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Slaughterhouse Wastewater: Treatment, Management and Resource Recovery

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Abstract

The meat processing industry is one of the largest consumers of total freshwater used in the agricultural and livestock industry worldwide. Meat processing plants (MPPs) produce large amounts of slaughterhouse wastewater (SWW) because of the slaughtering process and cleaning of facilities. SWWs need significant treatment for a sustainable and safe discharge to the environment due to the high content of organics and nutrients. Therefore, the treatment and final disposal of SWW are a public health necessity. In this chapter, the regulatory frameworks relevant to the SWW management, environmental impacts, health effects, and treatment methods are discussed. Although physical, chemical, and biological treatment can be used for SWW degradation, each treatment process has different advantages and drawbacks depending on the SWW characteristics, best available technology, jurisdictions, and regulations. SWWs are typically assessed using bulk parameters because of the various pollutant loads derived from the type and the number of animals slaughtered that fluctuate amid the meat industry. Thus, an on-site treatment using combined processes would be the best option to treat and disinfect the slaughterhouse effluents to be safely discharged into receiving waters.

Keywords: Anaerobic digestion, Activated sludge, Advanced oxidation processes, Combined processes, Slaughterhouse wastewater

1. Introduction

The meat processing industry consumes 29% of the total freshwater used by the agricultural sector worldwide [1, 2]. Moreover, the global production of beef, pork, and poultry meat has been doubled in the past decade and is projected to grow steadily until 2050. Thus, the number

of slaughterhouse facilities is increasing, which results in an expected higher volume of slaughterhouse wastewater (SWW) to be treated [3]. SWWs are classified as one of the most detrimental industrial wastewaters to the environment by the United States Environmental Protection Agency (US EPA) because the inadequate disposal of SWW is one of the reasons for river deoxygenation and groundwater pollution [4]. Thus, SWWs require significant treatment for a safe and sustainable release to the environment, and the treatment and disposal of wastewater from slaughterhouses are an economic and public health necessity [5, 6].

The organic matter concentration in meat processing plant (MPP) effluents is usually high, and the residues are moderately solubilized, leading to a polluting effect due to the high levels of organics and pathogens present in SWW along with detergents used for cleaning purposes. SWWs are typically assessed using bulk parameters because of the various pollutant loads derived from the type and the number of animals slaughtered that fluctuate amid the meat industry [7].

Anaerobic treatment is the preferred biological treatment because of its effectiveness in treating high-strength wastewater such as SWW with less complex equipment requirements [8]. Although anaerobic treatment is efficient, anaerobically treated effluents require posttreatment to comply with required discharge limits where the complete stabilization of the organic matter is not possible by anaerobic treatment alone. Anaerobically treated effluents contain solubilized organic matters, which are more suited for treatment using aerobic processes. Therefore, aerobic treatment systems are more frequently used in wastewater treatment systems since they operate at higher rates than conventional anaerobic treatment methods. Taking into account that oxygen requirements and treatment time are directly proportional to an increase in wastewater strength, aerobic treatment is frequently applied as posttreatment of anaerobic effluents as well as for nutrient removal [9].

Nevertheless, biological processes alone do not produce effluents that comply with current effluent discharge limits when treating high-organic-strength wastewaters. The use of combined anaerobic and aerobic processes is beneficial for its potential resource recovery and high treatment efficiency [10].

On the other hand, some slaughterhouse effluents contain toxic, bioresistant, recalcitrant, and nonbiodegradable substances. Thus, advanced oxidation processes (AOPs) could be used to improve the biodegradability of SWW and inactivate pathogenic microorganisms and viruses, left after biological treatment of the wastewater. Consequently, AOPs are an attractive alternative and a complementary treatment method to biological processes for the treatment of slaughterhouse effluents, especially as a posttreatment method [5–7]. Adopting combined biological treatment and AOPs for the treatment of slaughterhouse effluents is considered operationally and economically advantageous. Combined processes incorporate advantages of diverse technologies to achieve high-quality effluents from industrial and high-strength wastewaters for water reuse and resource recovery purposes [9, 10].

In this chapter, the regulatory frameworks relevant to the SWW management, environmental impacts, and health effects are discussed along with common practices for SWW treatment. Significant progress in the combination of biological treatment and AOPs is emphasized. A

case study for the treatment of an actual SWW by integrated anaerobic baffled reactor (ABR)-aerobic activated sludge (AS)-UV/H₂O₂ processes is presented. The overall treatment efficiency of organics and nutrients, the potential energy recovery from CH₄ production, and the H₂O₂ residual are discussed. A cost-effectiveness analysis is used to minimize the treatment time as well as the overall incurred treatment costs required for the efficient treatment of slaughterhouse effluents. Finally, the chapter ends with a discussion on the need for an adequate SWW management, resource recovery, and the improvement actions required.

2. Characteristics of slaughterhouse wastewater

Meat processing effluents are considered harmful worldwide due to the SWW complex composition of fats, proteins, fibers, high organic content, pathogens, and pharmaceuticals for veterinary purposes. Slaughterhouse effluents are typically evaluated using bulk parameters because of the broad range of SWW and pollutant loads. SWW contains large amounts of biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS) [7]. Typical characteristics of an actual SWW are summarized in **Table 1**.

