degrade Nafcillin antibiotic [112]. Another proof-of-concept AOP is the use of electrochemical oxidation for removal of COD, TOC, TN, TSS, and color [104,105]. Joao et al. (2020) studied pollutant removal of swine slaughterhouse wastewater containing a high pollutant load by an ultrasound-assisted Fenton process (pH 3; hydrogen peroxide concentration, 90 mg/L; nail

unit, 2.7 g). Under these conditions, color, turbidity, COD, and BOD removal of 98, 98.2, 84.6, and 98%, respectively, were achieved [113].

Another study focused on the use of the Fenton process (using Fe, Cu, and Fe/Cu nanoparticles) in nafcillin (a β -lactams used to treat bacterial infections in human and animals) degradation. Despite being important to maintain good health in humans and animals, nafcillin is found in wastewater produced by hospitals, pharmaceuticals, and livestock industries, and has generated tremendous environmental problems as for its elimination from these effluents. In this context, heterogeneous electro-Fenton (HEF) was used to completely remove nafcillin from slaughterhouse wastewater after 15 min of treatment by HEF and using Fe/Cu bimetallic nanoparticles (NPs). Interestingly, the generation of hydroxyl radicals in the BDD (boron-doped diamond) electrode and Fenton reaction with Fe and Cu nanoparticles were involved in the nafcillin degradation [112].

3.4.2. Combined Biological/AOPs

A series of studies have explored coupling electrochemical oxidation with a combined biological process. Vidal et al. (2016) first employed a combined process of anaerobic digestion followed by different configurations for electrochemical advanced oxidation processes [114]. The electrochemical AOP included electro-oxidation, electro-Fenton, and solar photoelectron-Fenton processes. Anaerobic digestion in the study removed 90% COD (initial COD of 1494 mg/L), producing 90 mL of CH_4 after 30 days of retention time. The combined process increased COD removal to 97%. Solar photoelectron-Fenton process was found to result in almost complete mineralization.

Brooms et al. (2020) looked into leveraging the biodegradability enhancement advantage of AOP through photodegradation and coupled anaerobic digestion and photodegradation (see Figure 2 for example schematic) [115]. SWW was first treated using anaerobic digestion to remove FOG and to produce energy for photodegradation. The subsequent photodegradation step then removed recalcitrant pollutants of *O*-cresol and dibutyl phthalate and increased biodegradability of the digester effluent. The treated SWW was recycled back into anaerobic digester after photodegradation as post-treated SWW.

