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Review

# Slaughterhouse wastewater characteristics, treatment, and management in the meat processing industry: A review on trends and advances

Ciro Fernando Bustillo-Lecompte [a], Mehrab Mehrvar [b, *]

[a] Graduate Programs in Environmental Applied Science and Management, Ryerson University, 350 Victoria Street, Toronto, ON, M5B 2K3, Canada
[b] Department of Chemical Engineering, Ryerson University, 350 Victoria Street, Toronto, ON, M5B 2K3, Canada

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ABSTRACT

A thorough review of advancement in slaughterhouse wastewater (SWW) characteristics, treatment, and management in the meat processing industry is presented. This study also provides a general review of the environmental impacts, health effects, and regulatory frameworks relevant to the SWW management. A significant progress in high-rate anaerobic treatment, nutrient removal, advanced oxidation processes (AOPs), and the combination of biological treatment and AOPs for SWW treatment is highlighted. The treatment processes are described and few examples of their applications are given. Conversely, few advances are accounted in terms of waste minimization and water use reduction, reuse, and recycle in slaughterhouses, which may offer new alternatives for cost-effective waste management. An overview of the most frequently applied technologies and combined processes for organic and nutrient removal during the last decade is also summarized. Several types of individual and combined processes have been used for the SWW treatment. Nevertheless, the selection of a particular technology depends on the characteristics of the wastewater, the available technology, and the compliance with regulations. This review facilitates a better understanding of current difficulties that can be found during production and management of the SWW, including treatment and characteristics of the final effluent.
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## 1. Introduction

The increasing growth of world population has augmented the pollution of freshwater due to the inadequate discharge of wastewater, especially in developing countries (US EPA, 2004; Leitão et al., 2006; Gopala Krishna et al., 2009; Feng et al., 2009). For this reason, water and wastewater treatment has become crucial for the continuing development of the society. Moreover, the progressively stricter standards for effluent discharge worldwide have made the developing of advanced wastewater treatment technologies necessary (Environment Canada, 2000, 2012; US EPA, 2004; World Bank Group, 2007). Besides, the continuing decreasing availability of freshwater resources has rearranged the objectives in the wastewater treatment field from disposal to reuse and recycling. As a result, a high level of treatment efficiency has to be achieved. Given the differences in location, economic resources, living standards of different countries, and characteristics of water and its pollutants, many nations adopt diverse techniques for water and wastewater treatment (Daigger, 2009).

The meat processing sector produces large volumes of slaughterhouse wastewater (SWW) due to the slaughtering of animals and cleaning of the slaughterhouse facilities and meat processing plants (MPPs). The meat processing industry uses 24% of the total freshwater consumed by the food and beverage industry (Table 1) and up to 29% of that consumed by the agricultural sector worldwide (Mekonnen and Hoekstra, 2012; Gerbens-Leenes et al., 2013). SWW composition varies significantly depending on the diverse industrial processes and specific water demand (Matsumura and Mierzwa, 2008; Debik and Coskun, 2009; Bustillo-Lecompte et al., 2013, 2014). Slaughterhouses are part of a large industry, which is common to numerous countries worldwide where meat is an important part of their diet. Therefore, SWWs require significant treatment for a safe and sustainable release to the environment (Johns, 1995). Nevertheless, review articles on SWW and the meat processing industry are not widely available (Bull et al., 1982; Tritt and Schuchardt, 1992; Johns, 1995; Salminen and Rintala, 2002;

* Corresponding author.
*E-mail address:* mmehrvar@ryerson.ca (M. Mehrvar).

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**Table 1**
Freshwater consumption in beverage and food industries.

| Food industry | Water consumption (%) |
|---|---|
| Meat processing | 24 |
| Beverages | 13 |
| Dairy | 12 |
| Other food | 11 |
| Fruits and vegetables | 10 |
| Bakery and tortilla products | 9 |
| Grain and oilseeds | 9 |
| Sugar and confectionary | 5 |
| Animal food | 5 |
| Seafood | 2 |

Mittal, 2006; Arvanitoyannis and Ladas, 2008), rather characterization of microorganisms present in SWW and disinfection are the main focus in recent years (Franke-Whittle and Insam, 2013).

According to Mittal (2006), slaughterhouses and MPPs in Ontario, Canada, commonly discharge the SWW into the municipal sewer system after preliminary onsite treatment (Mittal, 2006). Thus, MMPs usually pay fines to dispose of their wastewater at municipal wastewater treatment plants (Massé and Masse, 2000). According to Wu and Mittal (2011), there are approximately 142 MPPs in Ontario that can process 100–200 animals per month. 53% of Ontario's slaughterhouses do not treat their wastewater prior to disposal. Only 16% of Ontario's slaughterhouses use dissolved air flotation (DAF) or aeration. The remaining 31% of slaughterhouses utilize passive systems such as storage tank or lagoon to settle solids.

This review aims to identify the most recent trends and advances in meat processing effluent management and SWW treatment technologies, common practices on storage, management, treatment, and disposal, along with SWW characteristics, guidelines, and regulations. Furthermore, this study presents current technologies based on the technical advances in efficiency, design, performance, and optimization of the SWW treatment processes for organics and nutrient removal, including biological treatment, combined processes, advanced oxidation processes (AOPs), and water reuse. Thus, the assessment of possible alternatives to minimize operational and maintenance (O&M) costs is also discussed.

## 2. Characterization of slaughterhouse wastewater

The global meat production was doubled in the last three decades (Mekonnen and Hoekstra, 2012; FAO, 2013). Bouwman et al. (2013) have projected a steady doubling growth of meat production until 2050. Furthermore, the production of beef has been increasing continuously in recent years, mostly in India and China due to income increases and the shift toward a western-like diet rich in proteins (Pingali, 2007). From 2002 to 2007, the annual global production of beef was increased to $14.7 \times 10^6$ metric tons, representing an increase of 29% over eight years (FAO, 2013). As a result, it can be inferred that the number of slaughterhouse facilities will increase, resulting in a greater volume of high-strength wastewater to be treated.

According to Table 1, the meat processing industry is one of the major consumers of freshwater among food and beverage processing facilities, which makes slaughterhouses a significant producer of wastewater effluents (De Sena et al., 2009). The World Bank Group (2007) classifies a slaughterhouse plant as a meat processing facility that may consume between 2.5 and 40 $m^3$ of water per metric tons of meat produced.

Common SWW characteristics have been described in previous studies and summarized in Table 2. SWW is usually evaluated in terms of bulk parameters due to the specific amounts of SWW and pollutant loads related to the animals slaughtered and processed that vary among the meat processing industry, usually containing considerable amounts of total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC), chemical oxygen demand (COD), total suspended solids (TSS), and biochemical oxygen demand (BOD) (Tritt and Schuchardt, 1992; Johns, 1995; Mittal, 2006; Cao and Mehrvar, 2011; Wu and Mittal, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014).

SWW is considered detrimental worldwide due to its complex composition of fats, proteins, and fibers from the slaughtering process (Johns, 1995; Ruiz et al., 1997; Wu and Mittal, 2011; Bustillo-Lecompte et al., 2014). The major part of the contamination is caused by blood and by stomach and intestinal mucus (Tritt and Schuchardt, 1992). Furthermore, SWW contains high levels of organics, pathogenic and non-pathogenic microorganisms, and detergents and disinfectants used for cleaning activities (Massé and Masse, 2000; Debik and Coskun, 2009). SWW samples also include nutrients, heavy metals, color, and turbidity, among others. It is also important to note that disinfectant, cleaning agents, and pharmaceuticals for veterinary purposes can be present in the SWW (Tritt and Schuchardt, 1992).

In the present study, a questionnaire was distributed to 128 slaughterhouses licensed by the Ontario Ministry of Agriculture and Rural Affairs (OMAFRA, 2014) in order to gather information on the current characteristics of the actual SWW, type of animals processed, and the type of treatment, storage, or disposal methods used in Ontario, Canada. Thirty-nine questionnaires were returned for an overall response rate of 30.47%. It was found that 51% of the MPPs do not treat their wastewater onsite; 17% use aerobic treatment, i.e. DAF; 32% utilize passive systems such as storage tanks to settle solids; and only 2% utilize grease trap for fat separation and blood collection. Moreover, a typical MPP in Ontario has been established more than 20 years ago, it operates 30 weeks per year, slaughters approximately 600 animals per day, with a maximum capacity of over 2500 animals/day, and mean water usage per day of 2000 $m^3$. Besides, there were 10 SWW samples taken from selected provincially licensed MPPs at the time of study. Table 3 shows overall SWW characteristics gathered from the returned questionnaires and the 10 SWW samples.