Parameter	Range	Mean
BOD (mg/L)	150–8500	3000
COD (mg/L)	500–16,000	5000
TOC (mg/L)	50–1750	850
TN (mg/L)	50–850	450
TP (mg/L)	25–200	50
TSS (mg/L)	0.1–10,000	3000
K (mg/L)	0.01–100	50
Color (mg/L Pt scale)	175–400	300
Turbidity	200–300	275
pH	4.9–8.1	6.5

Table 1. Typical characteristics of the slaughterhouse wastewater.

As a result, due to the diverse characteristics of the SWW, it is appropriate to classify and minimize wastewater production at its source. Meat processing effluents are becoming one of the major agribusiness concerns due to the vast amount of water used during slaughtering, processing, and cleaning of the slaughtering facilities.

3. Regulations for slaughterhouse wastewater management

Regulations are necessary to mitigate the environmental impact of slaughterhouses, and the treatment methods are used as the main regulatory requirement [11]. The compliance with current environmental legislation and the state-of-the-art technologies may also provide some economic relief via resource recovery from biogas generation using high-rate anaerobic treatment.

Table 2 describes current regulations and discharge limits for organics and nutrients in SWW for an adequate release to the environment in different jurisdictions worldwide, including the World Bank Group [12], the Council of the European Communities [13], the US EPA [14], the Environment Canada [15, 16], the Colombian Ministry of Environment and Sustainable Development Colombia [17], the People's Republic of China Ministry of Environmental Protection [18], the Indian Central Pollution Control Board [19], and the Australian and New Zealand Environment and Conservation Council [20, 21].

Parameter	World Bank	EU	USA	Canada	Colombia	China	India	Australia
BOD (mg/L)	30	25	16–26	5–30	50	20–100	30–100	5–20
COD (mg/L)	125	125	n.a.	n.a.	150	100–300	250	40
TN (mg/L)	10	10–15	4–8	1.25	10	15–20	10–50	10–20
TOC (mg/L)	n.a.	n.a.	n.a.	n.a.	n.a.	20–60	n.a.	10
TP (mg/L)	2	1–2	n.a.	1.00	n.a.	0.1–1.0	5	2
TSS (mg/L)	50	35–60	20–30	5–30	50	20–30	100	5–20
pH	6–9	n.a.	6–9	6–9	6–9	6–9	5.5–9.0	5–9
Temperature (°C change)	n.a.	n.a.	n.a.	<1 °C	n.a.	n.a.	<5 °C	<2 °C

Table 2. Comparison of standard limits for slaughterhouse wastewater discharge in different jurisdictions worldwide.

Although it can be seen that Canadian standards are stricter than other international regulations such as those in the European Union (EU), Australia and New Zealand, or the USA, Canada does not have a specific regulation for the meat processing industry. Moreover, Australia and New Zealand and the USA have been incorporating an integrated approach to the regulation of the MPPs, where industry and regulatory sectors are working together to achieve a common goal of reducing the threats caused by the hazardous and high-strength wastewaters produced in slaughterhouses. Finally, emerging economies such as India, China, and Colombia have less strict standards, but their legislation is focused on specific industries to attain certain levels of treatment depending on the wastewater strength. Therefore, the selection of a specific treatment method depends on the characteristics of the SWW being treated, the best available technology economically achievable (BAT), and the compliance with regulations in different political jurisdictions.

4. Environmental impact and health effects of slaughterhouse wastewater

The commercialization of animal products for consumption leads to the production of a large volume of SWW. Although the environment can handle a certain amount of pollutants through natural degradation processes, as the SWW concentration increases, these mechanisms come to be overburdened, where contamination problems commence [22].

The discharge of raw SWW to water bodies affects the quality of water particularly by causing a reduction of dissolved oxygen (DO), which may lead to the death of aquatic life [23]. Moreover, macronutrients, such as nitrogen and phosphorus, may cause eutrophication events. The discharge of these nutrients triggers an excessive algae growth and subsequent decay. Thus, the mineralization of the algae may lead to the deterioration of aquatic life due to depletion of DO levels. Finally, SWW may contain compounds, such as chromium and un-ionized ammonia, which are directly toxic to aquatic life [24].

Another source of contamination of the meat processing industry is the addition of surfactants as a result of the cleaning process. Surfactants, major components in detergents, may enter the aquatic environment due to an inadequate SWW treatment, causing short-term and long-term changes in the ecosystem that affect humans, fish, and vegetation [25].

The environmental impact of SWW is not only characterized by pollution via surfactants, nitrate, and chloric anions but also pathogens, which persist in the soil and reproduce continuously. Pathogens from SWW can also be transmitted to humans who are exposed to the water body, making those areas unsuitable for drinking, swimming, or irrigation purposes [5, 26].

The general public health effects of the meat processing industry are related to the direct interaction of human communities with the slaughterhouse activities and indirect interactions with the environment, which can be previously affected by the inadequate management of the liquid effluents, solid waste, and obnoxious odors [27]. According to Um et al. [28], conventional treatment processes have no major impact on the reduction of antibiotic-resistant *Escherichia coli* strains present in SWW, highlighting the public health risks associated with inadequately treated slaughterhouse effluents concerning the propagation of antibiotic-resistant and pathogenic bacteria into the environment.

The unsanitary conditions in some slaughterhouses allow the proliferation of pathogens to the final meat product to be consumed. People from developing countries in Africa, Asia, and South America have experienced serious gastrointestinal diseases, bloody diarrhea, liver malfunctions, and, in some cases, death associated with the presence of viruses, protozoa, helminthic eggs, and bacteria in SWW [5, 27]. Furthermore, the presence of hepatitis A and E viruses has been reported in the sewage of animal origin in Spain. Therefore, SWW must be treated efficiently before discharge into water bodies to avoid environmental pollution and human health effects [29].

