

Review

Slaughterhouse Wastewater Treatment: A Review on Recycling and Reuse Possibilities

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Abstract: Slaughterhouses produce a large amount of wastewater, therefore, with respect to the increasing water scarcity, slaughterhouse wastewater (SWW) recycling seems to be a desirable goal. The emerging challenges and opportunities for recycling and reuse have been examined here. The selection of a suitable process for SWW recycling is dependent on the characteristics of the wastewater, the available technology, and the legal requirements. SWW recycling is not operated at a large scale up to date, due to local legal sanitary requirements as well as challenges in technical implementation. Since SWW recycling with single-stage technologies is unlikely, combined processes are examined and evaluated within the scope of this publication. The process combination of dissolved air flotation (DAF) followed by membrane bioreactor (MBR) and, finally, reverse osmosis (RO) as a polishing step seems to be particularly promising. In this way, wastewater treatment for process water reuse could be achieved in theory, as well as in comparable laboratory experiments. Furthermore, it was calculated via the methane production potential that the entire energy demand of wastewater treatment could be covered if the organic fraction of the wastewater was used for biogas production.

Keywords: review; slaughterhouse wastewater; recycling; wastewater treatment



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1. Introduction

Providing all people with drinking water, food and energy are three of the central challenges of modern times. Due to the increasing growth of the world population and the rising standard of living, the demand for resources is rising, in particular the consumption of fresh water [1,2]. According to the Food and Agriculture Organization of the United Nations, 1.8 billion people are expected to live in countries or regions with absolute water scarcity (<500 m³ per person per year) by 2025 [3]. Worldwide, agriculture accounts for 92% of the global freshwater footprint, 29% of which is used in agriculture to produce meat products [4]. The decreasing availability of fresh water resources leads to new strategies in the field of water and wastewater management. Wastewater reuse represents an opportunity to use resources more sustainably [5]. As a result, a high treatment efficiency is of great importance [6]. In this context, the recycling of SWW appears to be a desirable goal.

Slaughterhouses are a large industry, as meat is an important part of the diet in many countries around the world [7]. Global meat production has increased in the recent years [3]. As shown in Figure 1, there was an almost linear increase in global meat production until 2015. Since 2015, the production level seems to be constant. Annual meat production is expected to increase to 366 Mt by 2029 according to the OECD [3]. The average water requirement for the production of one tonne of meat is 15,500 m³ for cattle, 4800 m³ for pigs, 6100 m³ for sheep and 4000 m³ for poultry [8]. As meat production increases, so does the volume of SWW. Among the food processing industries, the meat processing industry

is, with a percentage of 24% followed by the beverages industry with 13% and dairy industry with 12%, considered to have the highest demand for fresh water [6,9]. With 1.5 to 18 m³ of wastewater discharged per ton of meat produced, the meat industry has a significant impact on the global water balance [10]. In more detail, slaughtering cattle and pigs produces about 1.6 to 9, sheep 5.5 to 8.3 and poultry 5 to 15 m³ of wastewater per ton of meat [11].

However, the composition of SWW varies considerably depending on the different industrial processes and specific water requirements [6]. SWW is considered harmful worldwide due to its complex composition of fats, proteins and fibers, as well as the pathogenic risk from fecal bacteria and possible infectious carcasses [6]. Therefore, it requires specialized treatment methods [7]. An overview of SWW characteristics is given in Table 1.

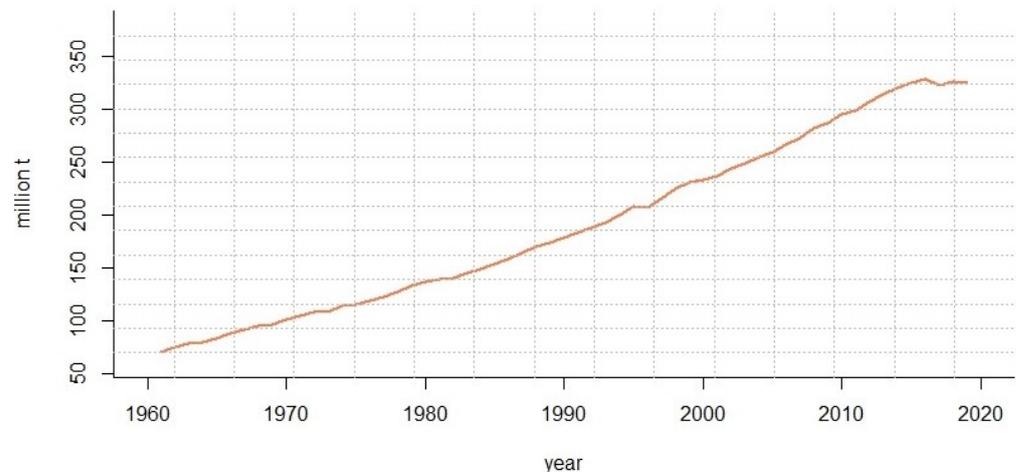


Figure 1. Global meat production from 1961–2019 [3].

A number of review articles that deal with technologies used for treatment of SWW are available [6,7,12–14]. However, up-to-date review articles on SWW recycling have not been published, although there are a number of publications in the field as shown in Table 2. In contrast, review articles in the field of waste water recycling in the food and beverages industry are available [15–17]. According to the Reference Document on Best Available Techniques in the Slaughterhouses and Animal By-products Industries [11], Many slaughterhouses in Europe use a screen often followed by a DAF as a pretreatment process and then discharge the wastewater to the municipal wastewater treatment plants for further treatment. In some countries, such as Sweden, the wastewater is discharged directly to the municipal treatment plant after screening. The goal of this review is to compare the treatment technologies and opportunities for the in situ recycling of meat processing wastewater, with the aim of providing a theoretical basis for the technical implementation within the framework of pilot or large-scale plants. This could have a positive impact on the increasing water scarcity, which is one of the most important development goals of our time. It can also be a further step towards zero liquid discharge in industrial water management, which is important for a long-term sustainable circular economy.

Table 1. Slaughterhouse wastewater characteristics.

Parameter	Unit	Germany ¹	Germany [18]	BREF [11]	Canada [19]	Brazil [20]	Mean
TOC	[mg·L ⁻¹]	700–915			100–1200		730
TN	[mg·L ⁻¹]	237–440	150–500	40–300	50–841	62–313	300
COD	[mg·L ⁻¹]	2100–3193	2000–8000	1000–5000	1250–15,900	2790–5520	4700
BOD ₅	[mg·L ⁻¹]	700–1100	1000–3000	500–2500	610–4635	1558–2988	1900
TP	[mg·L ⁻¹]	80–120	5–50		25–200		80
TSS	[mg·L ⁻¹]	1920–2960		1000–2000	300–2800		1800
PH		6.3–6.9		6.0–9.0	4.90–8.10	6.8–7.8	7
		TN:COD	TOC:TSS	BOD ₅ :COD	TSS:COD	TN:TOC	
		0.06	0.4	0.4	0.4	0.4	

¹ SWW collected from a local slaughterhouse near Berlin.

Table 2. Keyword search hits in combination with SWW.

Keyword	ScienceDirect	Web of Science	Google Scholar
aerobic	1336	70	10,500
anaerobic	2273	311	21,400
biological treatments	2333	122	20,400
dissolved air flotation	327	7	9010
meat	1218	101	10,500
membrane separation process	794	3	19,600
physicochemical treatments	697	30	17,300
recycling	1405	47	11,100
reuse	963	54	9200
zero-liquid discharge	350	0	197
Keyword after 2017	Science Direct	Web of Science	Google Scholar
aerobic	602	27	4490
anaerobic	1086	143	9970
biological treatments	1133	55	15,000
dissolved air flotation	132	2	2540
meat	572	57	4570
membrane separation process	433	2	10,600
physicochemical treatments	447	19	8190
recycling	685	22	4940
reuse	541	27	4440
zero-liquid discharge	180	0	121

2. Materials and Methods

Literature Research

This review article was conducted based on the most relevant and current literature [21]. In order to make a selection of publications relevant to the topic, the following steps were pursued. Initially, peer-reviewed references (books, book chapters, articles, and reviews) were searched in scientific databases. Furthermore, non-peer-reviewed references, such as government reports on public policy on the topic were also included in the search. Afterwards, the key results were evaluated. Based on this, a selection of current references relevant to the topic of this review could be made. Among the most used databases were: ScienceDirect, Web of Science and Google Scholar. The following keywords in combination with slaughterhouse wastewater were used as the main search terms: aerobic, anaerobic, biological treatments, DAF, meat, membrane separation process, physicochemical treatments, recycling, reuse and zero-liquid discharge. Table 2 shows the hit count for the searched keywords. In the context of this review, publications were selected that both had a large correlation with the topic and were cited most frequently.

Subsequently, the most important publications according to these criteria were reviewed for technologies that enable SWW recycling. These were then examined with regard to their performance and where this was sufficient, the energy consumption and other costs were determined and evaluated. The process combinations that seemed suitable were then examined in more detail, and based on this, two models were created that would enable SWW recycling on a large scale.

Following Wang and Serventi [17], the possibilities of wastewater reuse in the processing of the third major protein source (meat) in the human diet are discussed here. The aim of this work is to address specific challenges related to the water use in the meat processing industry and to evaluate the possibilities of water reuse through the combination of proven knowledge and current innovations. For this purpose, SWW was first characterized with regard to quantities, composition and special properties and then evaluated for its reusability which was classified into four categories.