## 3. Slaughterhouse wastewater guidelines and regulations

Regulations and guidelines are essential components in dealing with the environmental impact of slaughterhouses in the meat processing industry. The treatment systems used in the meat processing industry are commonly viewed as a regulatory requirement. Therefore, it increases capital and O&M costs, which yields

**Table 2**
General characteristics of slaughterhouse wastewater.

| Parameter | Range | Mean |
|---|---|---|
| TOC (mg/L) | 70–1200 | 546 |
| $BOD_5$ (mg/L) | 150–4635 | 1209 |
| COD (mg/L) | 500–15,900 | 4221 |
| TN (mg/L) | 50–841 | 427 |
| TSS (mg/L) | 270–6400 | 1164 |
| pH | 4.90–8.10 | 6.95 |
| TP (mg/L) | 25–200 | 50 |
| Orto-$PO_4$ (mg/L) | 20–100 | 25 |
| Orto-$P_2O_5$ (mg/L) | 10–80 | 20 |
| K (mg/L) | 0.01–100 | 90 |
| Color (mg/L Pt scale) | 175–400 | 290 |
| Turbidity (FAU[a]) | 200–300 | 275 |

[a] FAU, formazine attenuation units.

**Table 3**
Characteristics of slaughterhouse wastewater from selected provincially inspected meat processing plants in Ontario.

| Parameter | Range | Mean |
|---|---|---|
| TSS (mg/L) | 0.39–9938 | 3092 |
| COD (mg/L) | 527–15,256 | 5577 |
| BOD (mg/L) | 200–8231 | 2649 |
| TOC (mg/L) | 72.5–1718 | 862 |
| TN (mg/L) | 60–339 | 156 |
| TP (mg/L) | 25.7–75.9 | 42.8 |
| Orto-$PO_4$ (mg/L) | 30.1–77.3 | 52.1 |
| Orto-$P_2O_5$ (mg/L) | 27.2–76.2 | 48.3 |
| K (mg/L) | 0.01–0.06 | 0.04 |
| Pb (mg/L) | n.a. | 34.3 |
| Color (mg/L Pt scale) | 178–391 | 289 |
| Turbidity (FAU[a]) | 271–279 | 275 |
| pH | 6.0–6.9 | 6.5 |

[a] FAU, formazine attenuation units.

negative financial impacts (Sneeringer, 2009). Nevertheless, compliance with current environmental legislation may provide an extra source of revenue by including energy recovery from the treatment, such as biogas production from anaerobic treatment. The standards and regulations governing the meat processing industry vary significantly worldwide. In several countries, slaughterhouses are regulated by tradition and practice (Casani et al., 2005).

SWWs have been considered as an industrial waste in the category of agricultural and food industries and classified as one of the most harmful wastewaters to the environment by the United States Environmental Protection Agency (US EPA). SWW discharge may cause deoxygenation of rivers and contamination of groundwater (US EPA, 2004). Typically, anaerobic treatment is used because of the high organic concentrations present in SWWs (Cao and Mehrvar, 2011; Akbaripoor et al., 2014). Nevertheless, a complete degradation of organic matter present in SWW is not conceivable using anaerobic treatment alone. MPP effluents contain solubilized organic material that is adequate for post-treatment using aerobic systems. For that reason, either anaerobic or aerobic processes should not be used as the sole treatment alternative because of the characteristics of their final effluents that are required to comply with current effluent discharge limits and standards (Chan et al., 2009; Bustillo-Lecompte et al., 2013).

Table 4 describes the standard levels and concentration limits of organic constituents to be discharged into water bodies as recommended by different worldwide agencies, including the Australian and New Zealand Environment and Conservation Council (ANZECC, 2000), Environment Canada (2000, 2012), the Council of the European Communities (CEC, 1991), US EPA (2004), among others.

However, the selection of a particular treatment technology is subject to the SWW characteristics, available technology, and compliance with current regulations. For instance, some MPPs are allowed to discharge their effluent into the municipal sewer system after demonstrating an adequate reduction of BOD loads by preliminary treatment (Mittal, 2006). The main factors determining whether a plant can discharge into a municipal sewer or not are related to the plant size as well as the volume and organic concentration of the wastewater produced (US EPA, 2004). Benefits of the combined anaerobic–aerobic processes include potential resource recovery from the conversion of organic pollutants into biogas with high overall treatment efficiency (Chan et al., 2009). However, SWWs may contain toxic and non-biodegradable organic substances that make biological treatment alone insufficient (Oller et al., 2011). Thus, advanced oxidation processes (AOPs) can be employed as an alternative to improve the SWW biodegradability containing recalcitrant, non-biodegradable, refractory, and toxic compounds.

## 4. Slaughterhouse wastewater treatment

Direct discharge of raw SWW effluents to a water body is impractical due to their high organic strength. Therefore, appropriated disposal, preliminary treatment, and/or further treatment of SWW are performed. The first step in SWW management is the minimization of the process inputs (Johns, 1995). It is usually preferable to identify and minimize wastewater generation at its source. Although typical water consumption varies considerably in the meat processing business, a regular slaughterhouse generates vast amounts of wastewater and is commonly not an efficient user of fresh water. Recovery of valuable by-products from SWW is currently focused on high-quality effluents, biogas, fertilizers, and nutrients (Amorim et al., 2007; Kist et al., 2009).

SWW treatment methods are similar to current technologies used in municipal wastewater and may include preliminary, primary, secondary, and even tertiary treatment. Thus, SWW management methods after preliminary treatment are various, but they can be divided into five major subgroups: land application, physicochemical treatment, biological treatment, AOPs, and combined processes (Valta et al., 2015). Each system has its own advantages and disadvantages, which are discussed below.

Land application usually involves direct irrigation of the SWW onto agricultural land (Bull et al., 1982; Mittal, 2006). Physicochemical treatment involves the separation of the SWW into various components, typically the separation of solids from the liquor by sedimentation or coagulation/flocculation, and removal of pollutants using electrocoagulation (EC) and membrane technologies (Bull et al., 1982; Johns, 1995; San José, 2004; Mittal, 2006; Eryuruk et al., 2014; Almandoz et al., 2015). Biological treatment are divided into anaerobic and aerobic systems as well as constructed wetlands (CWs). Aerobic systems are more common since they commonly operate at a higher rate than anaerobic systems; whereas, anaerobic systems require less complex equipment since no aeration system is required; nevertheless, both anaerobic and aerobic systems may be further sub-divided into other processes, which have their own advantages and disadvantages (Bull et al., 1982; Tritt and Schuchardt, 1992; Johns, 1995; San José, 2004; Mittal, 2006; Bugallo et al., 2014; Vymazal, 2014). AOPs are diverse and include UV/$H_2O_2$ and UV/$O_3$ for the oxidation and

**Table 4**
Comparison of standard limits of different jurisdictions worldwide for slaughterhouse wastewater discharge.

| Parameter | World Bank standards | EU standards | US standards | Canadian standards[a] | Australian standards |
|---|---|---|---|---|---|
| BOD (mg/L) | 30 | 25 | 26 | 5–30 | 6–10 |
| COD (mg/L) | 125 | 125 | n/a | n/a | 3 × BOD |
| TSS (mg/L) | 50 | 35 | 30 | 5–30 | 10–15 |
| TN (mg/L) | 10 | 10 | 8 | 1 | 0.1–15 |

[a] In the case of Canadian standards, the limits of BOD and TSS are 5, 20, and 30 mg/L in freshwater lakes and slow-flowing streams; rivers, streams, and estuaries; and shoreline, respectively.

degradation of organic and inorganic materials present in SWW through reactions with hydroxyl radicals (•OH) (Mittal, 2006; Melo et al., 2008; Luiz et al., 2009, 2011; Cao and Mehrvar, 2011; Barrera et al., 2012; Bustillo-Lecompte et al., 2013, 2014). Finally combined processes are cost-effective with high removal efficiencies that can lead to a reduction in O&M costs compared to individual processes (Tritt and Schuchardt, 1992; Chan et al., 2009; Luiz et al., 2011; Cao and Mehrvar, 2011; Bustillo-Lecompte et al., 2013, 2014).