5. Treatment methods for slaughterhouse wastewater

The freshwater consumption substantially varies in the meat processing sector, and a typical MPP generates a large amount of wastewater from the slaughtering process and cleaning of the facilities. Therefore, the water reuse and the recovery of valuable by-products from the meat processing effluents are the main focus in the agribusiness toward a cleaner production focused on high-quality effluents, biogas production and exploitation, and recovery of nutrients and fertilizers [7].

Treatment methods for SWW are comparable to those used in municipal wastewater treatment and include primary, secondary, and tertiary treatment. However, this does not eliminate the need for primary treatment. There are numerous SWW treatment methods after preliminary treatment, which can be divided into four main categories: physicochemical treatment, biological treatment, AOPs, and combined processes [2, 7]. Each method has advantages and disadvantages, which are discussed below.

5.1. Preliminary treatment

The purpose of the preliminary treatment is to separate solids and large particles from the liquid portion in SWW and remove up to 30% of the BOD. The most common unit operations for preliminary treatment of SWW include screeners, sieves, and strainers. Thus, large solids with a 10–30 mm diameter are retained while the SWW passes through. Other preliminary treatment methods include homogenization and equalization and flotation, among other systems such as catch basins and settlers [30].

5.2. Physicochemical treatment

After preliminary treatment, the effluent should be further treated using primary and secondary treatment. One of the most practical methods of primary treatment for SWW is dissolved air floatation (DAF) for the reduction of fat, oil, grease, TSS and BOD [31]. The most commonly used physicochemical treatment methods are presented below.

5.2.1. Coagulation-flocculation and sedimentation

In the coagulation process, colloidal particles in the SWW are grouped into larger particles, called flocs. The colloidal particles in SWW are nearly negatively charged which make them stable and resistant to aggregation. For this reason, coagulants with positively charged ions are added to destabilize the colloidal particles to form flocs and facilitate the sedimentation process. Various coagulant types can be found in the market, and the most widely used are inorganic metal based-coagulants such as aluminum sulfate, aluminum chlorohydrate, ferric chloride, ferric sulfate, and poly-aluminum chloride with removal efficiencies of up to 80% for BOD, COD, and TSS [32].

5.2.2. Dissolved air flotation

The DAF technology refers to the method of liquid-solid separation by air introduction. The fat and grease along with light solids are moved to the surface creating a sludge blanket. Thus, it can be continuously removed via scum scraping. Furthermore, flocculants and blood coagulants can be added to enhance the effectiveness of the DAF treatment for COD and BOD removals of up to 75%. Nevertheless, common DAF disadvantages include occasional malfunctioning, poor TSS elimination, and moderate nutrient removal [33].

5.2.3. Electrocoagulation

The electrocoagulation (EC) process has been employed as a cost-effective technology for the removal of organics, heavy metals, and pathogens from slaughterhouse effluents by inducing an electric current without chemical addition. The EC process generates M^{3+} ions, mainly Fe^{3+} and Al^{3+} , using different electrode materials. Other electrode types including Pt, SnO_2 , and TiO_2 can interact with H^+ or OH^- ions in acidic or alkaline conditions, respectively. Thus, removal efficiencies of up to 80, 81, 84, 85, and 96% can be achieved for BOD, TSS, TN, COD, and color, respectively [34, 35].

5.2.4. Membrane processes

Membrane processes are becoming an alternative treatment method for meat processing effluents. Different membrane processes, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), have been used for SWW treatment to remove particulates, colloids, macromolecules, organic matter, and pathogens with overall efficiencies of up to 90%. However, membrane processes are required to be coupled with conventional processes for nutrient removal in SWW. Another drawback of membrane processes refers to the membrane fouling when treating high-strength wastewater because of the formation of biofouling layers on the membranes, restricting the permeation rate [36].

5.3. Biological treatment

Primary treatment and physicochemical processes typically do not treat SWW completely, to a degree of satisfaction set by regulations. Thus, secondary treatment is used for the removal of the remaining soluble organic compounds from primary treatment. Biological processes include lagoons with anaerobic, aerobic, or facultative microorganisms, trickling filters, activated sludge (AS) bioreactors, and constructed wetlands (CWs) for organic and nutrient removal efficiencies of up to 90% [7].

5.3.1. Anaerobic treatment

Anaerobic digestion is the preferred method for SWW treatment due to its effectiveness in treating highly concentrated industrial effluents since organic compounds are degraded by anaerobic bacteria in the absence of oxygen into CO_2 and CH_4 . Anaerobic systems have the advantage of achieving low sludge production, minimum energy requirements with potential resource recovery, and high COD removal. Typical anaerobic processes for the treatment of

meat processing effluents comprise anaerobic baffled reactor (ABR), anaerobic digester (AD), anaerobic filter (AF), anaerobic lagoon (AL), septic tanks (ST), and up-flow anaerobic sludge blanket (UASB) [30].

Nevertheless, anaerobic treatment barely complies with current discharge limits. Complete stabilization of the organic compounds is difficult due to the high organic strength of SWW. Therefore, an additional treatment stage is recommended to remove the organics, nutrients, and pathogens that remain after anaerobic treatment. On the other hand, anaerobic treatment requires a higher space and a higher residence time to achieve high overall treatment efficiency, affecting the economic viability of anaerobic treatment alone. Accordingly, the combination of anaerobic and aerobic processes is necessary to achieve a maximum efficiency for the treatment of SWW [37].