Assessment Tool

In order to assess the recycling possibilities of SWW, the systems described in the publications were evaluated and compared based on their performance and technical feasibility, taking into account their different operating conditions. Subsequently, in order to create comparability, the purified water is classified into different categories:

1. Wastewater discharge;
2. Process water reuse;
3. Reuse without product contact;
4. Agricultural irrigation.

For the first category related to the wastewater discharge, the limit values of the German Waste Water Ordinance (AbwV) are used as a reference [22]. In the case of process water reuse, the regulation applies that only drinking water according to [23] 98/83/EC can be used as process water in the food industry. However, this directive provides legal leeway for the use of alternative water qualities if it can be proven that the water quality does not affect the wholesomeness of the product [24]. Nevertheless, the assessment of the compliance of the water of the second category must comply with the limits of Directive 98/83/EC concerning the quality of drinking water, which is part of the regulation of water supply and sanitation in the European Union. Category 3 reuse without product contact (e.g., external rinsing and cleaning processes or boiler feed water) may have very different requirements. For this category, the requirements are specified in Table 3. For the evaluation of the quality of water used for agricultural irrigation, the guidelines of the European Commission on “Minimum Reclaimed Water Quality Criteria and Preventive Measures” are applied [25]. Table 3 summarizes the limit values applied to the use of the mentioned categories according to the existing regulations.

Table 3. Limits for wastewater reuse.

Parameter	Unit	Category 1 [22,26] Wastewater Discharge	Category 2 [23] Process Water Reuse	Category 3 [26] Cleaning Water	Category 3 [27] Boiler Feed Water	Category 4 [25] Agricultural Irrigation
BOD ₅	[mg·L ⁻¹]	25	<1	-	-	10
COD	[mg·L ⁻¹]	110	5	-	-	-
TN	[mg·L ⁻¹]	18	-	-	-	-
Nitrate	[mg·L ⁻¹]	-	50	-	-	-
TOC	[mg·L ⁻¹]	-	-	-	<0.5	-
TP	[mg·L ⁻¹]	2	-	-	-	-
TSS	[mg·L ⁻¹]	-	-	-	-	10
Oxygen	[mg·L ⁻¹ O ₂]	-	-	-	<0.02	-
<i>E. coli</i>	(cfu· 100 mL ⁻¹)	-	<0	<0	-	10
<i>Legionella</i> spp.	(cfu· L ⁻¹)	-	-	<1000	-	1000
Turbidity	[NTU]	-	10	5	-	5
Conductivity	[μS·cm ⁻¹]	-	2500	-	≤30	-
pH		-	6.5–9.5	-	9.2–9.5	-

3. Results

3.1. Slaughterhouse Wastewater Guidelines and Regulations

Regulations can be a helpful tool to control the impact of the discharge of SWW into the environment [28]. To this end, regulations are used, which set limits for the emission into the EU environment, such as the “Urban Wastewater Treatment Directive 91/271/EEC” [29], the “Effluent Limitations Guidelines and New Source Performance Standards for the Meat and Poultry Products Point Source” [30] of the USA or the Chinese “Integrated wastewater discharge standard (GB 8978-1996)” [31]. There are also rules and recommendations to regulate emissions into the environment, namely the European Best Available Techniques Reference Document [11], which summarizes the technologies that are considered to have the least negative impact on the environment according to the state of the art, and is also used to regulate for approval by the authorities. There are also regulations, such as the Waste Water Ordinance in the case of Germany [32]. This represents the implementation of the Water Framework Directive into national law.

Table 4 shows the limits applied for direct discharge of treated wastewater issued from different regulations. It can be seen that the limit values were set at comparable levels. For the scope of this paper, the limits of the Urban Wastewater Treatment Directive 91/271/EEC [29] will be used as a representative for the assessments. Apart from limits, other approaches exist to reduce the environmental impact of wastewater [5]. For example, countries such as Australia and the USA are working on an integrated approach [5]. The goal is for industry and the regulatory authorities to work together to find the best possible approach [5]. Other countries, such as India and Colombia, have passed laws that prescribe specific wastewater treatment technologies for certain industries [5].

Table 4. Limits for wastewater discharge.

Parameter	Unit	EU [29]	USA [30]	China [31]
BOD ₅	[mg·L ⁻¹]	25	16–26	30
COD	[mg·L ⁻¹]	125	n.a.	100
TN	[mg·L ⁻¹]	10–15	4–8	15
TOC	[mg·L ⁻¹]	n.a.	n.a.	n.a.
TP	[mg·L ⁻¹]	1–2	n.a.	0.5
TSS	[mg·L ⁻¹]	35–60	20–30	n.a.

3.2. Slaughterhouse Wastewater Characteristics

As already mentioned, SWW is considered hygienically hazardous and contains a large amount of organic contaminants and, in particular, a comparatively high amount of nitrogen [18]. The average 1.6 to 9 m³ wastewater per ton of meat produced [11] can be distinguished based on its occurrence at different process steps. Three main classes of water demand can be classified. A total of 40% to 50% of the total water consumption is for direct slaughter, meaning that direct product contact takes place. Another 40% to 50% are used for cleaning the factory and cars, without product contact. About 6% to 12% are required as cooling and boiler feed water, without product contact but with special quality requirements [11,27].

Slaughterhouses can be divided into three categories in regard to their size and waste water quantity:

1. small: up to 20 m³·d⁻¹;
2. medium: up to 500 m³·d⁻¹;
3. large: more than 500 m³·d⁻¹.

Figure 2 shows an overview of wastewater volumes, recycling possibilities and the water requirements of the individual process steps.

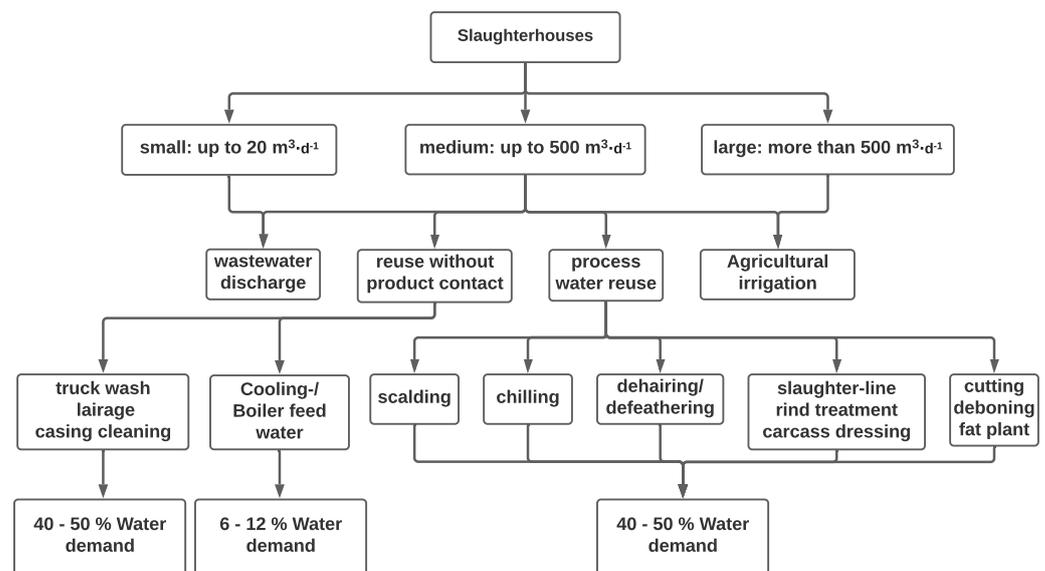


Figure 2. Overview wastewater reuse possibilities [11].

SWW is characterized by a high biological oxygen demand (BOD₅) (500–4000 mg·L⁻¹) and chemical oxygen demand (COD) (1000–15,000 mg·L⁻¹) as well as high concentrations of fat oil and grease (FOG) (300–2000 mg·L⁻¹), total solids (TS) (400–8000 mg·L⁻¹), total suspended solids (TSS) (300–6000 mg·L⁻¹), total nitrogen (TN) (50–800 mg·L⁻¹) and chlorides (300–800 mg·L⁻¹) [6,33,34]. Table 1 shows average SWW compositions. The high variations can be explained by daily changes within a company, but also by different types of processing in different companies [11]. The blood separation efficiency of the processes is an important factor in enabling low loads in the wastewater [35]. In Europe, a blood separation efficiency of 90% is usually required [11]. Particularly high N to C ratios can occur, for instance, in slaughterhouses where little or no blood is separated and most of the blood can enter the wastewater. However, lower wastewater pollution concentrations is oftentimes achieved by increasing water consumption through dilution of wastewater. This leads to excessive wastewater generation and should be avoided [35].

In order to assess the properties of the wastewater, specific ratios were calculated taking into account average characteristics presented in Table 1. The BOD₅:COD ratio shows that almost half of the organic matter contained in the wastewater is readily biodegradable, which is comparable to municipal wastewater [36]. The TSS to COD ratio of 0.6 allows a conclusion to be made regarding the compounds that can be separated by physico-chemical treatment [37]. The high content of nitrogen in relation to organic matter indicates special challenges for the nitrogen elimination [18].

Due to the contamination with pathogens and the high content of proteins, fats and organic fibers, slaughterhouse wastewater is considered one of the most harmful wastewaters in the food processing industry [6,38,39]. The pathogenic microorganisms that are introduced into the wastewater by washing out the intestines are potentially hazardous and, therefore, a germ reduction measure is required, such as disinfection [39,40]. Due to the use of pharmaceuticals for the veterinary treatment of animals, residues in the form of micropollutants can be present in the wastewater [6,39,41]. The concentration of these micropollutants vary from plant to plant and can lead to special challenges in wastewater treatment with regard to biological treatment and reuse [41,42].