### 4.1. Preliminary treatment

In preliminary treatment, all solids and large particles generated during the slaughtering process are separated from wastewater. Typical unit operations for the preliminary removal of TSS in wastewater include regular screeners, strainers, or sieves. Large solids in wastewater with a diameter of 10–30 mm are retained on the mesh of the screener. Rotary screeners are used to retain solids with a diameter of more than 0.5 mm in order to avoid fouling, clogging, or jamming of the equipment. Screw screen compactors are used to transport, dewater, and compact all the remaining solids from the previous screeners, minimizing the moisture content and volume in order to be treated as solid waste (San José, 2004; Mittal, 2006).

Other pretreatments include catch basins, homogenization/equalization, flotation, and settlers. Furthermore, screening can separate up to 60% of the solids from the SWW and remove more than 30% of the BOD (Mittal, 2006).

### 4.2. Land application

In land application, biodegradable materials can be used to provide nutrients to the soil by directly placing them into the land. One drawback of the land application is related to the temperature and the geography (San José, 2004). For instance, the land application in temperate countries is not feasible throughout the year due to the winter season. Therefore, the SWW requires to be stored during that period; thus, energy usage related to the treatment and transportation increases. Other disadvantages include aesthetics, odor, soil contamination, possible surface and groundwater pollution, and pathogens presence and persistence (Avery et al., 2005). On the other hand, advantages of land application include the recovery of useful by-products from the SWW, alternative source of fertilizer, and improvement of soil structure (Mittal, 2004, 2006).

### 4.3. Physicochemical treatment methods

Following preliminary treatment, it is recommended to send the effluent to a subsequent primary or secondary treatment, depending on the strength of the SWW. One of the typical methods of the primary treatment is the DAF process, especially for reducing fat, TSS, and BOD in SWW (Al-Mutairi et al., 2008; De Nardi et al., 2011). Physicochemical treatment methods usually involve the separation of solids from the liquid. Different physicochemical treatment technologies are discussed in the following subsections.

#### 4.3.1. Dissolved air flotation

DAF systems refer to the water–solid separation method by introducing air into a SWW influent, where the air is introduced from the bottom of the vessel. Hence, light solids, fat, and grease are transported to the surface forming a sludge blanket, where a scraping assembly constantly removes scum.

The efficiency of the DAF system can be enhanced by adding polymers and other flocculants for pH adjustment and flocculation of particulate matter. Blood coagulants such as ferric chloride and aluminum sulfate can be also added to the SWW to promote protein aggregation and precipitation in addition to fat and grease flotation. The DAF process efficiencies for COD and BOD removal are usually from 30 to 90% and from 70 to 80%, respectively. DAF systems are also capable of achieving moderate to high nutrient removal (Johns, 1995; Mittal, 2006; Al-Mutairi et al., 2008; De Nardi et al., 2011). Conversely, DAF drawbacks are related to regular malfunctioning and poor TSS separation (Kiepper, 2001).

#### 4.3.2. Coagulation and flocculation

Coagulants and flocculants are added into a reactor vessel where the floc is conditioned. The ideal size for separation during flotation is searched, and it is necessary to balance the pH after addition of the coagulant in order to achieve an appropriate flocculation (San José, 2004). Aluminum sulfate, ferric chloride, ferric sulfate, and aluminum chlorohydrate have been used as coagulants to treat SWW. Results show TP, TN, and COD removals of up to 99.9, 88.8, and 75.0%, respectively, using polyaluminum chloride as the reagent. Moreover, if inorganic coagulant aids are used, the sludge volume can be reduced by 41.6% (Núñez et al., 1999; Aguilar et al., 2002; Mittal, 2006; De Sena et al., 2008).

Satyanarayan et al. (2005) studied the physicochemical treatment of SWW effluent using anionic polyelectrolyte, ferrous sulfate, lime, and alum as coagulants. Among these coagulants, lime alone achieves removal rates of up to 38.9, 36.1, and 41.9% for BOD, COD, and TSS, respectively. The combination of ferrous sulfate and lime improves the COD removal rate to 56.8%. Likewise, the combination of lime and alum also results in an increased COD removal of up to 42.6%. On the other hand, using combined ferrous sulfate and anionic polyelectrolyte, although not cost-effective, results in good removal rates of up to 54.2, 49.6, and 43.8% for TSS, BOD, and COD, respectively. Whereas, if alum is used in combination with lime, the generation of sludge is increased.

The coagulation–flocculation technology was used by Amuda and Alade (2006) at the laboratory-scale for the removal of TP, TSS, and COD from SWW. Several coagulants including ferric chloride, ferric sulfate, and alum were used. Results show that although alum was effective for the removal of TP and TSS from SWW, ferric sulfate was more efficient in reducing COD. Results show maximum COD, TP, and TSS removal efficiencies of up to 65, 34, and 98%, respectively.

Tariq et al. (2012) used lime and alum individually and in combination as coagulants for the treatment of SWW. Results show that as the alum dose increases, COD removal increases to a maximum of 92% along with the sludge volume, which makes the process not feasible. Conversely, an increase in lime dosage increased the COD reduction to a maximum of 74%, whereas the sludge settling was high, and the sludge volume decreased as compared to that of alum. At the end, the combined dosages of lime and alum give a maximum removal of 85% in COD with low sludge volume.

#### 4.3.3. Electrocoagulation

The EC process has been recently used for SWW treatment as a cost-effective advanced wastewater treatment technology. EC has been confirmed to be an effective technology for the removal of organics, nutrients, heavy metals, and even pathogens from SWW by introducing an electric current without adding chemicals (Kobya et al., 2006; Emamjomeh and Sivakumar, 2009; Bayar et al., 2011; Qin et al., 2013). Fig. 1 illustrates a typical EC reactor.

Al, Fe, Pt, $SnO_2$, $TiO_2$, among others, can be utilized as electrodes for the EC process, being Fe and Al the most widely used. Thus, the EC process involves onsite generation of $M^{3+}$ ions using sacrificial anodes. Additionally, these sacrificial electrodes might be interacting with $H^+$ ions in an acidic medium, or with $OH^-$ ions in an alkaline medium (Bayramoglu et al., 2006; Kobya et al., 2006; Bayar

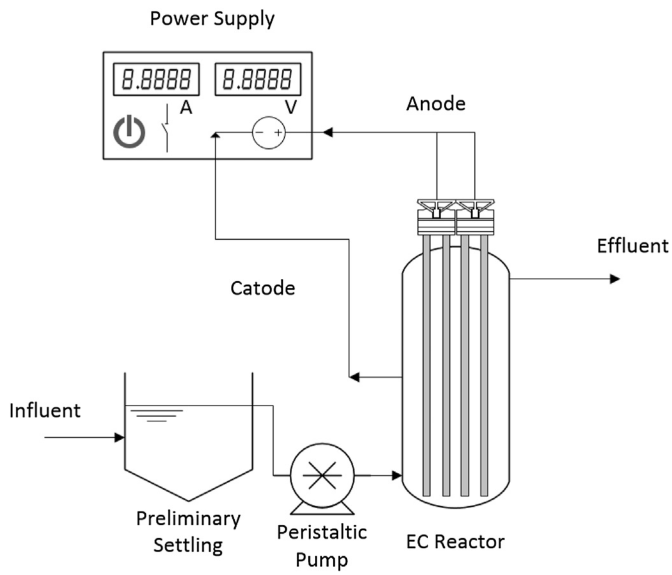


**Fig. 1.** Schematic diagram of a typical electrocoagulation unit.

et al., 2011, 2014; Ozyonar and Karagozoglu, 2014).

Kobya et al. (2006) studied the influence of pH, operating time, electrode material, and current density of the EC process for SWW treatment on oil–grease and COD removal, sacrificial electrode and electrical energy consumption. Up to 93% of COD was removed using Al as the electrode material, whereas maximum oil–grease efficiency was obtained using Fe as the electrode material, reaching 98% removal. Nevertheless, it was found that further work is required at the pilot-scale to assess the cost-effectiveness of the EC process.