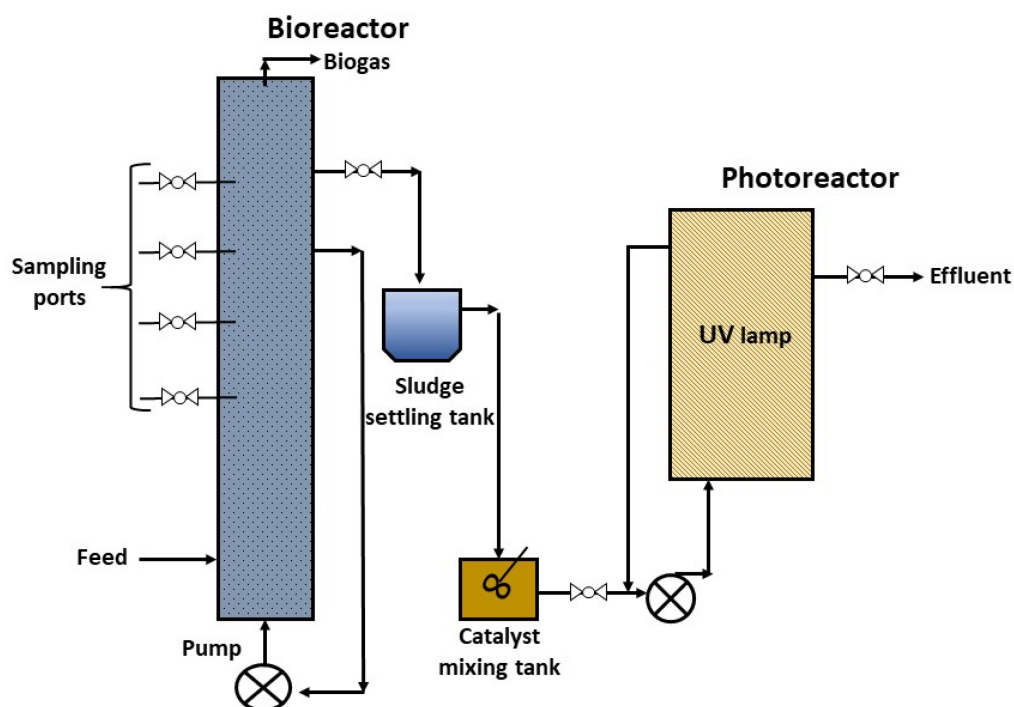


Figure 2. Schematic of coupled anaerobic digester and photoreactor (modified from Brooms et al. 2020) [115].

Bustillo-Lecompte et al. (2015) also studied combined biological/AOPs and conducted a series of studies on photocatalysis using H_2O_2 coupled with UV photolysis, as well as anaerobic digestion [4]. Another study further explored a combined process using anaerobic baffled reactor followed by conventional activated sludge for removal of TOC, TN, and TSS [116].

Fard et al. (2019) studied the use of two stages of up-flow anaerobic sludge blanket (UASB) reactor and advanced oxidation processes to treat wastewater from a local slaughterhouse plant in Guilan (Iran) [68]. The UASB removal efficiencies of tCOD and phosphate were 62.2 and 36.5%, respectively. Further, a post-treatment was performed to remove organic matter and nutrients using a Fenton process. At optimum conditions (pH, 3; H_2O_2 , 1000 mg/L; Fe (II), 400 mg/L), the removal efficiencies of tCOD and phosphate reached 95.41 and 85.29%, respectively. The combination of both methods removed tCOD and phosphate by 98.6 and 90.5%, respectively. These suggested the essential role of Fenton (H_2O_2 /Fe II) in the removal of contaminants from slaughterhouse wastewaters [117].

3.4.3. Combined Physical and Chemical Processes/AOPs

The combination of electrocoagulation, ultrafiltration, and photochemical processes allowed removal of BOD, COD, phosphates, and microbial contamination processes and to reach water quality sufficient for reuse and recycle back into the slaughterhouse operations (see Figure 3 for schematic) [118]. A novel method of oxidation employed cold plasma oxidation to treat both organic and inorganic pollutants and deactivate pathogens [11]. Another technology explored is the electric discharge plasma for total coliform and COD removal [119].

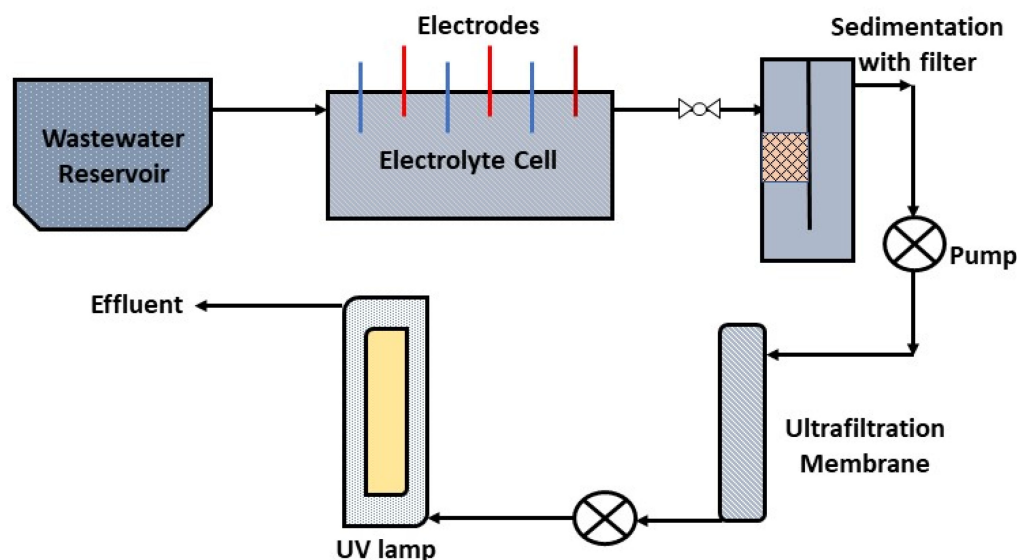


Figure 3. Combined electrocoagulation, ultrafiltration, and photodegradation system for SWW (modified from Meiramkulova et al. 2019) [118].