3.3. Slaughterhouse Wastewater Treatment

3.3.1. Physicochemical Treatment Methods

Dissolved Air Flotation

Dissolved air flotation (DAF) is commonly used as a primary treatment [7,14]. In the DAF process, air is gassed into the fluid at a pressure of 4–6 bar up to supersaturation. The

pressure is then reduced and the dissolved air escapes from the fluid in the form of small bubbles [43]. These attach themselves to the target ingredients and form the flotote on the surface. This is removed by a skimmer and collected for further treatment. This process, in particular with the addition of flocculants, can be used to denature proteins present in the wastewater and achieve a high separation efficiency [43]. The use of the DAF system as a primary treatment prior to the biological treatment allows the separation of suspended and/or fatty particles from the fluid [43,44]. Figure 3 shows the working principle. In large-scale slaughterhouse wastewater applications, the DAF system can achieve reductions in chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP) and fat oil and grease (FOG) of 70%, 55%, 70% and 85%, respectively [18,35]. With an energy requirement of 0.05–0.30 kWh·m⁻³ in the case of SWW, the DAF is clearly above the sedimentation, but it was repeatedly observed that due to the high FOG content, the sedimentation cannot provide the necessary separation [18].

Flotation has proven to be an efficient pretreatment for SWW [11]. However, it should be noted that limitations also exist with respect to the use of this technology. Namely, the dependence of chemical addition to improve the flocculation process, as well as a higher energy demand [45]. In addition, the use of synthetic polymeric coagulants in the process can lead to secondary contamination of the sludge, this can be avoided by using natural additives such as Tanin [34].

In the study conducted by de Nardi et al. [46], the use of a chemically enhanced DAF for the treatment of poultry SWW was investigated using different coagulants. Polyaluminum chloride (PAC), a cationic polymer and tanine were used as coagulant, and anionic polyacrylamide was used as a flocculant. The highest separation rates were achieved with PAC and tanin in laboratory tests at a recycling rate of 40% and a solubility pressure of 400 kPa. In particular, by using 24 mg·L⁻¹ PAC in combination with 1.5 mg·L⁻¹ anionic polymer at pH 7.25, removal efficiencies of: 77% of COD, 74% of total suspended solids (TSS), and 34% of TP were achieved [46].

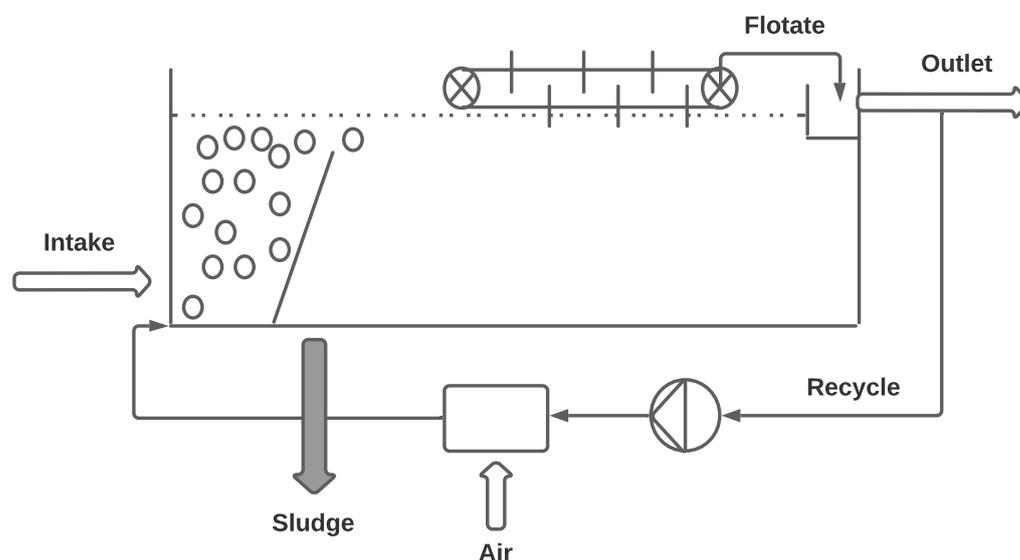


Figure 3. Dissolved air flotation system schematic [47].

In a more recent study conducted by Dlangamandla et al. [43], the use of a bioflocculant-supported DAF for SWW was investigated. For this purpose, the microorganisms species *Comamonas aquatica* (BF-3) and *Bacillus* sp. (BF-2) were cultured with the aim that they produce biological flocculants. Direct addition of biological flocculant and the co-culture (*C. aquatica* BF-3 and *Bacillus* sp. BF-2) to the flotation chamber at a ratio of 2% (v/v) (bioflocculant:SWW) resulted in reductions of 91%, 79% and 93% for TSS, proteins and FOG, respectively. This was achieved with a DAF system on a laboratory scale with a

flotation chamber with a capacity of 2 L. Whether a large-scale implementation is possible could not be clarified within the scope of this publication by Dlangamandla et al. [43].

Ultrafiltration

Membrane technologies are an important process in wastewater treatment. In particular, ultrafiltration (UF) appears to be economically advantageous since, in addition to its efficiency in retaining larger solids in wastewater, it also allows the reduction of chemical agents. UF is a pressure-driven process for the separation of particles in the range of 5–100 nm (protein, pyrogens) based on their molecular diameter [48]. In this process, the wastewater is divided into a purified permeate and a concentrated retentate [49]. Figure 4 shows the principle of the process schematically. The permeate can then be further treated or discharged, and the retentate can be returned to an earlier treatment step or withdrawn. Molecular separation size can be used as a characterization for pore membranes, UF is covering a range between 10 to 7000 kDa [49]. UF appears to be a particularly advantageous technology for the treatment of SWW, as it is able to separate most of the solids from the wastewater at low operating costs, and hygienization can also be achieved, advantageous is as well the possibility of combination with biological processes such as mbr, which is an effective treatment option [6,50].

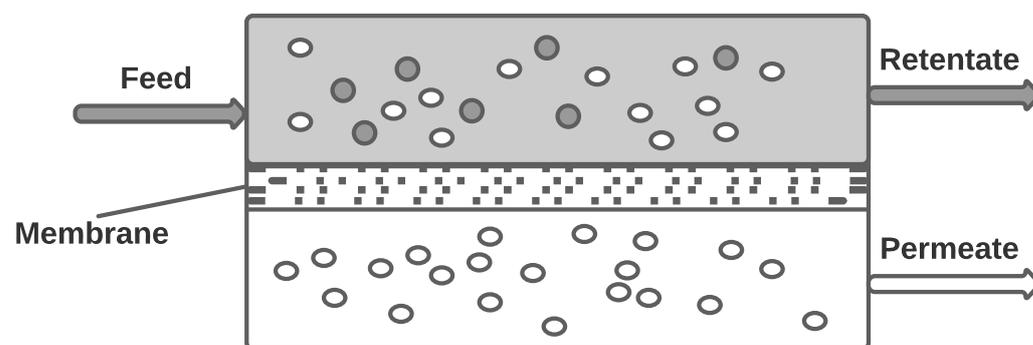


Figure 4. Membrane system schematic.

However, membrane fouling problems due to the accumulation of rejected particles on the membrane surface need to be addressed to avoid the decreasing permeate flux [51]. In this process, a blanket layer forms on the membrane surface, which has a significant influence on filter performance and transmembrane flux [49,52]. This can lead to a considerable reduction of the transmembrane flux after a short time, up to a point where there is almost no permeate flux [51]. However, this can be overcome by either pretreating the wastewater [51], flushing/cleaning the membrane regularly [52], and/or selecting operating conditions in terms of pressure and overflow velocity such that membrane fouling is minimized [49].

Avula et al. [53] investigated UF for the purpose of SWW reuse. The outcome was that UF for SWW treatment is a possible solution for wastewater management, as valuable products, such as crude proteins, can be separated by UF, thereby reducing the chemical oxygen demand of the process wastewater. They also pointed out some advantages for using the UF process, such as the compact configuration and the recovery of most of the total solids as byproducts. Pretreatment using DAF was recommended to minimize membrane blocking [53].

Malmali et al. [48] tested commercially available UF membranes which have nominal molecular weight cut-offs ranging between 10 and 300 kDa and made of different polymeric materials (polyethersulfone and regenerated cellulose) for the treatment of poultry SWW obtained from bird washer and chiller operations. Bird washer water and chiller water disposed of about $1400 \text{ mg}\cdot\text{L}^{-1}$ COD and $840 \text{ mg}\cdot\text{L}^{-1}$ COD, respectively. Using a regenerated cellulose membrane at an inlet pressure of 67.5 kPa, the highest removal of 79% COD was achieved for the chiller wash water. The removal efficiencies of TSS and FOG

were 100% and 98%, respectively. The use of polyethersulfone and regenerated cellulose for the treatment of bird washer water allowed the achievement of high removal rates: 100% for TSS and FOG. Moreover, significant removal of COD (up to 95%) was recorded for both membranes [48].