A cost-effectiveness analysis (CEA) for the treatment of SWW using EC was conducted by Bayramoglu et al. (2006) with a particular focus on COD removal. Total operating cost included O&M, electricity, sacrificial electrodes (Fe and Al) depreciation, and sludge handling costs. Other performance parameters included pH, current density, and operating time. Results show that Fe sacrificial electrodes are more cost-effective than Al electrodes, with total operating costs between 0.30 and 0.40 $\$/m^3$, nearly 50% of the total costs of using Al. Similar results were obtained by Ozyonar and Karagozoglu (2014), when calculating total costs for Al and Fe sacrificial electrodes at optimum conditions. Al electrodes were found less cost-effective than Fe electrodes with total costs of 2.76 and 0.87 $\$/m^3$, respectively.

Likewise, Asselin et al. (2008) evaluated the EC process in economic terms for the removal of organic compounds from SWW. Experiments were conducted at laboratory pilot-scale by using mild steel and Al sacrificial electrodes. Results show that using mild steel bipolar electrodes achieves COD, BOD, TSS, turbidity, and oil–grease removals of up to 84, 87, 93, 94, and 99%, respectively. Thus, involving a total cost, including energy, electrode consumptions, chemicals, and sludge disposal, of 0.71 $\$/m^3$ of treated SWW effluent, which is comparable to that found by Bayramoglu et al. (2006).

Awang et al. (2011) used the EC process for the post-treatment of SWW. The effects of current density, reaction time, and influent COD on color, COD, and BOD removal efficiencies were investigated using a 3-level factorial design and response surface methodology (RSM). The optimum conditions were obtained at COD influent concentrations of 220 mg/L, 55 min reaction time, and current density near 30 $mA/cm^2$. Thus, a removal response of 96.80, 81.30, and 85.00% was achieved for color, BOD, and COD, respectively.

On the other hand, Bayar et al. (2011, 2014) studied the influence of current density and pH on the treatment of SWW by means of EC with Al electrodes. High removal efficiencies at low pH and current density values were obtained. Thus, COD removal efficiencies of up to 85% were obtained with the current density of 0.5 $mA/cm^2$ at pH of 3.0. Likewise, Ahmadian et al. (2012) examined the performance of EC for SWW treatment in a batch system using Fe electrodes. Organic matter and nutrient removal rates were improved by augmenting current density, operating time, and electrode number. Results show removal efficiencies of up to 97, 93, 84, and 81% for BOD, COD, TN, and TSS, respectively.

#### 4.3.4. Membrane technology

Membrane technology is becoming an alternative for SWW treatment. Reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) processes are able to remove particles, colloids, and macromolecules depending on the pore size (Table 5). Membrane processes are also increasingly used for removal of bacteria, microorganisms, particulates, and organic matter in SWW treatment (Almandoz et al., 2015).

Bohdziewicz and Sroka (2005) studied the performance of the RO process for SWW treatment as secondary effluent. The raw SWW was first pretreated using activated sludge (AS). Thus, the characteristics of the influent SWW for RO treatment were 76.0, 10.0, 3.6, and 13.0 mg/L for COD, BOD, TP, and TN, respectively. Results showed a removal efficiency of 85.8, 50.0, 97.5, and 90.0%, after RO treatment, for COD, BOD, TP, and TN, respectively. Therefore, it can be concluded that RO is a feasible technology for SWW post-treatment.

Yordanov (2010) investigated the feasibility of using UF for SWW treatment. Results showed that the UF could be an efficient purification method by achieving 98 and 99% removal of TSS and fats, respectively. The efficiencies of BOD and COD removals were 97.80–97.89 and 94.52–94.74%, respectively.

Gürel and Büyükgüngör (2011) investigated the performance of membrane bioreactors (MBRs) for nutrients and organics removal from SWW. The initial COD, TP, and TN concentrations were 571, 16, and 102 mg/L, respectively. An UF membrane was utilized in the MBR. Up to 44, 65, 96, and 97% removals were obtained for TN, TP, TOC, and COD, respectively. Although organic matter was successfully removed, a high nitrate concentration in the treated effluent remained. Thus, denitrification is required to further treat this effluent.

Almandoz et al. (2015) evaluated the effectiveness of a MF ceramic composite membrane (CM). The results show a total insoluble residue rejections of 100%, high bacterial removal (87–99%), as well as TOC, TN, and COD removal rates of 44.81, 45.22, and 90.63%, respectively. Thus, making the ceramic CM suitable for MF treatment of SWW.

Although high organic removal can be achieved by membrane processes, still nutrients' removals require this process to be coupled with another conventional process (Gürel and Büyükgüngör, 2011). Furthermore, membrane processes can face major problems of fouling while processing highly concentrated feed streams such as SWW, which is difficult to remove and can greatly restrict the permeation rate through the membranes due to the formation of thick biofouling layers onto the membrane surfaces (He et al., 2005; Selmane et al., 2008).

### 4.4. Biological treatment

Reducing BOD concentration in SWW is the main focus of the secondary treatment by removing soluble organic compounds that remain after primary treatment (Pierson and Pavlostathis, 2000).

**Table 5**
Comparison of different membrane dimensions and pore size exclusion used in SWW treatment.

| Membrane type | Pore size (μm) | TOC removal (%) | COD removal (%) | BOD removal (%) | TN removal (%) | Reference |
|---|---|---|---|---|---|---|
| Microfiltration (MF) | 0.080–0.550 | 44.81 | 90.63 | – | 45.22 | Almandoz et al. (2015) |
| Ultrafiltration (UF) | 0.030 | 75.00–96.00 | 83.00–97.00 | – | 27–44 | Gürel and Büyükgüngör (2011) |
| Ultrafiltration (UF) | 0.010–0.100 | – | 94.52–94.74 | 97.80–97.89 | – | Yordanov (2010) |
| Reverse Osmosis (RO) | 0.001–0.005 | – | 85.80 | 50.00 | 90.00 | Bohdziewicz and Sroka (2005) |

Biological treatment is usually applied as a secondary treatment process in MPPs, where aerobic and anaerobic digestion are used as individual or combined processes depending on the characteristics of the SWW being treated (Martínez et al., 1995).

Biological treatment is used to remove organics and eventually pathogens from SWW effluents using microorganisms. Furthermore, the biological treatment is able to remove up to 90% BOD from MPP effluents by aerobic or anaerobic processes (Mittal, 2006). Biological treatment may include different combinations of various processes including anaerobic, aerobic, and facultative lagoons, AS, and trickling filters among others (Massé and Masse, 2000).

*4.4.1. Anaerobic treatment*

Anaerobic digestion is the preferred biological treatment that is applied in SWW treatment due to its effectiveness in treating high-strength wastewater (Cao and Mehrvar, 2011). During anaerobic treatment, organic compounds are degraded by different bacteria into $CO_2$ and $CH_4$ in the absence of oxygen. Besides, anaerobic systems have several advantages such as high COD removal, low sludge production (5–20%) compared to those of aerobic systems, and less energy requirements with potential nutrient and biogas recovery (Massé and Masse, 2000; Mittal, 2006; Chan et al., 2009; Bustillo-Lecompte et al., 2014).

Although anaerobic treatment possesses great advantages, it hardly produces effluents that comply with current discharge limits and standards (Table 4). Generally speaking, although anaerobic treatment is an efficient process, the SWW organic strength makes it difficult to achieve complete stabilization of the organic compounds (Chan et al., 2009). Hence, anaerobically treated effluents usually need additional post-treatment, in which the removal of organic matter and other constituents such as TN, TP, and pathogenic organisms, is completed (Chernicharo, 2006; Oliveira and Von Sperling, 2009; Gomec, 2010). Moreover, the associated higher space–time yield contributes considerably to the economic viability of anaerobic treatment plants (Tritt and Schuchardt, 1992). Thus, the combination of anaerobic–aerobic systems is a potential alternative to conventional methods in order to satisfy current effluent discharge standards (Chan et al., 2009; Bustillo-Lecompte et al., 2013). Typical configurations for SWW anaerobic treatment include anaerobic baffled reactor (ABR), anaerobic filter (AF), anaerobic lagoon (AL), up-flow anaerobic sludge blanket (UASB), and anaerobic sequencing batch reactor (SBR).