Table 5. AOPs/Combined treatments. Abbreviations for common terms in table footnotes.

Process	Significant Results	Advantage	Disadvantage	Reference
Combined system: electrocoagulation, UF, and photochemical system as UV sterilization	Treatment lasted 40 min; BOD, COD, and phosphates had removal efficiency of almost 100%; microbiological colonies were all eradicated	Use of aluminum and graphite electrode combination proved to be effective during the EC process	Water from 3 different sections of poultry SWW was used (defeathering, evisceration, cooling) and tested separately; removal of nitrates was only 71% for evisceration water	[118]
Combined AOP system: UV-C/H ₂ O ₂ –VUV system	Optimum conditions to achieve TOC removal of 46.19% and minimum H ₂ O ₂ residual of 1.05% were TOC ₀ of 213 mg/L, H ₂ O ₂ of 450 mg/L, and irradiation time of 9 min	Maximize TOC removal while minimizing H ₂ O ₂ residuals; experimental results matched response surface methodology modeling	Biological treatment must be considered prior to the use of the UV-C/H ₂ O ₂ –VUV system, especially at TOC concentrations higher than 350 mg/L	[116]
Combined system: anaerobic digestion followed by solar photoelectro-Fenton (SPEF) process	Combination of processes produced a mineralized, clarified, odorless effluent, without TSS and with a COD removal of 97%	Almost complete mineralization was achieved with a high efficiency; uses UV radiation from the sun	Methane production is low compared to previously reported values	[114]
UV/H ₂ O ₂ with recycle	TOC removal of 81% and a minimum H ₂ O ₂ residual <2% found at 24 mg/L influent TOC, 860 mg/L influent H ₂ O ₂ concentration, 15 mL/min flow rate, and 0.18 recycle ratio	Experimental results matched response surface methodology modelling; recycle ratio is found to be significant in minimizing the H ₂ O ₂ residual	Conditions must be optimized: as the influent TOC concentration increases, the percent TOC removal decreases. Conversely, there is an optimum influent TOC concentration value at which the H ₂ O ₂ residual is minimum	[120]
Electro-Fenton	Optimum conditions found at pH of 4.38, reaction time of 55.60 min, H ₂ O ₂ /Fe ²⁺ molar ratio of 3.73, current density of 74.07 mA/cm ² , volume ratio of H ₂ O ₂ /PSW of 1.63 mL/L for 92.37% COD removal	Electro-Fenton method advantages include large amount of pollutant removal, small amount of sludge production, short reaction time, easy operation, low energy consumption; real SWW used in experiments	Optimal conditions required for different pollutants	[121]
Combined system: anaerobic baffled reactor, aerobic AS reactor, and a UV/H ₂ O ₂ photoreactor with recycle in continuous mode at laboratory scale	TOC and TN removals of 91.29 and 86.05%, respectively, maximum CH ₄ yield of 55.72%, and minimum H ₂ O ₂ residual of 1.45% in the photoreactor effluent were found at optimal operating conditions	Actual SWW used in experiment	The minimum total retention time was determined to be 10 h with individual residence times of 6.82 h, 2.40 h, and 47 min in the ABR, AS bioreactor, and UV/H ₂ O ₂ photoreactor	[122]

Table 5. Cont.