5.3.2. Aerobic treatment

Aerobic processes are frequently employed for nutrient removal and further treatment after primary treatment. The required oxygen and treatment time are directly related to the strength of the SWW, which makes it inadequate as primary treatment of SWW but adequate after anaerobic treatment [38].

There are many advantages of using aerobic wastewater treatment processes, including low odor production, fast biological growth rate, and rapid adjustments to the temperature and loading rate changes. Conversely, the operating costs of aerobic systems are higher than those for anaerobic systems due to the maintenance and energy requirements for artificial oxygenation. There are different aerobic unit operations for SWW treatment, such as aerobic AS, rotating biological contactors (RBCs), and sequencing batch reactors (SBRs) [39].

5.3.3. Constructed wetlands

Constructed wetlands (CWs) emulate the degradation mechanisms of natural wetlands for water decontamination, integrating biological and physicochemical processes from the interaction of vegetation, soil, microorganisms, and atmosphere for the adsorption, biodegradation, filtration, photooxidation, and sedimentation of organics and nutrients.

The performance of CW systems for the treatment of SWW has been evaluated using both horizontal and vertical subsurface flow CWs. Results have shown a wide range of organic and nutrient removal for different vegetation with encouraging maximum removals of 99, 97, 85, and 78% for BOD, COD, TSS, and TN, respectively [40]. As a result, CWs are simple methods with low operation and maintenance costs and few negative impacts on the environment, which make them an attractive alternative to conventional treatment [41].

5.4. Advanced oxidation processes

AOPs are an interesting complementary treatment option for primary or secondary treatment of SWW, showing excellent overall treatment efficiencies for water reuse. AOPs are diverse and include gamma radiation, ozonation, ultrasound technology (UST), UV/H₂O₂, UV/O₃, and

photocatalysis, among others, for the oxidation and degradation of organic matter. The disinfection is another benefit of AOPs, which can inactivate pathogens without adding additional chemicals in comparison to other disinfection methods, such as chlorination, preventing the formation of hazardous by-products [5]. Another main advantage of the AOPs is the high reaction rates as well as very low treatment time.

Photocatalysis using photo-Fenton-based processes and photooxidation using UV/H₂O₂ are the most commonly used AOPs for SWW treatment. Although these processes are usually expensive if applied alone, removal efficiencies of over 90% can be achieved for SWW secondary effluents in terms of TOC and COD as a posttreatment method. Thus, the combination of biological processes and AOPs is recommended for SWW treatment [42, 43].

5.5. Combined processes

The implementation of combined processes is operationally and economically beneficial for SWW treatment since it couples the advantages of different technologies to treat high-strength industrial wastewaters. The combined ABR-AS-UV/H₂O₂ system is recognized as a cost-effective solution for SWW treatment with removal efficiencies of over 95% for organics and nutrients at optimum operating conditions [6, 9, 10].

An overview of the state-of-the-art technologies for SWW treatment, during the last two years, is presented in **Table 3**. Particular attention is given to organic and nutrient removal, in terms of bulk parameters such as BOD, COD, TOC, TN, and TP. As shown in **Table 3**, SWW treatment efficiencies vary extensively and depend on the SWW characteristics, the treatment time, and the influent concentration, as well as the type of treatment and BAT to comply with current regulations [7].

Method	HRT (h)	BOD _{in} (mg/L)	COD _{in} (mg/L)	TOC _{in} (mg/L)	TN _{in} (mg/L)	BOD _{rem} (%)	COD _{rem} (%)	TOC _{rem} (%)	TN _{rem} (%)	Ref.
EC	1	1123	2171	–	148	–	85	–	–	[44]
ABR-AS-AOP	41	4635	–	1200	841	100	–	100	82	[10]
SBR	96	–	6580	–	3321	–	81	–	95	[45]
AF	46	–	15800	–	–	–	60	–	–	[46]
AL	48	5088	9216	–	343	73	59	–	–	[47]
SBR	12	–	356	–	175	–	–	–	91	[48]
EC	1	1950	3337	–	–	–	78	–	–	[49]
SBR	161	4240	6057	1436	576	–	98	–	98	[50]
AF	24	–	88	–	–	–	80	–	90	[51]
AD	2640	–	18600	–	5200	–	–	–	66	[52]
MF	48	–	480	183	115	–	91	45	45	[53]
UST-AF-UF	144	–	3000	–	–	–	96	–	–	[54]
CW	28	–	468	–	61	–	60	–	46	[55]
AF-UF	48	–	1778	–	374	–	95	–	78	[8]

Method	HRT (h)	BOD _{in} (mg/L)	COD _{in} (mg/L)	TOC _{in} (mg/L)	TN _{in} (mg/L)	BOD _{rem} (%)	COD _{rem} (%)	TOC _{rem} (%)	TN _{rem} (%)	Ref.
SBR	12	4240	6057	1436	576	–	93	–	93	[56]
AOP	1	–	406	–	–	–	84	–	–	[57]
SBR	3	–	8604	–	1493	–	80	–	88	[58]
UST-AF-UF	343	–	5200	–	74	–	96	–	–	[59]
AOP	2	340	–	94	55	–	–	81	–	[42]
UF-RO	160	–	7970	–	–	–	80	–	–	[60]
AD-AOP	723	658	1494	513	181	98	98	97	31	[43]
ABR-AS-AOP	55	1635	2000	1200	841	100	99	100	85	[6]
ABR-AS-AOP	10	1831	2043	1691	866	100	99	100	90	[61]

Table 3. Comparison of different slaughterhouse wastewater treatment methods.