*4.4.1.1. Anaerobic baffled reactor.* ABRs are considered an optimized version of a common septic tank. ABRs have a series of compartments and baffles under which the SWW flows under and over from the inlet to the outlet. Since there is an increased contact time with the active biomass, a higher biodegradation occurs. The up-flow compartments provide an improved removal of organics with BOD and COD removals of up to 90% (Barber and Stuckey, 1999; Kuşçu and Sponza, 2005).

Cao and Mehrvar (2011) evaluated the performance of the combined ABR and UV/$H_2O_2$ processes at a laboratory-scale to treat SWW. Results show that combined processes had higher removal efficiencies for SWW treatment rather than using individual processes. Maximum TOC removals of up to 95% were obtained for influent concentrations of 973 mgTOC/L after 3.8 days of treatment.

Individual biological treatment using an ABR at a laboratory-scale was studied by Bustillo-Lecompte et al. (2013) to treat SWW with an influent concentration of 183.35 mgTOC/L and 63.38 mgTN/L. Maximum removals of TOC and TN were achieved by up to 88.88 and 51.52%, respectively.

Bustillo-Lecompte et al. (2014) also evaluated the effectiveness and performance of the ABR process for the treatment of SWW using a CEA by assessing the total electricity cost, hydraulic retention time (HRT), and removal percentage of TOC. Results show that costs increase with the amount of TOC removed, especially if high TOC removal rates are required.

As a result, if low or intermediate amounts of TOC are to be removed, the ABR as an individual process can be comparable to combined processes in economic terms since electricity costs gradually increase. Therefore, biogas production is an important asset to be used due to its potential energy recovery that will be translated into cost savings for MPPs because of the characteristics of SWWs (Bustillo-Lecompte et al., 2014).

*4.4.1.2. Anaerobic filter.* Anaerobic filters (AFs) are fixed-bed biological reactors with filtration chambers. AFs are commonly found working in series. When the SWW runs through the filtration chambers, particles are confined inside; then, the organic material is removed by the active biomass attached to the filter surface. AFs are used as secondary treatment due to its high solid removal and biogas recovery rates. An AF is designed as an anaerobic digestion column packed with different types of media (Mittal, 2006). A typical anaerobic filter is presented in Fig. 2.

The performance of up-flow anaerobic filters (UAFs) has been examined under thermophilic and mesophilic conditions for SWW treatment (Gannoun et al., 2009, 2013). The results showed that COD removal efficiencies of up to 90% can be achieved for organic loading rates (OLRs) of 9000 mg/L day under mesophilic conditions and 72% under thermophilic conditions.

Rajakumar et al. (2011) evaluated the performance of an UAF

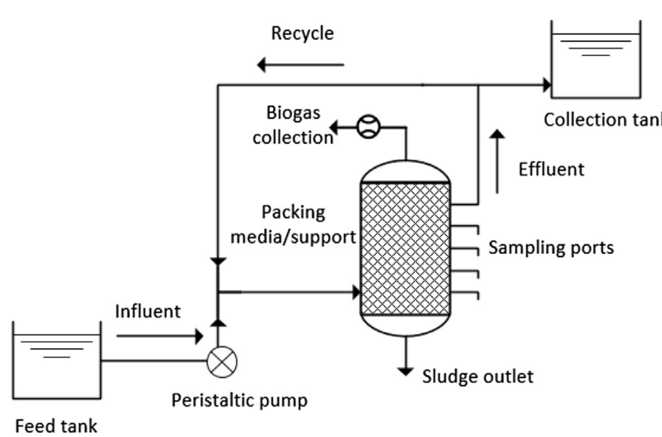


**Fig. 2.** Schematic diagram of a typical anaerobic filter system.

reactor for SWW treatment under low up-flow velocity at mesophilic conditions of up to 35°C. COD removals of 79% were achieved at OLRs of 10.05 kg/m$^3$ day and HRT of 12 h. The average produced methane varied between 46 and 56%. The lower velocity used in the study conducted by Rajakumar et al. (2011) allowed an active microbial formation with stable pH demonstrating that SWW can be treated using AFs under low up-flow velocity.

The performance of AF bioreactors for SWW treatment was assessed by Stets et al. (2014) by evaluating the influence of the characteristics of the support medium, substrate, and microorganisms present in the sludge. Three AF configurations were studied using different support media resulting in maximum COD removals of up to 80% and TN removals of up to 90% at HRT of 1 day.

Martinez et al. (2014) compared the effectiveness of two up-flow anaerobic packed-bed filters (UAPFs) for SWW treatment at a laboratory-scale, under mesophilic conditions, and using different packing material. The production of $CH_4$ was assessed at various OLRs and feeding conditions. The COD removal reached 60% for an influent concentration of up to 15,800 mg/L. The UAPF was proven to be self-sufficient in terms of energy requirements, providing sufficient heating power for the SWW treatment plant.

*4.4.1.3. Anaerobic lagoon.* ALs are popular in countries where weather and land availability permit the construction of lagoons for the treatment of SWW (Johns, 1995; Mittal, 2006). The wastewater influent usually flows from the bottom of the lagoon, and although some gas mixing may be present, ALs are not mechanically mixed. Thus, a scum layer is typical to appear on the surface of the ALs, ensuring anaerobic conditions and low heat loss. Typical ALs are constructed with a depth of 3–5 m for HRTs of 5–10 days. Efficiencies of ALs to remove BOD, COD, and TSS have been reported to be 97, 96, and 95%, respectively (US EPA, 2004; Mittal, 2006; McCabe et al., 2014).

The main drawbacks of ALs are related to odor regeneration and weather conditions. Therefore, synthetic floating covers are used to trap odor and collect biogas; these covers must be durable to resist inclement weather, temperature change, wind, ice and snow accumulation (Mittal, 2006). On the other hand, ALs are the preferred option because of their simplicity and low O&M costs (McCabe et al., 2014).

*4.4.1.4. Up-flow anaerobic sludge blanket reactor and anaerobic sequencing batch reactor.* An anaerobic SBR requires low capital and O&M costs. The feeding, reactions, settling, and decanting stages take place in the same basin and anaerobic SBRs also eliminate the requirements of complete mixing. Nevertheless, intermittent mixing may occur in the course of the reacting cycles (Massé and Masse, 2000; Mittal, 2006). Moreover, in order to optimize the performance of anaerobic SBRs, an intermittent feeding strategy of the SWW influent eliminates the need for a recycling stream or an equalizing tank (Masse and Massé, 2005).

UASB reactors are similar to anaerobic SBRs. The UASB process uses granules to capture bacteria, the SWW enters from the bottom of the reactor, flows upward through the sludge blanket, the biomass film, and exits at the top of the vessel. Essentially, UASB reactors consist of three stages: liquid as SWW, solid as biomass, and gas as $CO_2$ and $CH_4$ produced during digestion (Mittal, 2006; Del Nery et al., 2007, 2008).

Caldera et al. (2005) evaluated the performance of a UASB reactor of 4 L at mesophilic conditions for the treatment of SWW. Influent COD concentrations were varied from 1820 to 12,790 mg/L. Experiments were conducted for 90 days at HRT of 24 h. The results demonstrated an adequate efficiency of the UASB reactor to treat SWW of up to 94.31% for the removal of COD.

Chávez et al. (2005) evaluated the removal of BOD from SWW using 3 L UASB reactors and a 3-levels factorial design and RSM. A maximum 95% removal of BOD was obtained with OLRs up to 31,000 mg/L under optimum conditions, with temperature values ranging between 25 and 39°C at HRTs between 3.5 and 4.5 h.

Miranda et al. (2005) assessed the performance of an 800 m$^3$ UASB for SWW treatment. Influent concentrations of COD and oil and grease (O&G) were in the range of 1400–3600 and 413–645 mg/L, respectively. Results show that the UASB performance was enhanced when influent COD/O&G ratios remained at 10%. Thus, O&G and COD removal efficiencies reached 27–58 and 70–92%, respectively.

Rajakumar and Meenambal (2008) evaluated the performance of the UASB process for SWW treatment. Influent COD concentrations varied from 3000 to 4800 mg/L. The UASB reactor showed an optimum COD removal efficiency of up to 90% at a HRT of 10 h. Moreover, results show that by reducing HRT to less than 10 h in the UASB, sludge wash out appears and lower COD removal efficiencies of less than 70% are obtained (Rajakumar et al., 2012).