Process	Significant Results	Advantage	Disadvantage	Reference
Combined system: anaerobic digestion and photodegradation	Achieved > 92% removal of the aromatic compounds, color, TOC, and COD; anaerobic digestion as a stand-alone process removed up to 80% COD; photodegradation, as a post-treatment to the AD, removed 92% of the aromatic compounds	BMP could supplement up to 20% of the electricity requirement by the energy-intensive photodegradation process; AD process was also able to remove the FOG and color	AD and photodegradation were not found to have great results when tested as standalone treatments—needs to be used as combined system; photocatalysis is considered energy-intensive	[115]
Fenton process with ultrasound	Optimum conditions were pH = 3, hydrogen peroxide concentration 90 mg L ⁻¹ , and a nail unit (2.7 g); in these conditions, color, turbidity, COD, and BOD ₅ removal of 98, 98.2, 84.6, and 98%, respectively, were achieved.	Higher removal of organic load and nutrients in a shorter time when compared with biological systems; uses recycled nails as iron sources for the ultrasound-assisted Fenton process	Removal efficiency decreases as the pH increases; oils and grease removal was only 70% for ultrasound-assisted Fenton process	[113]
Combined system: upflow anaerobic sludge blanket reactor and AOP	UASB removal efficiency of TCOD and phosphate were 62.2% and 36.5%, respectively; combined method removed COD _t and phosphate up to 98.6% and 90.5%, respectively	Fenton process indicates an appropriate performance in removing COD _t and phosphate; can remove up to 99.3% turbidity	Long initial set-up for UASB reactor to stabilize conditions for use (120 days for biomass growth and 30 more days to be stabilized); requires acidic conditions and optimal dose of H ₂ O ₂	[117]
Combined system: semicontinuous upflow anaerobic sludge blanket (UASB) reactor and solar photoelectron-Fenton (SPEF)	UASB reactor achieved up to 70% COD removal for the highest organic loading rate of 8.15 g COD L ⁻¹ d ⁻¹	SPEF is less costly; proposed semicontinuous processes eliminate at least 91% of the total COD	Low efficiency of suspended solid removal in anaerobic digester; variable range of removable in combined process	[123]
AOPS with hydrogen peroxide and potassium persulfate as oxidants	74% TOC removal with UV/H ₂ O ₂ ; 85% TOC removal with UV/K ₂ S ₂ O ₈	Effluent quality of UV/K ₂ S ₂ O ₈ treatment was below discharge limits	Pilot scale testing needed to determine feasibility of UV/K ₂ S ₂ O ₈ treatment at a larger scale	[124]

SWW = slaughterhouse wastewater; UF = ultrafiltration; UV = ultraviolet; BOD₅ = 5-day biochemical oxygen demand; COD = chemical oxygen demand; EC = electrocoagulation; UV-C = ultraviolet C light; VUV = vacuum-ultraviolet; TOC = total organic carbon; SPEF = solar photoelectron-Fenton; TN = total nitrogen; ABR = anaerobic baffled reactor; AS = activated sludge; AD = anaerobic digester; BMP = biomethane potential; FOG = fats, oils, and grease; UASB = upflow anaerobic sludge blanket; TCOD = total chemical oxygen demand; OLR = organic loading rate.

4. Critical Assessment and Future Research

This literature review outlined challenges related to the treatment of SWW relative to public and environmental health and discusses the biological, physical/chemical, and advanced treatments to mitigate these concerns. Presented here is an assessment of those treatment followed by recommendations for future research.

4.1. Biological Processes

Significant recent research has been conducted on biological processes for SWW. Anaerobic digestion can remove the pollutants in high-strength wastewater while producing valuable biogas as a byproduct. However, high organic loading rates often lead to a de-

crease in biogas production and/or lower removal of COD [58,62]. A promising area of research is the co-digestion of SWW with FOG, which can result in enhanced biomethane production compared to anaerobic digestion of SWW alone [61].

While phytoremediation processes or the use of constructed wetlands for treating SWW have been explored, the effluent from these treatments often does not meet water quality criteria. There are advantages of these methods (production of biodiesel or biomass); however, these treatments would have to be combined with additional methods to improve effluent quality before discharge into the environment.

For biological processes, combined aerobic and anaerobic processes show the most promise for treatment of SWW. These combined treatments are effective at removing SWW pollutants over a wider range of organic loading rates and hydraulic residence times due to the aerobic/anaerobic conditions [72,74,125]. If combined aerobic and anaerobic processes are followed by disinfection, the effluent can meet water quality standards for BOD, COD, nutrients, and pathogens [73].

4.2. Physical and Physical/Chemical Processes

Physical processes such as membrane filtration show promise for removal of SWW pollutants. The major disadvantages include necessary pretreatment steps to remove solids and fats (often requiring chemicals or biological treatments first) and a final effluent that may not meet requirements for nutrients [86,90]. Additionally, the most efficient membranes for SWW pollutant removal often present the highest overall system cost [89].

Combined physical/chemical processes (e.g., electrochemical oxidation followed by membrane filtration) are effective at removing SWW pollutants; these combined methods do have some advantages over biological processes (e.g., membrane filtration can also remove pathogens, [17,33]). However, these methods often require pre-treatment to remove grit, chemicals to raise pH, and long treatment times for full mineralization [104,105].