6. Case study

Actual SWW samples with average concentrations of 1950, 1400, 850, 750, 200, and 40 mg/L for COD, BOD, TOC, TSS, TN, and TP, respectively, were taken from selected licensed MPPs in Ontario, Canada [62]. Anaerobic and aerobic sludge inocula in concentrations of 40,000 and 3000 mg/L, respectively, were obtained from the Ashbridges Bay Municipal Wastewater Treatment Plant in Toronto, Canada. The inocula were acclimatized in a period of 60 days.

The combined ABR-AS-UV/H₂O₂ system consisted of a 36-L ABR with five equal-volume chambers and individual biogas collection, a 12.65-L aerobic AS reactor with controlled air flow to maintain DO concentrations of 2 mg/L, and a 1.35-L UV-C photoreactor with recycle, output power of 6 W, and uniform light distribution (**Figure 1**).

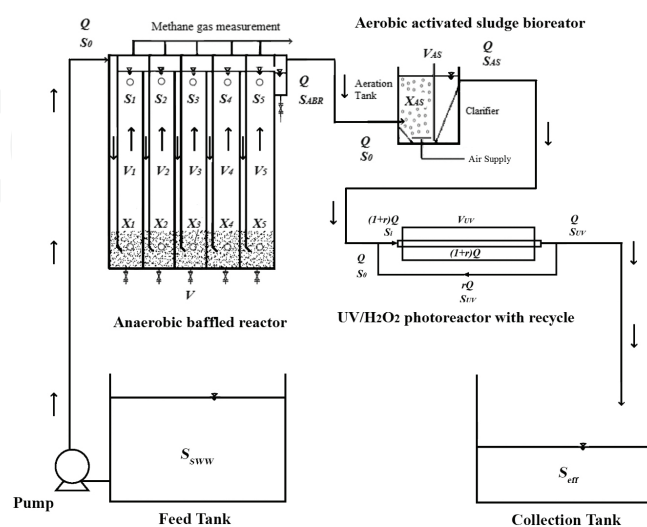


Figure 1. Schematic diagram of the combined ABR-AS-UV/H₂O₂ system for SWW treatment.

Bulk parameters including BOD, COD, TOC, TN, TP, and TSS were analyzed as the main parameters for the treatment of an actual SWW. **Figure 2** shows the obtained maximum removal values of more than 99% for COD (**Figure 2a**), BOD (**Figure 2b**), TOC (**Figure 2c**), TSS (**Figure 2d**), TN (**Figure 2e**), and TP (**Figure 2f**) from the SWW by the combined ABR-AS-UV/ H_2O_2 processes, operated in continuous mode.

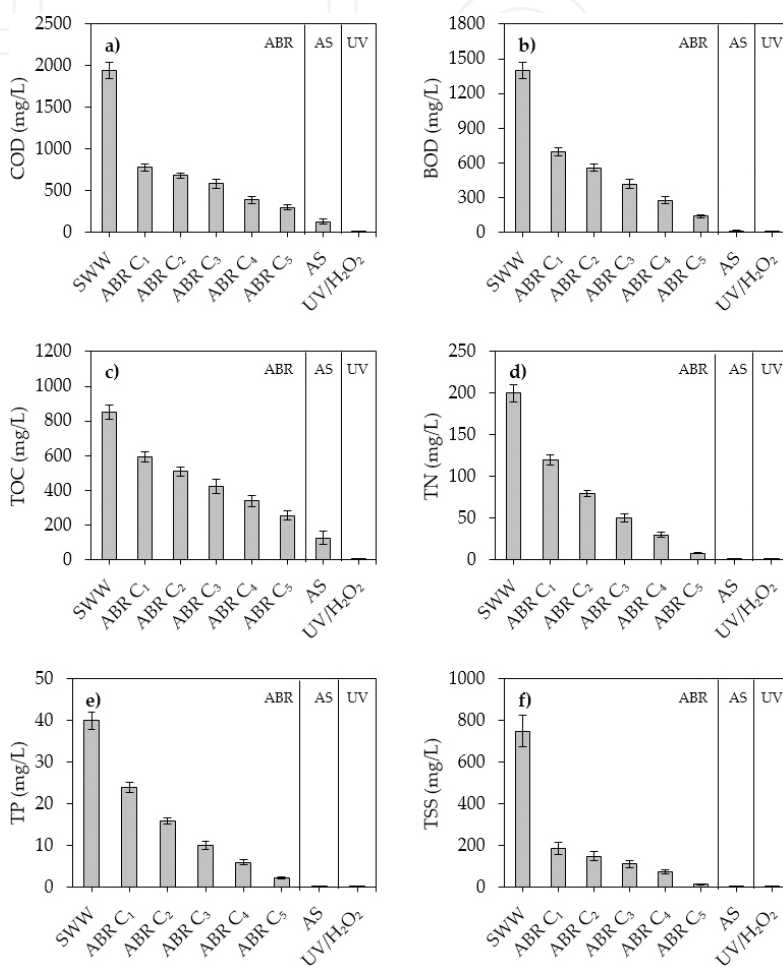


Figure 2. Maximum removal values of (a) COD, (b) BOD, (c) TOC, (d) TN, (e) TP, and (f) TSS from an actual slaughterhouse wastewater using combined ABR-AS-UV/ H_2O_2 processes.