Other studies also investigated the treatment of SWW using UF. Marchesi et al. [54] used a polyethersulfone hollow-fiber UF membrane with 0.1 μm pore size and polyimide hollow fiber microfiltration membranes with 0.20 μm pore size for the treatment of wastewater collected separately from the carcass-chilling step. The final purpose of the treatment was the reuse of poultry pre-chiller wastewater. It was reported that the used membranes achieved high removal efficiencies of COD and total organic carbon (TOC) with 94% and 92%, respectively.

Sardari et al. [51] investigated the use of UF for SWW pretreated with electrocoagulation (EC). Using a laboratory membrane test system with a 1 L storage tank, experiments were carried out over 7 days with raw and pretreated SWW at 0.7 bar. A regenerated cellulose flat sheet membranes with a molecular separation size of 30 kDa were used. It was shown that the pretreatment had a positive influence on the fouling potential of the UF treatment. The permeate flux was reduced by over 91% for raw SWW after one day and decreased to almost zero after 3 days. For the pretreated SWW, the permeate flux was reduced from 106 to 22 $\text{L}\cdot\text{m}^{-2}\cdot\text{h}^{-2}$ after 7 days. However, the permeate flux continued to decrease until the end of the experiment. The treatment resulted in reductions for COD, TSS, and TN of 75%, 95%, and 50%, respectively.

Reverse Osmosis

Reverse osmosis (RO) presents an effective process as a refining treatment of SWW for reuse [55,56]. Coskun et al. [55] investigated different combinations of membrane technologies. This included the nanofiltration (NF)-only, RO-only, UF + NF and UF + RO treatment processes. It was found that the treatment with only RO achieved a COD removal efficiency of 97% and the COD concentration decreased from 7970 $\text{mg}\cdot\text{L}^{-1}$ in the influent to 10 $\text{mg}\cdot\text{L}^{-1}$ in the effluent. However, a stable permeate volume flow could not be maintained under these conditions. The UF and RO systems achieved the highest removal efficiency for COD with 99%.

Cristóvão et al. [57] studied the use of RO in the post-treatment of wastewater from the fish processing industry. They observed that after pretreatment by flocculation and activated sludge (AS) process, the reduction of TSS, DOC and electrical conductivity was 98, 99.8 and 99%, respectively. This allows the wastewater to be treated until it can be reused [57].

A challenge of the membrane treatment is fouling which declines the permeate flux due to the accumulation of the rejected dissolved solids, suspended solids and other components on the membrane surface [58]. Hence, a pretreatment step is necessary to avoid fouling. On the other hand, scaling effects can also occur if certain minerals are present in high concentrations. If appropriate, this can be prevented by adjusting the pH value and/or the addition of antiscalants [49]. A specific challenge in the use of RO is the retentate produced. Depending on the exact composition of the components, a complex concentrate treatment or a corresponding deposit may be necessary [59].

3.3.2. Electrochemical Treatment

Electrocoagulation

As addressed in Section 3.3.1, DAF and coagulation–flocculation are widely used for the removal of TSS, colloids, and fats from SWW. In EC, removal of organic matter, nutrients, heavy metals, and even pathogens can be achieved by introducing electric energy without adding chemicals [60,61]. Al, Fe, Pt, SnO_2 , and TiO_2 , among others, can be used as electrodes, with Fe and Al being the most commonly applied. The electrocoagulation (EC) process involves the on-site generation of M^{3+} ions using sacrificial anodes. In addition, these sacrificial anodes can interact with H^+ ions in an acidic medium, or with OH^-

ions in an alkaline medium [60,61]. Furthermore, the hydrogen gas is released at the cathode. Hence, $M(OH)_3$ compounds are formed and allow the adsorption of soluble organic compounds [61]. The principle of operation is shown in Figure 5.

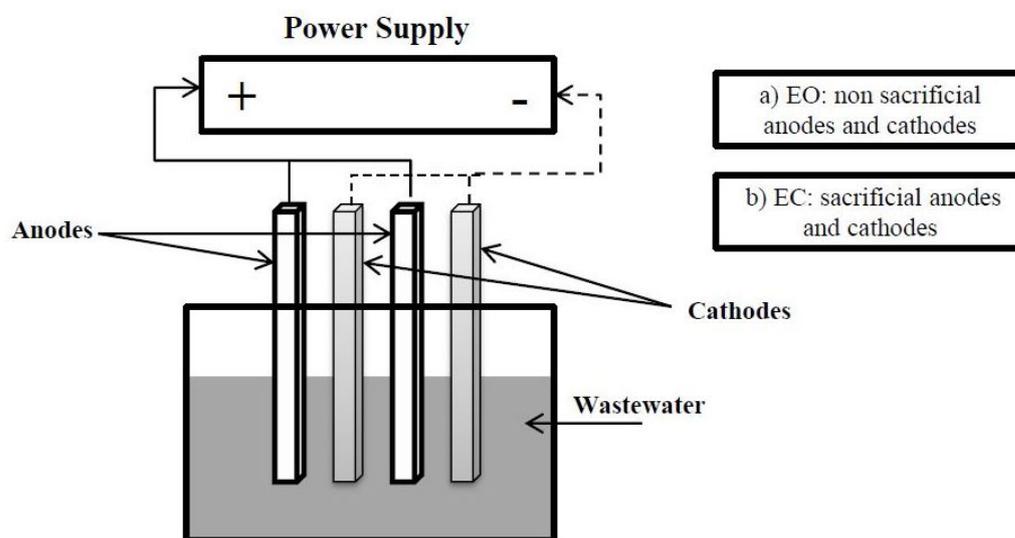


Figure 5. Electrochemical oxidation/Electrocoagulation conceptual diagram.

Recently, Sardari et al. [51] investigated EC as a pretreatment for UF membranes for SWW, with the intention to minimize membrane fouling and permeate flux reduction. The COD, TSS and SWW concentrations of the SWW were $1085 \text{ mg}\cdot\text{L}^{-1}$, $391 \text{ mg}\cdot\text{L}^{-1}$ and $235 \text{ mg}\cdot\text{L}^{-1}$, respectively. The EC system used in the mentioned study was composed of five aluminum electrodes with an effective surface area of 180 cm^2 per electrode, the experiments were conducted at 9 V. The comparison between the treatment of the SWW by individual UF and a hybrid system EC-UF showed an increase in the removal of COD, BOD_5 and FOG. The pretreatment with EC resulted in an increased COD reduction from 75% to 95%, as well as an almost complete reduction of TSS and FOG. This was achieved with an EC reaction time of 5 min, which corresponds to an energy consumption of $0.15 \text{ kWh}\cdot\text{m}^{-3}$.

Different research studies were interested in determining the optimum operating conditions for the highest performance of the process due to its effectiveness for the treatment of SWW. Thirugnanasambandham et al. [62] used an optimization method of the EC process. The system which is composed of iron electrodes with a total electrode surface area of 50 cm^2 achieved removal efficiencies of 92% and 98% for COD and turbidity, respectively, under the operating conditions: pH of 7, electrolysis time of 45 min, current density of $35 \text{ mA}\cdot\text{cm}^{-2}$ and electrolyte dose of $1.4 \text{ g}\cdot\text{L}^{-1}$. Under these conditions, the operating costs of $1.6 \text{ \$}\cdot\text{m}^{-3}$ were calculated with electricity costs of $0.085 \text{ \$}\cdot\text{kWh}^{-1}$.

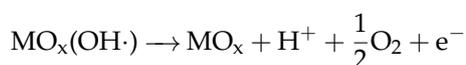
Likewise, Orssatto et al. [63] used the experimental design Rotatable Central Composite Design for the optimization of an electrocoagulation process used as a pretreatment step for wastewater from a slaughterhouse and packing plant. The reactor which is composed of aluminum electrodes achieved high removal efficiencies of turbidity and COD with 99% and 81%, respectively. Optimum operating conditions were at 25 min with 25 V and a current density of $21.6 \text{ mA}\cdot\text{cm}^{-2}$. This would result in an energy consumption of $14.175 \text{ kWh}\cdot\text{m}^{-3}$.

Recently, Eryuruk et al. [64] investigated the EC process using iron electrodes with supporting electrolyte (Na_2SO_4). Moreover, the peroxy-electrocoagulation method, which consists in adding H_2O_2 was investigated. Highly reactive hydroxyl radicals ($\text{OH}\cdot$) with non-selective oxidation effects are produced. The EC process achieved a COD removal efficiency of 89% at a current density of $50 \text{ mA}\cdot\text{cm}^{-2}$ for a treatment time of 38 min. In fact, the COD concentration decreased from $8800 \text{ mg}\cdot\text{L}^{-1}$ to $1000 \text{ mg}\cdot\text{L}^{-1}$. The treatment efficiency

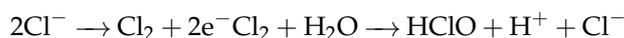
increased with the addition of 0.2 MH_2O_2 to reach 95% with a final COD concentration of $425 \text{ mg}\cdot\text{L}^{-1}$ for a current density of $50 \text{ mA}\cdot\text{cm}^{-2}$ and an initial pH of 3. This treatment would require an energy demand of $20.5 \text{ kWh}\cdot\text{m}^{-3}$.