4.3. AOPs

In general, AOPs have proven themselves in the treatment of wastewater like slaughterhouse wastewater. For example, photocatalysis was applied by Kanafin et al. (2022) to the treatment of poultry slaughterhouse wastewater under UV-C light (254 nm) after 150 min of treatment by evaluating TOC values [124]. Different chemical species such as hydrogen peroxide, potassium persulfate, titanium dioxide, and iron salts were combined to UV light. The efficiency was in the following order: $UV/S_2O_8 > UV/Fe/H_2O_2 > UV/TiO_2$ with 85%, 74%, and 44% of TOC removal, respectively. The combination of AOPs with each other can be counterproductive to some extent. Alfonso-Muniozguren et al. (2020) reported that combination of ultrasound with ozone led to a significant decrease in COD (44%) and BOD (78%) removal compared to ultrasound alone (300 kHz), which showed a reduction in chemical oxygen demand (COD, 18% reduction) and biological oxygen demand (BOD, 50% reduction). When combined with biological methods, AOPs can be a very effective treatment for SWW and produce high-quality effluent that is often safe for discharge to the environment. A major challenge with AOPs (e.g., electro-Fenton processes) is that the optimal conditions for pollutant removal will vary on a pollutant-by-pollutant basis [121,122]. Combined biological/AOPs provide an advantage over standalone methods in that the biomethane produced can supplement the energy required [115,120].

4.4. Future Research

While significant research has been conducted on treatment options for SWW, it is worth noting that the literature lacks studies on the optimization of existing SWW treatment technologies. Additionally, future studies to address new SWW pollution and decontamination threats such as antibiotics and enterobacteria should be explored further. Studies on technology treatments using swim bed system and advance processing system are also recommended. It is also important to note that many studies on SWW treatment

processes are carried out at the laboratory scale; therefore, it is suggested to perform more field studies and explore the practical utility of treatment technologies on commercial scale.

The removal of contaminants also depends on a variety of environmental factors including initial pH, batch conditions, temperature, hardness, and presence of natural organic compounds, among others. More detailed studies are needed to identify the role of each factor in SWW treatment and their contributions to the effectiveness of that treatment. It is recommended that future research prioritize environmental and health issues related to SWW, focusing first on the removal of chemicals like pharmaceutical compounds present in these effluents, followed by studies on photocatalytic deactivation of microorganisms like enterobacteria. Once these treatments have been optimized under different environmental conditions (and using real SWW matrix), research can focus on scalability, from lab, to pilot, to commercial.

5. Conclusions

Significant research has been conducted for untreated and treated SWW and the literature findings on both water quality parameters and toxicity assessments confirm the need for adequate treatment to avoid the potential consequences to both public health and environment. These studies have also illustrated the effects of the pollutants and microbial activity of SWW through identification of antibiotic-resistant strains of bacteria. Internal operations of slaughterhouses and the meat industry have a direct impact on downstream treatment, perpetuating environmental degradation and public health issues and creating treatment needs that are dynamic. To match the high-strength characteristics of complex recalcitrant pollutants, treatment through combined processes were found to be more effective than stand-alone treatment. Updates to the treatment train should incorporate a form of anaerobic digestion as well as AOPs. Future research should focus on optimization of combined processes under varying environmental conditions, followed by studies focused on scalability.

6. Highlights

- SWW discharged into the environment can have significant impacts on public health and the environment
- SWW contains high strength and recalcitrant pollutants that require more advanced treatments prior to disposal
- Combined processes treatment for SWW are more effective than stand-alone treatment
- A modernization of treatment facilities for SWW should include anaerobic digestion and AOPs

Author Contributions: All authors (M.N., S.D., J.W., B.P.K., M.B.T., H.K.P., H.D., A.A.A., P.N.-T. and A.K.) contributed to the study conception and design. Data collection, analysis and discussion were performed by all authors. All authors contributed to the design and implementation of the research. The first draft of the manuscript was written by M.N. and all authors commented on previous versions of the manuscript and contributed on the Writing—Reviewing and Editing. This review was supervised by A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no competing financial or non-financial interests that are directly or indirectly related to the work submitted for publication. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article.

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