The ABR process alone achieved high TSS and TN removals, providing an effluent that complies with most of the current standards worldwide (**Table 2**), with concentrations of 15 and 8 mg/L, respectively. A further treatment with the aerobic AS bioreactor was required to achieve high BOD and TP removals reaching concentrations of 14 and 0.04 mg/L, respectively. However, the COD and TOC concentrations, which are not included broadly as standard parameters, remain with considerable concentrations of 132 and 128 mg/L, respectively. These concentrations are more related to nonbiodegradable organics that can be mineralized using AOPs as a posttreatment process. Thus, after the treatment by the UV/ H_2O_2 process, the effluent concentrations for COD and TOC reached values of less than 0.4 and 0.1 mg/L, respectively, which could be used for water reuse.

The effects of the influent TOC concentration, flow rate, and pH on the TOC and TN removals, H_2O_2 residual, and CH_4 yield in the combined ABR-AS-UV/ H_2O_2 system were also evaluated. **Figure 3** shows that the influent TOC concentration and the flow rate are inversely proportional to both TOC and TN removals. On the other hand, results indicate that an optimum TOC concentration with no pH adjustment and low flow rate are required to achieve a minimum H_2O_2 residual in the effluent. Finally, results also demonstrate that a high influent TOC concentration is needed to achieve a maximum CH_4 yield with an optimum flow rate and no pH adjustments.

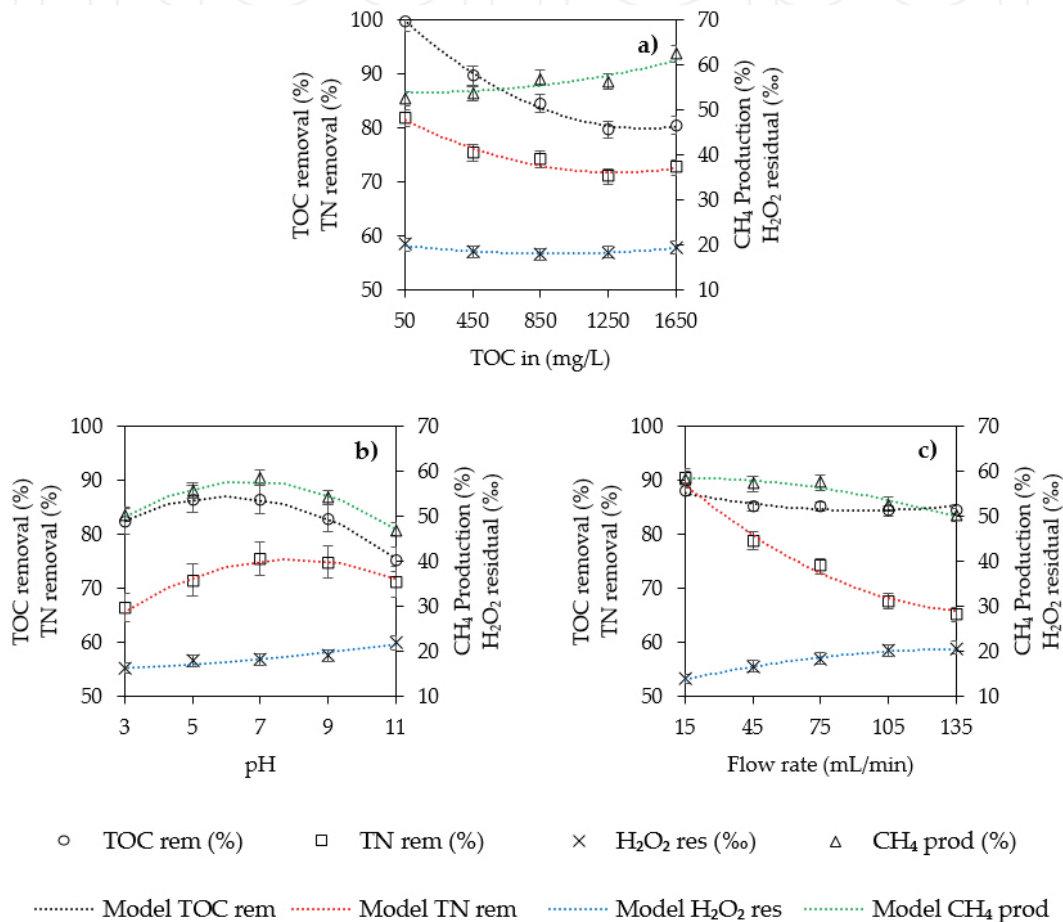


Figure 3. Individual effect of the (a) influent concentration of TOC, (b) flow rate, and (c) pH on the TOC removal, TN removal, H_2O_2 residual, and CH_4 yield. Dashed lines represent model predicted values, whereas marker points represent experimental values. The y-axis is in percentage (%) units, except H_2O_2 residual, which is expressed in per mil (‰) for scaling purposes.

As a final point, the treatment costs per volume for the individual ABR, AS, and UV/ H_2O_2 processes were compared with those of the combined ABR-AS-UV/ H_2O_2 system for the treatment of an actual SWW and plotted versus the TOC removal for each configuration (**Figure 4**). Consequently, a minimum overall treatment cost of 0.12 \$/m³ for a maximum TOC removal of more than 90 % can be achieved at optimum operating conditions in the combined ABR-AS-UV/ H_2O_2 system for the treatment of an actual SWW.