Electrochemical Oxidation

Besides EC, electrochemical oxidation (EO) was found to be a promising technology for the treatment of poultry slaughterhouse wastewater (PSHWW). The principle of operation of the electrochemical oxidation is shown in Figure 5. Treatment by electrochemical oxidation (EO) allows theoretically the complete mineralization of organic pollutants. Furthermore, EO allows the oxidation of highly toxic pollutants [65]. Wastewater treatment by EO involves two mechanisms which are direct and indirect oxidation processes. The direct oxidation concerns the anodic oxidation by hydroxyl radicals ($\text{OH}\cdot$), which are first adsorbed on the anode electrode. Afterwards, they produce oxygen according to the following reactions:



The indirect oxidation process occurs through the electro-generation of strong oxidizing agents, such as active chlorine, hydrogen peroxide and peroxodisulfuric acid. Active chlorine is the most common oxidizing agent generated from chloride oxidation and the reactions take place as follows:



Abdelhay et al. [66] investigated anodic oxidation using boron-doped diamond electrodes for the post-treatment of poultry slaughterhouse wastewater (PSHWW) which was already centrifugated and sieved. The process achieved a high COD removal efficiency of 100% and a turbidity removal of about 75% at a current density of $2.55 \text{ mA}\cdot\text{cm}^{-2}$ and a treatment time of 200 min. It is worth noting that the addition of both 1% of Na_2SO_4 as a supporting electrolyte and 2% of FeCl_3 as an electrocoagulant allowed the removal of 72% of COD at a current density of $3.83 \text{ mA}\cdot\text{cm}^{-2}$. The results were explained by the production of Fe^{3+} and Fe^{2+} , which can either combine with hydroxyl-ions—leading to electrocoagulation—or H_2O_2 generated by Na_2SO_4 , which is then followed by an electro-Fenton reaction. It was found that the use of NaCl with a concentration of 1% as a supporting electrolyte in the anodic oxidation for the treatment of PSHWW achieved a high removal efficiency of COD with more than 90% after 100 min of treatment at $3.83 \text{ mA}\cdot\text{cm}^{-2}$ [66].

Likewise, the study conducted by Ozturk and Yilmaz [67] confirmed these findings. In fact, the NaCl at 0.1 M concentration dominated NaNO_3 and Na_2SO_4 for the removal of TSS, TOC, COD, TN and color with 100%, 93.5%, 96.2%, 94.2% and 100%, respectively, for a treatment time of 4 h at $4.73 \text{ mA}\cdot\text{cm}^{-2}$. The high efficiency of NaCl was explained by the fact that it allows the production of active chlorine species which are characterized by their strong oxidizing effect. Optimum parameters for the treatment efficiency and energy consumption were found at a pH of 7.03, a current density of $4.73 \text{ mA}\cdot\text{cm}^{-2}$, a NaCl concentration of 0.025 M, and a reaction time of 4 h.

In the study conducted by Ghazouani et al. [68], PSHWW was subjected to two types of electrochemical treatment processes. These were: electrochemical oxidation/reduction (EOR) using a bipolar cell with boron-doped diamond supported on silicon electrodes and EC using mild steel electrodes in a parallel configuration. Both treatment processes were either used separately or combined. The PSHWW was characterized by COD, $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$, and $\text{PO}_4\text{-P}$ concentrations of $2366 \text{ mg}\cdot\text{L}^{-1}$, $0.4 \text{ mg}\cdot\text{L}^{-1}$, $105 \text{ mg}\cdot\text{L}^{-1}$ and $19 \text{ mg}\cdot\text{L}^{-1}$,

respectively. The electrochemical oxidation/reduction (EOR) process alone was able to remove 97% of COD and 99% of nitrate at a current density of $36 \text{ mA}\cdot\text{cm}^{-2}$ after 6 h of treatment time with a final effluent concentration of $73 \text{ mg COD}\cdot\text{L}^{-1}$. The recorded consumed electric energy for the treatment of PSHWW using EOR was about $0.2 \text{ kWh}\cdot(\text{g COD})^{-1}$. The process achieved a COD removal of 89% after 6 h of treatment at a current density of $5 \text{ mA}\cdot\text{cm}^{-2}$. In contrast to the EOR, which resulted in an increase of $\text{PO}_4\text{-P}$ concentration from 19 to $25 \text{ mg}\cdot\text{L}^{-1}$, the EC allowed a total removal of phosphorous after 30 min of treatment. It was demonstrated that although the combination of 1 h of EC treatment followed by 3 h of EOR achieved a higher COD removal efficiency, it consumed more energy with a recorded electrical energy consumption of $0.26 \text{ kWh}\cdot(\text{g COD})^{-1}$. Table 5 summarizes some examples related to the treatment of PSHWW using electrochemical treatment.

Table 5. Treatment of SWW with electrochemical treatment.

Treatment Technology	Removal Efficiencies	Energy Consumption	Reference
Electrocoagulation (EC) (PSHWW: $3000 \text{ mg COD}\cdot\text{L}^{-1}$)	TSS: 89% Turbidity: 90% BOD: 86% FOG: 99%	$4.2 \text{ kWh}\cdot\text{m}^{-3}$	[69]
Peroxy-electrocoagulation (PSHWW: $8800 \text{ mg COD}\cdot\text{L}^{-1}$)	COD: 95%	$20.5 \text{ kWh}\cdot\text{m}^{-3}$	[64]
Anodic oxidation (PSHWW: $1370 \text{ mg COD}\cdot\text{L}^{-1}$)	COD: 100%	$170 \text{ kWh}\cdot\text{m}^{-3}$	[66]
Oxidation/reduction (EOR)	COD: 97%	$185 \text{ kWh}\cdot\text{m}^{-3}$	[68]
Electrocoagulation (EC)	COD: 89%	$13 \text{ kWh}\cdot\text{m}^{-3}$	[68]
Hybrid system EOR + EC	COD: 96%	$90 \text{ kWh}\cdot\text{m}^{-3}$	[68]
Hybrid system EC + EOR	COD: 98%	$88 \text{ kWh}\cdot\text{m}^{-3}$	[68]

3.3.3. Biological Treatment

Biodegradation of organic contaminants in SWW offers the possibility of cost-effective wastewater treatment [6]. Biological treatment is commonly used as a secondary process in SWW treatment, where aerobic and anaerobic digestions are used as single or combined processes, depending on the characteristics of the SWW to be treated [5]. This process can remove organic matter, nitrogen, phosphorus and possibly pathogens from the wastewater using microorganisms. It is capable of removing up to 90% COD and 85% TN from wastewater [13,18].

Activated Sludge Process

Various reactor types exist for the aerobic biological treatment of SWW. Among the biological treatment technologies that have been investigated for the treatment of SWW is the moving bed biofilm reactor (MBBR). This technology is based on the growth of the active biofilm on carriers either made with plastic composed of polyethylene granular particles, polyethylen or with polyurethane foam material with open pore size structure, which is kept moving inside the reactor [70]. The moving bed biofilm reactor (MBBR) reactor, which was adopted by Baddour et al. [70] for the treatment of PSHWW, achieved removal efficiencies of COD, TDS and phosphate with 94%, 50% and 38%, respectively.

Rajab et al. [71] investigated the treatment of SWW using an integrated anaerobic/aerobic sequencing batch reactor (SBR) on a laboratory scale. The process was stable up to an organic loading rate (OLR) of $4.5 \text{ kg}_{\text{COD}}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ at a hydraulic retention time (HRT) of 48 h, establishing an F/M ratio of $0.24 \text{ mg}_{\text{BOD}}\cdot\text{d}^{-1}\cdot\text{mg}^{-1}_{\text{MLSS}}$. Thereby, an average removal efficiency for COD, $\text{NH}_3\text{-N}$, and TSS of 97%, 98%, and 96%, respectively, was obtained.

Keskes et al. [72] investigated the performance of a submerged membrane bioreactor (SMBR) for the treatment of SWW with an initial average COD concentration of $2040 \text{ mg}\cdot\text{L}^{-1}$. The submerged membrane bioreactor (SMBR) showed a high removal efficiency of COD with more than 98%. In fact, the COD concentration decreased from $2040 \text{ mg}\cdot\text{L}^{-1}$ to $10 \text{ mg}\cdot\text{L}^{-1}$ after 70 days of operation. Furthermore, the reactor achieved a complete TSS removal with a starting concentration of $1450 \text{ mg}\cdot\text{L}^{-1}$ due to the UF membrane.

Anaerobic Treatment

Besides aerobic treatment, biological treatment also encompasses anaerobic treatment technologies. For anaerobic treatment of SWW, the following conditions should be met. The COD concentration should be between 1.5 and $40 \text{ g}\cdot\text{L}^{-1}$ to ensure economic viability at least 500 kg COD per day should be treated, the dry matter should be less than 15% and the N/C ratio between $1/5$ and $1/20$, whereby a COD reduction of at least 50% can be achieved [18].

An already applied technology for the anaerobic treatment of SWW is the treatment via upflow anaerobic sludge blanket (UASB) reactors. The UASB reactor was investigated for the treatment of SWW under different OLR. The reactor achieved a COD removal of 90% at an OLR of $0.4 \text{ g}\cdot\text{L}^{-1}\cdot\text{d}^{-1}$ dropping to 70% at $3 \text{ g}\cdot\text{L}^{-1}\cdot\text{d}^{-1}$ to 65% at $10 \text{ g}\cdot\text{L}^{-1}\cdot\text{d}^{-1}$ and below 50% following the increase of the OLR to $15 \text{ g}\cdot\text{L}^{-1}\cdot\text{d}^{-1}$. Furthermore, the biogas production was about $5 \text{ L}\cdot\text{d}^{-1}$ and the methane yield reached $0.38 \text{ L CH}_4\cdot(\text{g COD}_{\text{added}})^{-1}$ at an OLR of $10 \text{ g}\cdot\text{L}^{-1}\cdot\text{d}^{-1}$. The authors confirmed that the UASB reactor could be a good alternative not only as a treatment technology but also as a method to convert waste into energy through methane production [73].