Mijalova Nacheva et al. (2011) analyzed the performance of a UASB reactor under ambient conditions for SWW treatment after solid separation. COD removal efficiencies increased proportionally to OLRs. Thus, COD removal efficiencies of up to 90% were obtained with the influent COD concentrations of 3437 mg/L. Although UASB reactors are found to be efficient for SWW treatment, a post-treatment is required to comply with current water quality standards for water body discharge.

*4.4.2. Aerobic treatment*

In aerobic systems, aerobic bacteria are accountable for the removal of organic materials in the presence of oxygen. The treatment time and the amount of required oxygen increase suddenly with the strength of SWW. Aerobic treatment is commonly used for final decontamination and removal of nutrients after using physicochemical or anaerobic techniques (Chernicharo, 2006). Aerobic reactors may have several configurations. However, the biological process is very similar, and being necessary to define if nitrogen removal is required (San José, 2004). Typical configurations for SWW aerobic treatment include activated sludge (AS), rotating biological contactors (RBCs), and aerobic SBR.

*4.4.2.1. Activated sludge process.* AS is an aerobic treatment method that brings the effluent into contact with air and free floating flocs of microorganisms including bacteria and protozoa. The AS process has been widely applied in different industries as a commonly known cost-effective method for the treatment of SWW. The purpose of the AS process is to remove soluble and insoluble organics from the wastewater and to change this material into a flocculent microbial suspension that is then settled in a clarifier. Two distinct mechanisms are applied in AS, adsorption and oxidation of the organic matter (Bull et al., 1982; Al-Mutairi, 2008). A typical AS system is depicted in Fig. 3.

AS systems treating SWW produce poor settling flocs because of fats present in SWW influents and low dissolved oxygen (DO) levels. Design criteria of the AS process for SWW treatment require extended aeration to minimize the sludge production. The HRT are longer than that of typical municipal wastewater treatment plants to guarantee a sludge age in the range of 5–20 days, recommended for SWW treatment (Johns, 1995).

Pabón and Gélvez (2009) evaluated the performance of a 144 m$^3$ full-scale AS reactor for SWW treatment. The average treated flow was 1.38 L/s with a 2-day HRT. Oxygen was injected using a high-efficiency air equipment. Bulk SWW parameters including BOD, COD, and TSS with an influent concentration of 5242, 9040, and

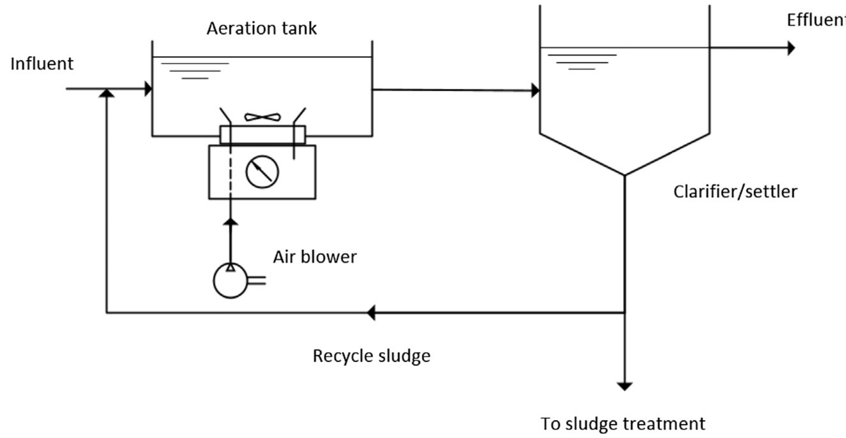


**Fig. 3.** Schematic diagram of a typical activated sludge system.

2973 mg/L, respectively, were evaluated. Maximum removal efficiencies of 94.09, 89.73, and 89.03% were achieved for TSS, BOD, and COD, respectively.

Fongsatitkul et al. (2011) examined the performance of the AS system to treat SWW. Two 10 L continuous-flow reactors running in parallel with internal recycle (IR) were used. The COD removal efficiency reached up to 97.60%, the total Kjeldahl nitrogen (TKN) removal rate ranged from 81.50 to 95.60%, and the TP removal reached its maximum around 85–89%.

Hsiao et al. (2012) evaluated different kinetic parameters for an AS reactor treating SWW using the Monod equation and compared to the data obtained from the experiment. The AS system at the temperature of 26°C removed up to 97.20% of COD from SWW. Predicted values were validated by the experimental values. The sensitivity analysis indicated that the COD residual concentration was highly sensitive to the variation of the maximum specific substrate utilization rate, producing a noticeable COD intensification.

Carvalho et al. (2013) aimed to evaluate the role of AS process in the removal of veterinary drugs including enrofloxacin, tetracycline, and ceftiofur from SWW in batch reactors. Sludge bioreactors with initial pharmaceutical concentrations of 100 g/L presented removal rates of 68% for enrofloxacin and 77% for tetracycline from the aqueous phase. Results showed that sorption to wastewater organic content and biomass was accountable for a significant fraction of the pharmaceuticals removal. Nevertheless, these removal rates are still low for effluent discharge. Therefore, it is required to consider alternative methods for treating this effluent such as AOPs.

Bustillo-Lecompte et al. (2013, 2014) evaluated the effectiveness, performance, and costs of an AS reactor for the treatment of SWW using a CEA. The aerobic AS reactor obtained the best performance under TOC and TN influent concentrations of 1009 and 254 mg/L with up to 95.03% TOC and 73.46% TN removals, respectively. At higher influent TOC and TN concentrations, the TOC and TN removal are higher. For an influent concentration of 639 mgTOC/L and 144 mgTN/L, TOC removals reached 89.66% and TN removals reached 43.19% at HRT of 5 days, whereas at 8 days, TOC removals reached 94.26%, and TN removals reached 75.15%. On the other hand, by means of the CEA, it was found that the AS process is an efficient process with optimum TOC removal of up to 88% at a cost of 4 $/kg of TOC removed. Thus, if low or intermediate amounts of TOC are to be removed, the AS process is comparable to combined processes in economic terms.

*4.4.2.2. Rotary biological contactor.* The RBC process allows the wastewater to come in contact with a biological medium in order to absorb and metabolize the organic content as well as to remove other pollutants before discharge to the environment (Mittal, 2006). However, the performance of an RBC to treat SWW has been reported as inadequate in literature (Bull et al., 1982; Johns, 1995) compared to conventional aerobic treatment systems such as the AS process.

The performance of a 6-stage RBC pilot plant for post-treatment of SWW was investigated by Torkian et al. (2003). The overall removal efficiencies for BOD and COD decreased by increasing the OLR. Results indicated successful post-treatment of SWW to meet regulatory requirements with a BOD removal efficiency of up to 88%. On the other hand, Al-Ahmady (2005) studied the COD removal in RBC systems as a function of the OLR. A wide range of COD removal of 40–85% can be obtained when treating SWW by RBCs as a result of the specific OLR applied, especially during the first stages of the system.

*4.4.2.3. Aerobic sequencing batch reactor.* In an aerobic SBR, there are five stages including filling, reaction, settling, decanting/drawing, and idle. In the first stage, the feed enters the reactor while mixing is provided by mechanical means in the absence of air (anoxic phase). Then, the aeration of the mixed liquor is executed for the reactions to occur (aerobic phase). During the third stage, the TSS start to settle since there is no aeration or mixing. During the fourth stage, the clean supernatant liquor exits the tank as the effluent.

Filali-Meknassi et al. (2005a; 2005b) studied the performance of an aerobic SBR for SWW treatment with influent concentrations of 5000 mgCOD/L and 360 mgTN/L. Overall efficiencies were achieved for COD and TN in the range 95–96% and 95–97%, respectively. Likewise, Lemaire et al. (2008, 2009) evaluated the performance of SBRs under 6 h cycles for SWW treatment. High efficiencies for COD, TP, and TN removal of 95, 98, and 97% were achieved, respectively.

Conversely, Li et al. (2008) assessed the influence of the aeration rate on organics and nutrients removal from SWW using two laboratory-scale SBRs operated at ambient temperature for 8 h. The influent concentrations of TN and COD were 350 and 4000 mg/L, respectively. Results show that at higher aeration rates, the TN removal efficiency increases considerably. For instance, at an aeration rate of 0.4 L/min, TN and COD removal efficiencies reached 34 and 90%, respectively. Conversely, aeration rates above 0.8 L/min permitted removal efficiencies of up to 97 and 95% for COD and TN, respectively.