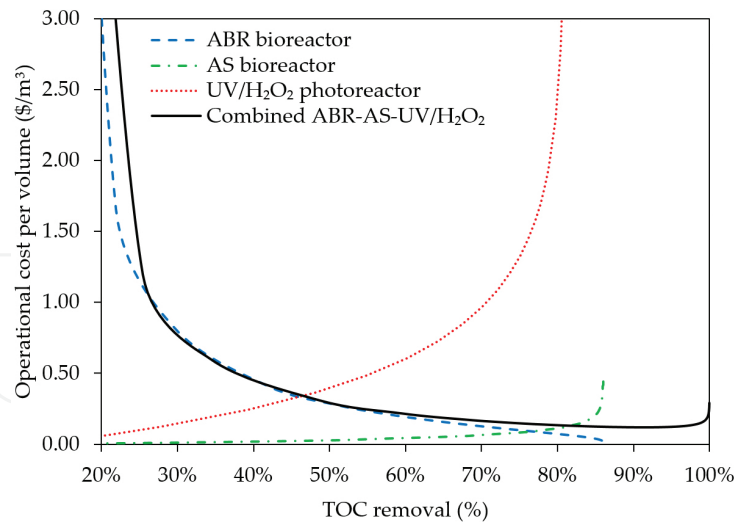


Figure 4. Comparison of operational costs per cubic meter of treated actual slaughterhouse wastewater using individual ABR, AS, and UV/H₂O₂ processes and the combined ABR-AS-UV/H₂O₂ system.

7. Slaughterhouse wastewater management and resource recovery

The meat processing industry needs to incorporate both waste minimization and resource recovery into SWW management strategies considering the portion of the industry’s waste and by-products that have a potential of recovery for direct reuse, including nutrients and methane as biofuel. **Figure 5** presents a schematic illustration of the ideal operation of a meat processing plant and supply chain from the animal farming and raw materials to the final product, waste disposal, and recoverable resources [27, 63].

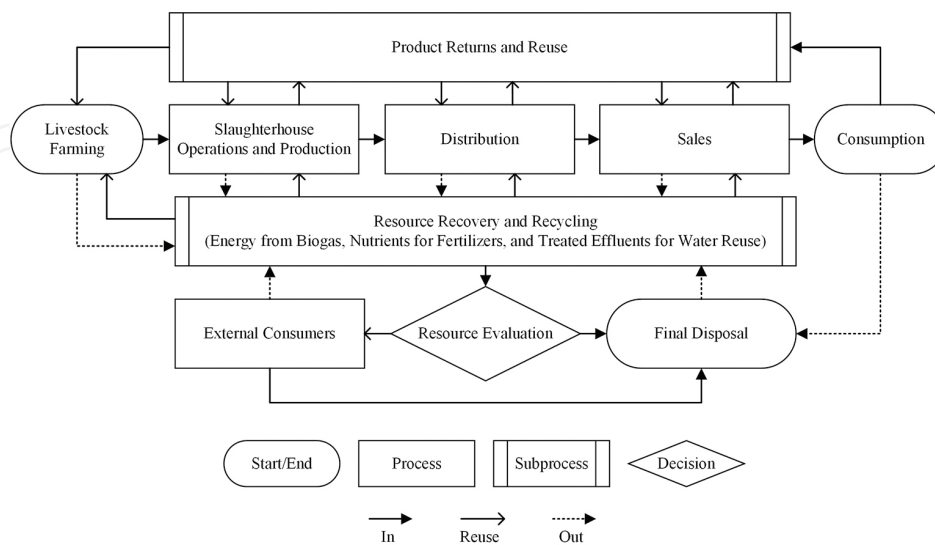


Figure 5. Schematic illustration of the ideal operation and supply chain of a meat processing plant.

A cleaner production should be the focus of meat processing plants due to the increasing interest in environmental initiatives and demands for green practices. Thus, it is appropriate to classify and minimize waste generation at the source, and on-site treatment is the preferred option for water reuse and potential energy recovery. As a result, there are some considerations to be made for the adequate treatment of SWW effluents. **Figure 6** presents a proposed layout of the pretreatment, treatment, and disinfection of slaughterhouse wastes for a typical meat processing plant, as well as the potential resource recovery for water reuse and products recycling [63, 64].