Loganath and Mazumder [74] used a hybrid UASB containing polypropylene media as attached growth surface. The addition of these media allowed the enhancement of TOC and TSS removal efficiency. Thus, the hybrid upflow anaerobic sludge blanket reactor achieved a high removal efficiency of 95% for a TOC loading rate of $7 \text{ kg TOC}\cdot\text{m}^{-3}\cdot\text{d}^{-1}$ at a hydraulic retention time (HRT) of 10 h. Moreover, the removal efficiencies for TOC and TSS were up to 96% and 98%, respectively.

In the comparative study of Chollom et al. [75], an attempt was made to find the ideal operating conditions for UASB in the treatment of SWW. It was found that the best performance can be achieved at $35 \text{ }^\circ\text{C}$, a HRT of 15 h, an OLR of $3.5 \text{ g COD}\cdot\text{L}^{-1}\cdot\text{d}^{-1}$ and a pH of 7. As a result, biogas production of $0.46 \text{ L}_{\text{biogas}}\cdot\text{gCOD}_{\text{rem.}}^{-1}$ and COD removal of 80% could be achieved.

In the anaerobic fermentation of protein-rich substrates, there is a risk of biological inhibition due to an increased ammonium concentration [76]. In the study of Wang et al. [77], it was investigated whether this challenge could be overcome by separating acidogenesis and methanogenesis spatially. A methane yield of $384 \text{ mL CH}_4\cdot\text{g COD}_{\text{added}}^{-1}$ and a COD reduction of 68% was achieved at an OLR of $0.7 \text{ g COD}\cdot\text{L}^{-1}\cdot\text{d}^{-1}$. For substrates with particularly high nitrogen concentrations, a struvite precipitation between pre-acidification and methanogenesis can also be applied to increase the methane yield [76].

Microalgal-Bacterial Process

Another approach for the biological treatment of SWW which promises to require less energy is the microalgal-bacterial process. In this process, the algae absorb the nutrients present in the wastewater for their growth, thus resulting in a reduction of the pollutant load. In addition, oxygen is produced by microalgae from carbon dioxide, which is then used by aerobic bacteria to metabolize organic matter present in the wastewater. This treatment method appears to be an environmentally friendly solution for the treatment of wastewater with low investment costs, but no large-scale application has been realized up to date [78–81].

The treatment of SWW by Hilares et al. [80] with Microalgae (*Chlorella vulgaris*) cultivation showed high removal efficiency of 83% of COD. The SWW was preceded by a precipitation step using acid solution (H_2SO_4). Hence, concentration of COD and TN decreased from 1500 to 100 $\text{mg}\cdot\text{L}^{-1}$ and from 120 to 50 $\text{mg}\cdot\text{L}^{-1}$, respectively [80].

Akizuki et al. [82] investigated nitrogen removal of digestate from anaerobic SWW treatment using microalgal-nitrifying bacterial. The removal of ammonia was observed, at an initial concentration of 100 $\text{mg}\cdot\text{L}^{-1}$, a reduction of 80% was achieved without aeration at a light intensity of 140 $\mu\text{mol}_{\text{photons}}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$.

Since good reductions of water impurities could be achieved on a laboratory scale with this treatment method without major energy input for aeration or the like, this approach appears to be a promising alternative to conventional activated sludge processes. However, challenges remain for large-scale implementation, especially in the area of non-sterile wastewater [78].

4. Slaughterhouse Wastewater Recycling Opportunities

After discussing the individual treatment options, this section first discusses publications that describe the reuse of SWW through combined treatment with specific examples. In conclusion, recommendations for processes for the purpose of SWW recycling are derived. It is important to highlight that for the development of the treatment models, it was assumed that different technologies maintain the same performance either at lab-scale or full-scale level.

4.1. Combined Treatment Examples

In the study conducted by Keskes et al. [72], the treatment of SWW using an submerged membrane bioreactor (SMBR) was examined. The wastewater was pretreated with a screen and a DAF. The submerged membrane bioreactor (SMBR) was operated with a reactor volume of 15 L for 115 days. From day 70, the operation was without sludge discharge. The process is shown in Figure 6. A polysulfone membrane with a pore size distribution of 0.03–0.4 μm was used. The system operated at a constant flux of 4.7 $\text{L}\cdot\text{h}^{-1}\cdot\text{m}^2$ and a transmembrane pressure between 0.08 and 0.5 bar. In Table 6, the inlet and outlet values of the SMBR are listed. COD values could be reduced from an average of 2040 $\text{mg}\cdot\text{L}^{-1}$ down to 10 $\text{mg}\cdot\text{L}^{-1}$. With regard to the TSS value, a reduction from 1450 $\text{mg}\cdot\text{L}^{-1}$ to under the limit of detection was achieved in the permeate. A measured value for the TN and phosphates in the permeate was not published. Therefore, an assessment of the quality of the effluent water is not conclusive. However, in the work itself, the water treated by the membrane bioreactor was classified as suitable for the fourth category which was mentioned above related to agricultural irrigation [72].

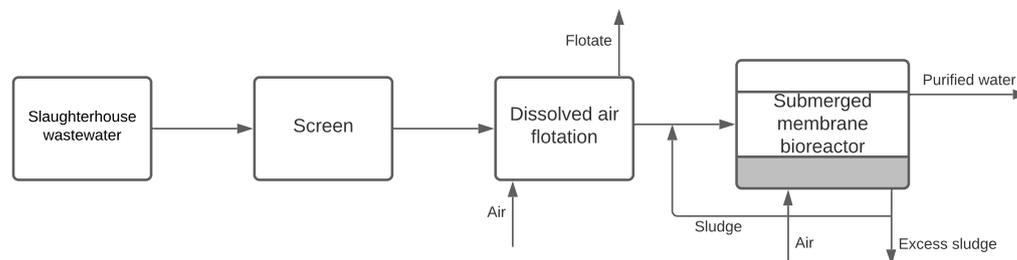


Figure 6. Flow sheet [72].

Coskun et al. [55] examined the treatment of poultry SWW using UF, NF and RO. In this study, the samples were pretreated with a centrifuge at 3750 rpm for 10 min. Subsequently, experiments were carried out with an NF membrane and an RO membrane. These tests were carried out with and without UF. As the best results were obtained with UF + RO, only these experiments will be considered here. The process is shown in Figure 7. A polysulfone UF membrane with a molecular weight-cut-off of 30 kDa was used. A

thin-film membrane with a molecular weight-cut-off of 150 to 300 Da was used as NF, and a polyamide brackish water membrane for RO, respectively. The membrane separation tests were carried out over 160 min at transmembrane pressures of 5, 10, 15, 20, and 25 bar, with the most stable performance being achieved at 20 and 25 bar. The highest flux was measured with the combination of UF and RO at $30 \text{ L}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, which remained stable over the period of the experiment. The characteristics of the wastewater and the influent and effluent of the treatment are shown in Table 6. RO shows the highest efficiency, the COD concentration can be decreased to $<10 \text{ mg}\cdot\text{L}^{-1}$. The very important values for nitrogen concentration both before and after treatment are not given. Therefore, an assessment is not entirely possible. In the publication itself, the treated water is classified as suitable for the second category related to the process water reuse.

Racar et al. [56] investigated rendering plant wastewater treatment and reuse opportunities. The process studied, consisted of sequential batch reactor—sand filter—UF—NF and RO. The process is shown in Figure 8. For UF, three membranes were tested with a molecular weight-cut-off at 50, 20 and 8 kDa and working pressures of 2.4 and 5 bar. After 9 h filtration, all membranes showed a comparable flux of $18.5 \text{ L}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$ and similar filter properties. Two membranes were tested for NF, the NF270 with a molecular weight-cut-off of 150 Da and the NF90 with 100 Da. In comparison, an XLE membrane with a molecular weight-cut-off of 100 Da was used for RO. All three membranes are made of polyamide and were operated at a pressure of 10 bar. The obtained flux for NF270 was about $85 \text{ L}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$, and, for NF90 and XLE, about $40 \text{ L}\cdot\text{h}^{-1}\cdot\text{m}^{-2}$. The filtration performance of the three membranes was comparable, except the nitrogen retention showing a significantly lower removal efficiency of the NF270 membrane. Looking at the qualities of the RO permeate in Table 7, it can be concluded that the conditions for category 2 and 4 are met. However, for the assessment of category 2, a value for nitrate is missing. According to their own statements, the permeate could be used for several applications in the rendering plant, such as cleaning of vehicles and factory floors. This corresponds also to water used in the third category [56].

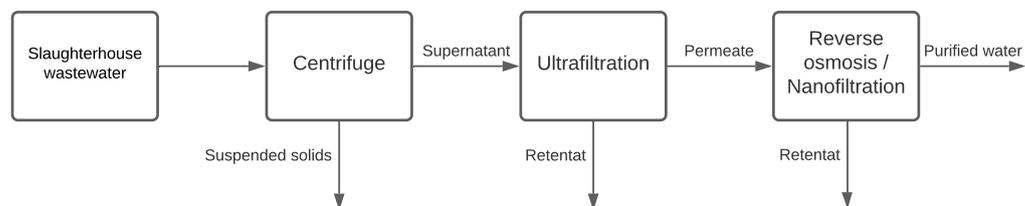


Figure 7. Flow sheet [55].