Zhan et al. (2009) examined the TN removal from SWW in a SBR at laboratory-scale using two aeration strategies, intermittent and continuous, at low DO range. Under the intermittent aeration strategy, the maximum DO was fixed at 10% saturation. On the other hand, under the continuous aeration strategy, the DO was maintained at 10% saturation during the first hour of the reaction phase, and then at 2% for the remaining reaction phase. TN removals of 91 and 95% were accomplished by continuous and intermittent aeration, respectively. Therefore, an on-site measurement of DO levels can be used to regulate the SBR operation in order to improve TN removal.

A 5-L aerobic SBR with suspended biomass was used by Mees et al. (2011, 2014) for the removal of organics and nutrients from SWW. Optimal conditions were obtained by a central composite design (CCD) at 16-h cycles. A total of 20 cycles were completed to investigate the kinetics for the degradation of COD and TN. Up to 85.91% and 62.13% removal efficiencies were achieved for TN and COD, respectively.

The performance of a SBR was evaluated by Kundu et al. (2013, 2014) for the removal of TN and COD from SWW at laboratory-scale. Influent concentrations of TN and COD were 90–180 and 950–1050 mg/L, respectively. Results showed a COD removal of up to 95% at 8 h. A reasonable degree of nitrification between 74.75 and 90.12% was achieved for TN influent concentrations of 176.85 and 96.58 mg/L, respectively. Kinetic coefficients were also determined.

Pan et al. (2014) evaluated the removal of TN from SWW at low temperatures of up to 11 °C through partial nitrification–denitrification by means of an 8-L SBR. The influent concentration of the SWW contained COD, TN, TP, and TSS concentrations of 6068, 571, 51, 1800 mg/L, respectively. OLRs of up to 610 mgCOD/L day were used at cycles of 12 h. The optimum aeration rate was found to be 0.6 L/min at maximum TP, COD, and TN removal efficiencies of 96, 98, and 98%, respectively.

#### 4.4.3. Constructed wetlands

Constructed wetlands (CWs) are an attractive alternative to conventional wastewater treatment, especially in rural areas since the biological treatment is a cost-effective method (Chan et al., 2009; Oller et al., 2011; Bustillo-Lecompte et al., 2014). This is due to low O&M costs, simplicity in design, and relatively few impacts on the environment. CWs simulate the mechanisms of natural wetlands for water purification, combining biological, physical, and chemical processes that occur when microorganisms, soil, atmosphere, plants, and water interact. This interaction results in the appearance of sedimentation, filtration, adsorption, biodegradation, photosynthesis, photo-oxidation, and subsequent organics and nutrients uptake by the system.

Gutiérrez-Sarabia et al. (2004) studied a full-scale constructed subsurface-flow wetland system. The CW accounted for 30% of the organic matter removal in the system. Although the treatment system achieved satisfactory pollutant removals of 91, 89, and 85% for $BOD_5$, COD, and TSS, respectively, the final effluent could not meet local standards. Moreover, the TP removal was null.

The performance of CW systems for the treatment of SWW was evaluated by Soroko (2007). Two vertical flow constructed wetlands (VFCWs) and one horizontal flow constructed wetland (HFCW) were used. The SWW influent had average concentrations of 3188, 2500, and 500 mg/L for COD, BOD, and TN, respectively. Results showed that sand and gravel beds of CWs could be effective in removal of organic substances, up to 97.40, 99.90, and 78.20% of COD, BOD, and TN from the SWW influent, respectively.

A CW with *Typha latifolia* was constructed by Carreau et al. (2012) for the treatment of SWW with HRT of 111 days and 89% active volume. Up to 95, 72, 88, and 87% removal efficiencies were achieved for BOD, TSS, TP, and TN, respectively. Likewise, Odong et al. (2013) investigated different CWs for the treatment of SWW with influent concentrations of COD, BOD, and TN in the ranges of 293–314, 79–87, and 56–64 mg/L, respectively. Results showed a broad range of removal for different vegetation. COD, BOD, and TN removal rates ranged from 28.28 to 75.03, 9.27 to 71.40, and 5.20 to 25.40%, respectively.

### 4.5. Advanced oxidation processes

AOPs are becoming an interesting alternative to conventional treatment and a complimentary treatment option, as either pretreatment or post-treatment, to current biological processes. Furthermore, AOPs may inactivate microorganisms without adding additional chemicals to the SWW in comparison to other techniques such as chlorination that are commonly used in water disinfection, thus, avoiding the possible formation of hazardous by-products (De Sena et al., 2009; Bustillo-Lecompte et al., 2015). Therefore, AOPs have come handy to be recognized as advanced degradation, water reuse, and pollution control processes showing excellent overall results as complimentary treatment (Tabrizi and Mehrvar, 2004; Mehrvar and Venhuis, 2005; Venhuis and Mehrvar, 2005; Mehrvar and Tabrizi, 2006; Edalatmanesh et al., 2008; De Sena et al., 2009; Cao and Mehrvar, 2011; Barrera et al., 2012; Mohajerani et al., 2012; Bustillo-Lecompte et al., 2013, 2014; Hamad et al., 2014; Mowla et al., 2014; Ghafoori et al., 2015).

Ozonation technology was used for the treatment of SWW by Millamena (1992). Results showed that the utilization of a low concentration ozone stream of 110 mg/h for the removal of the majority of organics in slaughterhouse wastewater was not feasible. With pretreatment, the overall efficiency of ozonation in terms of BOD removals was in the order of 42%, TOC reached 34% removal, and better removal was attained with COD at 58%.

Ozonation was also used by Wu and Doan (2005) for the treatment of SWW. Results show that ozone was effective in disinfecting SWW after 8 min using an ozone dosage of up to 23.09 mg/min per L. Up to 99% of microorganisms were inactivated. Nevertheless, the COD and BOD removal were only 10.70 and 23.60%, respectively.

Gamma radiation (GR) was evaluated by Melo et al. (2008) for the treatment of SWW. Low COD, BOD, and TSS efficiency removals were obtained at a dose rate of 0.9 kGy/h. Nevertheless, a decrease of BOD in the range of 38.65–85.75% was observed at high absorbed irradiation dosages (25 kGy/h). Although the results obtained at high doses, the costs associated with this technology are its main drawback.

The $UV/H_2O_2$ process is one of the most widely used AOPs. The $UV/H_2O_2$ process has been found to be effective for SWW treatment. Oxidation and degradation of pollutants by $UV/H_2O_2$ rely on hydroxyl radicals ($^\bullet OH$), a highly reactive species produced from the reaction of the $H_2O_2$ with the UV light (Tabrizi and Mehrvar, 2004; Mehrvar and Tabrizi, 2006; Edalatmanesh et al., 2008; De Sena et al., 2009; Luiz et al., 2009; Cao and Mehrvar, 2011; Barrera et al., 2012; Mohajerani et al., 2012; Hamad et al., 2014; Mowla et al., 2014; Bustillo-Lecompte et al., 2015; Ghafoori et al., 2015). A schematic diagram of a single lamp $UV/H_2O_2$ photoreactor system is presented in Fig. 4.