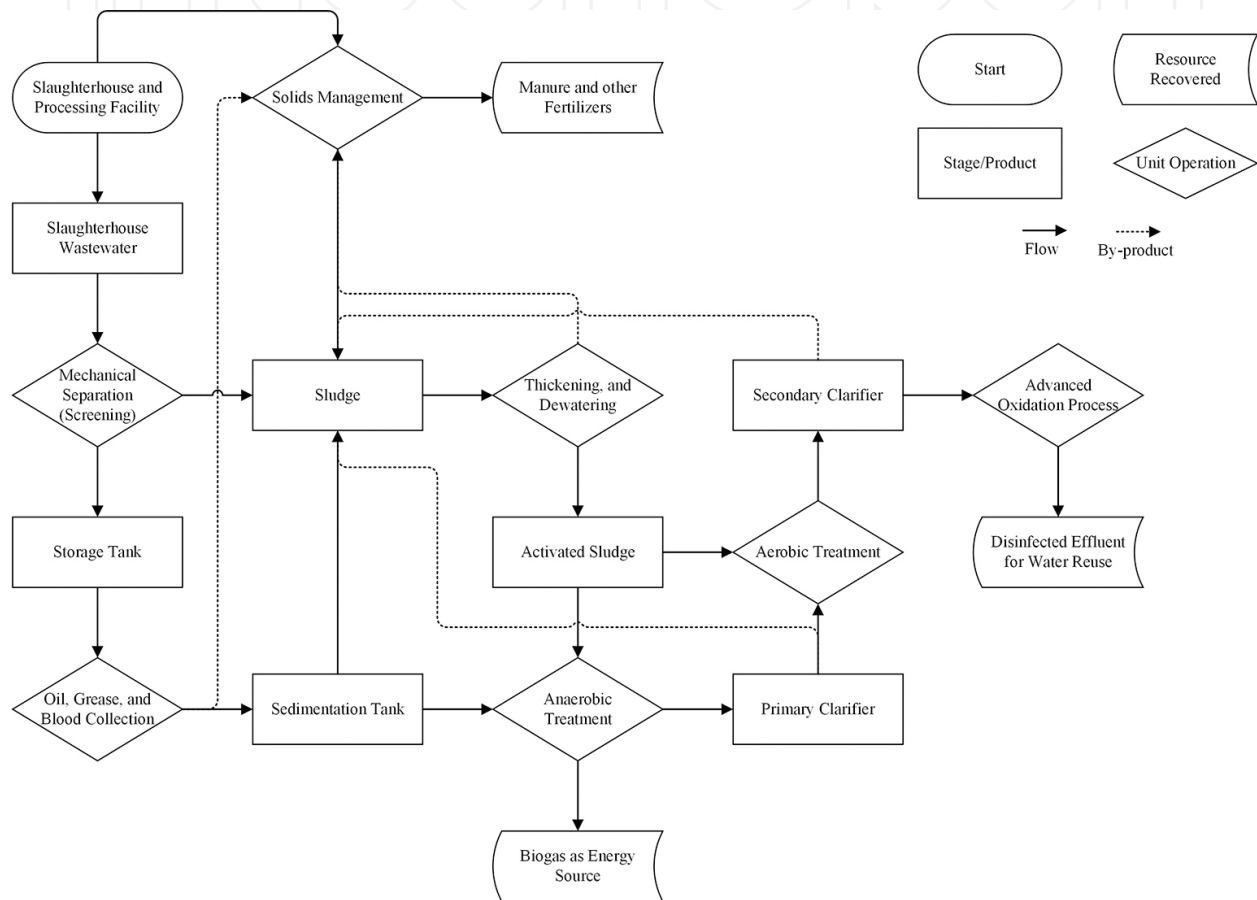


Figure 6. Proposed layout of the pretreatment, treatment, and disinfection of slaughterhouse wastes for a typical meat processing plant.

8. Conclusions

Meat processing effluents are usually pretreated using screeners, settlers, and blood collection systems, followed by physicochemical treatment methods, such as coagulation, flocculation, sedimentation, DAF, or secondary biological treatment. Although biological treatment is able to provide high organic and nutrient removal efficiencies, further treatment by AOPs, or other BAT, is required for a high-quality effluent.

The presented case study provided an example of the application of a combined ABR-AS-UV/H₂O₂ system for the treatment of an actual SWW. Maximum organic and nutrient removal reached over 90% in terms of TOC and TN, respectively. Moreover, a potential resource recovery achieved a maximum CH₄ yield of up to 56%, and minimization of residual by-products from disinfection was attained in terms of H₂O₂ residual of less than 2% at the effluent. Finally, the cost-effectiveness analysis found a minimum overall treatment cost of 0.12 \$/m³ for the treatment of an actual SWW using the combined ABR-AS-UV/H₂O₂ system at optimum operating conditions.

All types of waste, liquid, solid, or gaseous, must be treated prior to their release into the environment. Whereas the use of recoverable resources is recommended as a feasible and practical alternative to conventional energy sources in the long term, costs associated to the application of these technologies will be offset by the reduction in local electricity consumption and by-product recycling and reuse. Thus, the potential of biogas production as an energy source, the use of fertilizers from nutrient recovery, and the SWW high-quality treated effluents for water reuse are to be considered toward a sustainable and cleaner production in the meat processing industry.

Consequently, the use of combined processes as an alternative to conventional methods has become a cost-effective approach for the treatment of meat processing effluents to comply with applicable current regulations worldwide.

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Nomenclature

ABR	anaerobic baffled reactor
AD	anaerobic digester
AF	anaerobic filter
AL	anaerobic lagoon
AOP	advanced oxidation process
AS	activated sludge
BAT	best available technology economically achievable
BOD	biochemical oxygen demand
COD	chemical oxygen demand
CW	constructed wetland

DAF	dissolved air floatation
DO	dissolved oxygen
EC	electrocoagulation
EU	European Union
MF	microfiltration
MPP	meat processing plant
NF	nanofiltration
RO	reverse osmosis
SBR	sequencing batch reactor
ST	septic tank
SWW	slaughterhouse wastewater
TOC	total organic carbon
TN	total nitrogen
TP	total phosphorus
TSS	total suspended solids
UF	ultrafiltration
UASB	up-flow anaerobic sludge blanket
US EPA	United States Environmental Protection Agency
UST	ultrasound technology

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