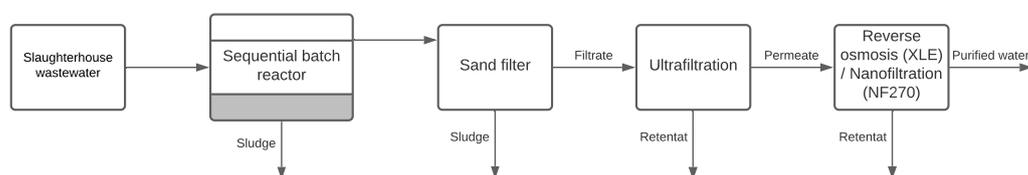


Figure 8. Flow sheet [56].

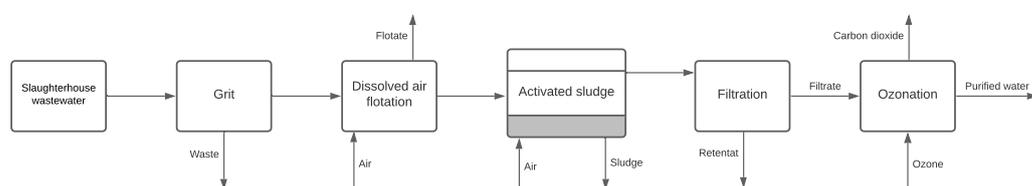
Table 6. Purification potential of combined treatments.

Parameter	Unit	DAF-SMBR [72]		Centrifuge-UF-RO [55]		SBR-UF-RO [56]		DAF-AS-O ₃ [83]		ABR-AS-UV/H ₂ O ₂ [5]	
		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
COD	[mg·L ⁻¹]	2000	10	7970	<10	5100	4	1800	130	1950	0.4
BOD ₅	[mg·L ⁻¹]	-	-	-	-	-	-	650	12	1400	-
TSS	[mg·L ⁻¹]	1450	n.d.	2760	n.d.	-	-	250	3	750	0.8
TN	[mg·L ⁻¹]	550	-	-	-	340	25	225	115	200	<8
PO ₄ ³⁻	[mg·L ⁻¹]	23	-	-	-	-	-	-	-	-	-
Conductivity	[μS·cm ⁻¹]	-	-	2750	94	2790	170	-	-	-	-

Table 7. Characterization of treatment process investigated by Racar et al. [56].

Parameters	Unit	Raw Wastewater	SBR	UF	NF	RO
COD	[mg·L ⁻¹]	5100	116	13	<1	4
TC	[mg·L ⁻¹]	358	67	46	8	8
IC	[mg·L ⁻¹]	122	39	32	4	3
DOC	[mg·L ⁻¹]	236	29	7	5	4
TN	[mg·L ⁻¹]	340	93	95	20–90	25
Conductivity	[μS·cm ⁻¹]	2790	1111	-	167	167

A process for SWW treatment via oxidation was investigated by Alfonso et al. [83]. For this purpose, the wastewater was pretreated by grit removal - coagulation/flocculation and DAF. The effluent of the DAF is the inlet presented in Table 6. Further treatment was carried out using activated sludge (AS)-filtration-ozonation. The process is shown in Figure 9. The 6 L AS reactor was operated in semi-batch mode with a hydraulic retention time of 24 h, a solid retention time of 13 days, a mixed liquor volatile suspended solids (MLVSS) to mixed liquor suspended solids (MLSS) ratio of 26–32% and an F/M ratio of 0.65 mg_{BOD}·d⁻¹·mg⁻¹_{MLVSS}. The treated water was filtered through a filter paper with a pore size between 4 and 7 μm. For ozonation, 400 mL of the filtrate was exposed to a fixed dose of 71 ± 17 mg O₃·L⁻¹ at a hydraulic retention time of 12 h. The characteristics of treated water are summarized in Table 6. The AS process was not designed for nitrogen removal and, therefore, the efficiency achieved in the process was lower than that reported in the literature for nitrogen removal. The analysis of the results show that the COD and TN are still too high for direct reuse. With regard to the assessment of treated water, according to its own statement, the water can meet the requirements for category 3 reuse without product contact.

**Figure 9.** Flow Sheet [83].

Bustillo-Lecompte and Mehrvar [5] researched a process for SWW reclamation without membrane separation processes. Here, the systems anaerobic baffled reactor (ABR) and aerobic AS bioreactor were combined as biological treatment. In order to reach wastewater recycling requirements, the purified water was further treated with an advanced oxidation process using a combination of ultraviolet light and hydrogen peroxide. The process is shown in Figure 10. The biological stage consisted of a 36 L ABR with five equal volume chambers and a 12.65 L AS reactor. In the ABR and the AS, a biomass concentration of 24 and 2.8 g·L⁻¹ volatile suspended solids (VSS) was achieved, respectively. The food to microorganism ratio (F/M) was 0.46 mgO₂·mg_{VSS}⁻¹. A methane yield of 2.21 L CH₄·kg TOC_{removed}⁻¹ is reported [84].

For the oxidative post-treatment, a 1.35 L UV photoreactor with recirculation, and an output power of 6 W and uniform light distribution was used. Table 6 shows the specified parameters of the purified water. According to this information, the purified water meets the requirements for process water reuse and can therefore be classified as category 2 [5,19].

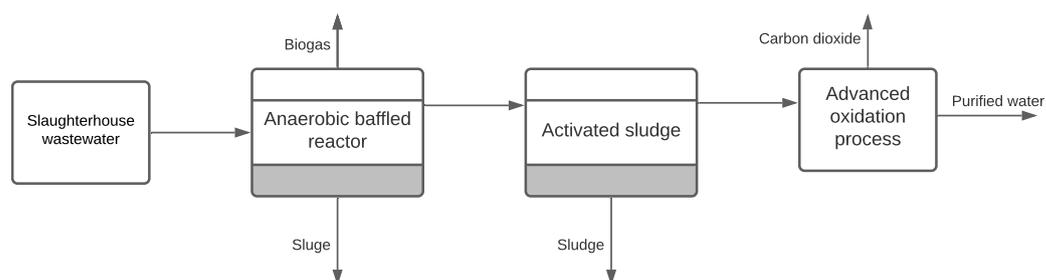


Figure 10. Flow sheet [5].

4.2. Suggestions and Assessment for Slaughterhouse Wastewater Treatment

Two models for slaughterhouse wastewater recycling were developed and balanced based on the presented examples and taking into consideration the state of the art in slaughterhouse wastewater treatment. These models examine two theoretical opportunities for SWW recycling and evaluate them in regard to their performance and potential applications. In order to characterize the theoretical raw wastewater, the mean concentrations of [18] presented in Table 1 were used as an example. Therefore, this theoretical wastewater has a volumetric flow rate of $100 \text{ m}^3 \cdot \text{d}^{-1}$, an electrical conductivity of $2500 \text{ }\mu\text{S} \cdot \text{cm}^{-1}$, and concentrations for COD, TN, and TP of $5000 \text{ mg} \cdot \text{L}^{-1}$, $300 \text{ mg} \cdot \text{L}^{-1}$, and $30 \text{ mg} \cdot \text{L}^{-1}$, respectively. The literature values from Section 3.3 were used to calculate the reductions of the individual fractions.

The first option presented in Figure 11 was developed referring to Bustillo-Lecompte and Mehrvar [5]. In this model, an anaerobic reactor was selected as the first process step in order to be able to use a high proportion of the biomass for methane production. In addition to the anaerobic reactor, an AS process was proposed to further remove organic matter and nitrogen from the wastewater. A bypass was integrated around the anaerobic stage to provide sufficient carbon for nitrogen removal. The final step of the treatment is an advanced oxidation process to remove the remaining organic compounds in the water and to ensure hygienization [5]. The evaluation of the model in terms of its water reusability was based on the quality of the effluent of the oxidation process. In total, for the parameters COD, TN and TP, a reduction of 99%, 76% and 33% can be achieved, respectively. However, there is no reduction in electrical conductivity, consequently, an application as boiler feed water is excluded and, for others, the sensitivity towards salts has to be evaluated [85]. The comparison between the quality of the effluent and the limits for wastewater reuse from Table 3 leads to match category 3 (reuse without product contact) and category 4 (agricultural irrigation). For category 2 (process water reuse), the electrical conductivity is exactly at the limit value and a value for nitrite is missing, so it is not clear whether this value could be exceeded with the residual nitrogen contained, therefore an evaluation of this category is excluded here.

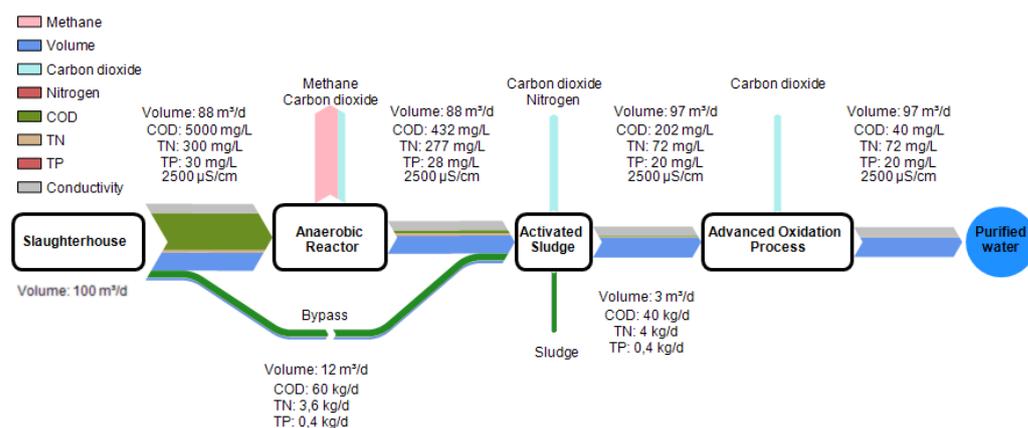


Figure 11. Sankey diagram and flow scheme for option 1.

The second option presented in Figure 12 is an example of the treatment processes using membrane separation processes as a final treatment step. DAF was chosen as the first stage in this model. In this way, it is possible to remove not only most of the suspended solids, but also most of the fats from the wastewater [6,11]. Similar to the first option, the nitrogen is then removed from the wastewater by means of an AS process. The final wastewater treatment is carried out by a combination of UF followed by RO [55,56]. In this model, there is no energy recovery in the form of biogas, but the flotates collected from DAF can be used for on-site anaerobic digestion or as co-substrate in a larger biogas plant [18]. In addition, this would allow co-digestion of slaughterhouse waste for higher biogas yields [77]. For the parameters COD, TN, TP, and electrical conductivity, this model resulted in a overall reduction of more than 99%, 98%, 99%, and 95%, respectively. The assessment of the permeate stream of the RO in this model, in terms of its reusability, shows that the quality of the effluent meets the requirements of category 1 to 4. Therefore, even direct process water reuse would be possible in theoretical terms.

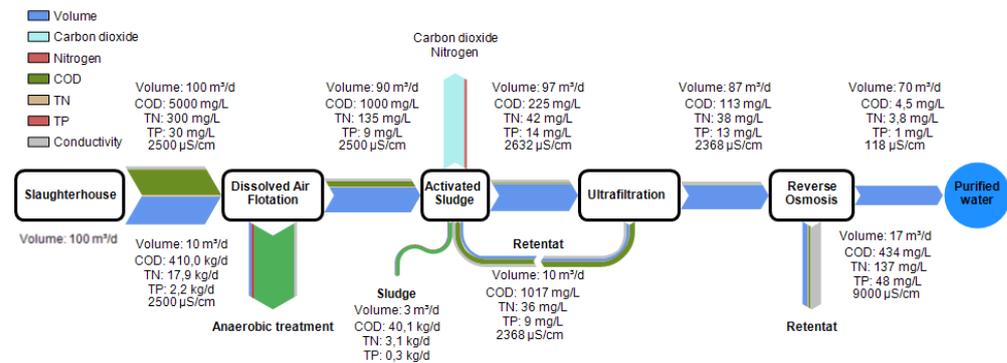


Figure 12. Sankey diagram and flow scheme for option 2.

According to these two models, both process combinations are suitable for treating SWW for reuse. For a real application, the specific characteristics of the wastewater and the reuse objective should be considered in detail. In regard to the question of whether the DAF is the appropriate first treatment process, or whether an anaerobic process can be used directly, it should be noted that a minimum quantity of 500 kg COD per day should be available for economic anaerobic treatment. By using the DAF, this can be partially avoided, as the flotates can be used as a partial substrate in a larger biogas plant or slaughterhouse waste can be included in the anaerobic treatment and the necessary requirements can be met. Therefore, direct anaerobic treatment of SWW can be recommended for large slaughterhouses. For slaughterhouses where these conditions are not met, DAF can be considered as an efficient first wastewater treatment step. Despite these models, laboratory and pilot tests should be carried out in advance of an industrial application, in order to ensure process reliability.

4.3. Energetic Assessment of the Processes

Apart from the technical feasibility, investment costs and the cleaning performance, the energy consumption is important to evaluate a process. Table 8 shows the average energy consumption for each individual treatment. The calculated energy demand is 135 kWh·d⁻¹ for option 1 and 150 kWh·d⁻¹ for option 2. The produced methane for option 1 with a biogas composition of 65%vol methane and 35%vol CO₂, a methane yield of 0.3 Nm³ CH₄·(kg COD_{removed})⁻¹ and an electrical energy output of 3.5 kWh_{el}·Nm⁻³ leads to an energy production of 420 kWh_{el}·d⁻¹. Assuming that the DAF flotates is used for anaerobic methane production in option 2, the net energy gain is 385 kWh_{el}·d⁻¹. It must be noted that used consumables and chemicals, the necessary treatment of the excess sludge as well as the brine management were not considered in this calculation. However, due to the biogas utilization, an energy self-sufficient treatment of SWW can be considered. Figure 13 shows the energy outcome of both models as a flow chart.

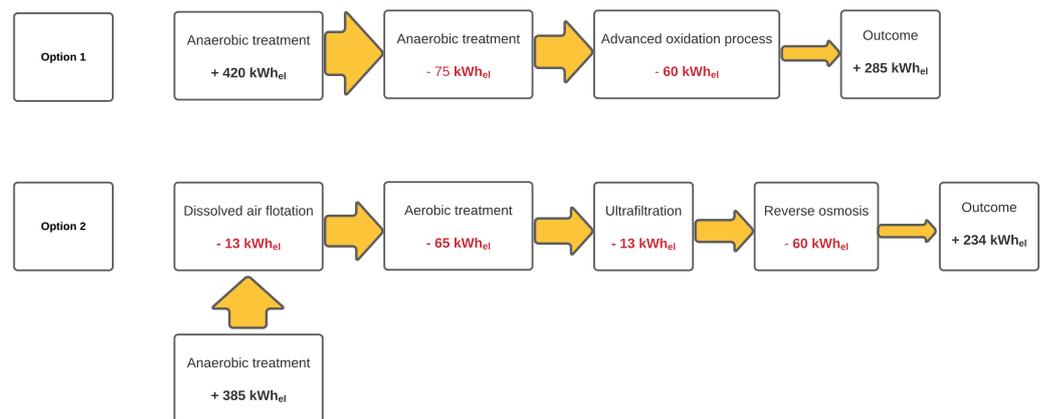


Figure 13. Energy outcome of the models.

Table 8. Energy consumption of the treatment processes.

Process	Electrical Energy Consumption	Unit	Reference
Dissolved air flotation	0.03	kWh·m ⁻³	[86]
	0.05–0.30	kWh·m ⁻³	[18]
Aerobic activated sludge treatment	0.62	kWh·m ⁻³	[87]
	0.49–0.71	kWh·m ⁻³	[88]
	0.61	kWh·m ⁻³	[89]
	0.45–1.50	kWh·m ⁻³	[18]
Ultrafiltration	0.10–0.16	kWh·m ⁻³	[90]
Reverse osmosis	0.50–0.75	kWh·m ⁻³	[91]
	0.75–0.80	kWh·m ⁻³	[92]
Advanced oxidation processes (UV/H ₂ O ₂)	0.50–0.68	kWh·m ⁻³	[93]
Electrochemical oxidation	10.0–14.0	kWh·m ⁻³	[93]

5. Conclusions

In this study, recycling possibilities of treated wastewater were classified into four categories which are namely: wastewater discharge, process water reuse, reuse without product contact, agricultural irrigation. Moreover, requirements related to the quality of the wastewater were presented for each category according to the state of the art.

In the case of the European Union, the amendment of the EU Drinking Water Regulation 2016 allows the use of sources other than drinking water as process water in the food industry, if it can be ensured that no impairment of the product is possible [23]. Thus, treated wastewater is possible for reuse as long as all requirements are met. Depending on the purpose of reuse, different wastewater treatment processes can be used.

Two model options were developed. Thereby, it was found that SWW treatment for reuse is possible in theory. The results showed that the quality of the water produced by Option 2 is suitable for Category 2 process water reuse and Category 3 reuse without product contact, respectively, and the water produced by Option 1 is suitable for Category 3 reuse without product contact. It was found that energy consumptions were close for option 1 and option 2 with 135 kWh_{el}·d⁻¹ and 150 kWh_{el}·d⁻¹, respectively.

The results of this review offer data to industrialists, authorities and main actors in the field of wastewater management on the different options for the sustainable treatment of slaughterhouse wastewater. Hence, it was demonstrated that the proposed treatment combinations allow not only the decrease of freshwater demand and the discharge of wastewater into environment through recycling but also the possible reduction of sludge disposal and operational cost through the production of biogas. In conclusion, SWW recycling is

theoretically possible and has already been implemented at a laboratory scale. Pilot-scale investigations are recommended to transfer water recycling into slaughterhouses.

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Abbreviations

The following abbreviations are used in this manuscript:

ABR	anaerobic baffled reactor
AS	activated sludge
BOD ₅	biological oxygen demand
COD	chemical oxygen demand
DAF	dissolved air flotation
EC	electrocoagulation
EO	electrochemical oxidation
EOR	electrochemical oxidation/reduction
FOG	fat oil and grease
HRT	hydraulic retention time
MBBR	moving bed biofilm reactor
MBR	membrane bioreactor
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
NF	nanofiltration
OLR	organic loading rate
PAC	polyaluminum chloride
PSHWW	poultry slaughterhouse wastewater
RO	reverse osmosis
SBR	sequencing batch reactor
SMBR	submerged membrane bioreactor
SWW	slaughterhouse wastewater
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TS	total solids
TSS	total suspended solids
UASB	upflow anaerobic sludge blanket
UF	ultrafiltration
VSS	volatile suspended solids

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