Luiz et al. (2009) evaluated the $UV/H_2O_2$ process for the treatment of a secondary SWW effluent. Results show that the $UV/H_2O_2$ treatment was more effective than conventional UV alone in removing organic matter. The $UV/H_2O_2$ process was five times more rapidly in degrading aromatics than UV only. Up to 95% in COD removal efficiency was reached after 5 h of

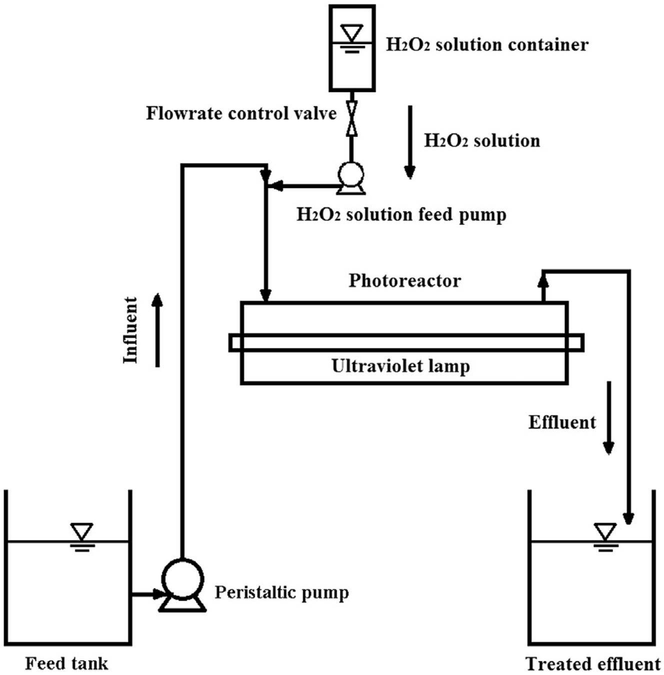


**Fig. 4.** Schematic diagram of a single lamp UV/$H_2O_2$ photoreactor.

treatment.

De Sena et al. (2009) studied the effectiveness of AOPs for the treatment of SWW using UV/$H_2O_2$ and photo-Fenton in a laboratory scale. Results showed that the AOPs increased the removal of organics from pre-treated SWW samples with overall COD and BOD removal rates of up to 97.60 and 95.70%, respectively. Thus, AOPs might be considered to enhance SWW effluents quality for water reuse purposes.

Cao and Mehrvar (2011) evaluated a UV/$H_2O_2$ photoreactor as the post-treatment of a synthetic SWW at a laboratory scale. A TOC influent concentration of 157.6 mg/L was used. Up to 84, 64, and 83% of BOD, TOC, and COD removals, respectively, were obtained at HRTs of 2.5 h with a $H_2O_2$ dosage of 529 mg/L. The $H_2O_2$ dosage of 3.5 mg$H_2O_2$/h per mg TOC in the influent was found to be the optimum for the UV/$H_2O_2$ process.

The degradation of TOC and microorganism disinfection from synthetic SWW secondary effluents were investigated by Barrera et al. (2012) using UV-C and vacuum-ultraviolet (VUV). TOC removals ranged from 5.5 to 12.2% for UV-C/$H_2O_2$ and VUV/$H_2O_2$, respectively. Optimum $H_2O_2$/TOC molar ratios of 1.5 and 2.5 were found for VUV and UV-C, respectively. Furthermore, it was discovered that the photochemical processes were capable of rapid bacteria inactivation in less than 30 s.

Bustillo-Lecompte et al. (2013) evaluated the performance of the UV/$H_2O_2$ process for the SWW treatment. TOC loadings of up to 350 mg/L were used in the SWW influent. An optimum TOC removal of 75% was obtained for influent concentrations of up to 65 mgTOC/L and HRTs of 180 min with $H_2O_2$ dosages of 900 mg/L. An optimum molar ratio dosage of 14.03 mg$H_2O_2$/mgTOC$_{in}$ was also found for the UV/$H_2O_2$ process.

The UV/$H_2O_2$ alone was compared to other treatment technologies to treat SWW as an individual method by Bustillo-Lecompte et al. (2014). The UV/$H_2O_2$ alone was found to be the least efficient process with optimum removals of up to 50% at a cost of 67 $/kg of TOC removed. Moreover, the TOC removal was not significantly increased by augmenting the HRT. Therefore, although the UV/$H_2O_2$ process is effective to treat the SWW, the UV/$H_2O_2$ is expensive if applied alone. Consequently, SWW treatment by the combination of AOPs and biological processes is recommended while they are optimized at an appropriate residence time in each reactor.

### 4.6. Combined processes

SWW effluents are part of the food and beverage industry wastewaters (Oller et al., 2011; Vymazal, J. 2014; Valta et al., 2015). SWWs are one of the major concerns of the agro-industrial sector because of the high amounts of water used in the process of slaughtering and further cleaning of the facilities (De Sena et al., 2009; Oller et al., 2011; Valta et al., 2015).

It may be stated that it is beneficial, in terms of operation and economics, to implement combined processes for the treatment of SWW since it couples the benefit of different technologies to improve high strength industrial wastewater management (Kuşçu and Sponza, 2006; Ahn et al., 2007; Chan et al., 2009; Bazrafshan et al., 2012; Cao and Mehrvar, 2011; Barrera et al., 2012; Bazrafshan et al., 2012; Bustillo-Lecompte et al., 2013, 2014).

Del Pozo and Diez (2005) evaluated a combined anaerobic–aerobic fixed-film reactor for SWW treatment under sub-mesophilic conditions (25°C). Overall COD removals of up to 93% were obtained for OLRs of 0.77 kg/m$^3$ day, along with TN removals of up to 67% for a TN influent load of 0.084 kg N/m$^3$ day. Denitrification only implied 12–34% of the TN removal being limited by DO levels above 0.5 mg/L in the anaerobic section.

Bohdziewicz and Sroka (2005) considered combined AS-RO system for the treatment of SWW. The raw SWW was first pre-treated using activated sludge (AS). Results showed a high removal of contaminants from the SWW by the combined processes, including COD (99.80%), BOD (99.83%), TP (99.76%), and TN (99.77%).

A combined coagulation/adsorption process was evaluated by Mahtab et al. (2009) for SWW effluents using various coagulants, such as alum, ferrous sulfate, ferric chloride, and lime. Results show that optimum COD removal efficiencies of up to 92% are obtained by using alum as the coagulant. Nevertheless, it was concluded that the combined coagulation/adsorption process made not significant improvement in COD removal from SWW.

A laboratory scale anaerobic–aerobic system, consisting of an AF attached to an aerobic SBR, was used for SWW treatment (López-López et al., 2010). The AF operated with OLR in the range of 3.7–16.5 kg/m$^3$ day and at HRTs of up to 72 h. Up to 81% COD removals were obtained and was found to be inversely correlated to OLRs. When coupling the AF to the SBR, over 95% COD was removed in 9 h. Moreover, optimum conditions were detected at OLRs below 11 kg/m$^3$ day with HRT of 24 h.

On the other hand, Cao and Mehrvar (2011) evaluated the combined ABR and UV/$H_2O_2$ processes at laboratory scale for synthetic SWW treatment. Results showed that combined processes are more efficient than individual processes for SWW treatment. Up to 95% TOC, 98% COD, and 97% BOD removals were obtained for influent concentrations of 973 mg/L at HRTs in the ABR of up to 3.8 days and 3.6 h within the UV/$H_2O_2$ reactor.

Bazrafshan et al. (2012) assessed the performance of combined chemical coagulation (CC) and EC for the SWW treatment. BOD and COD removal rates were directly proportional to the applied voltage and coagulant dosage with up to 99% removal efficiencies for both parameters. As a result, the combined CC–EC processes were found to be more efficient than EC alone for SWW treatment.

Bustillo-Lecompte et al. (2013, 2014) evaluated the performance and operating costs of treating SWW using combined biological and AOPs. A comparison was made in terms of the treatment capability and overall costs for different technologies including

**Table 6**
Comparison of different technologies and their combination for slaughterhouse wastewater treatment.

| Processes[a] | HRT[b] (h) | $TOC_{in}$[c] (mg/L) | $COD_{in}$[c] (mg/L) | $BOD_{in}$[c] (mg/L) | $TN_{in}$[c] (mg/L) | TOC removal (%) | COD removal (%) | BOD removal (%) | TN removal (%) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| AeP-RO | 8–36 | – | 5300 | 2900 | 557 | – | 99.80 | 99.83 | 99.77 | Bohdziewicz and Sroka (2005) |
| AnaP | 24–2160 | 3500 | 1820–12,790 | – | 1176 | – | 71.51–94.31 | – | – | Caldera et al. (2005) |
| AnaP | 360 | – | 5800–11,600 | 4524–8700 | 11–11,150 | – | – | 20.20–95.60 | – | Chávez et al. (2005) |
| AnaP-AeP | 23–91 | – | 1190–2800 | 610–1150 | 150–260 | – | 93.00 | 97.00 | 69.00 | Del Pozo and Diez (2005) |
| AeP | 49 | – | 5000–5098 | – | 349–370 | – | 95.00–96.00 | – | 86.00–88.00 | Filali-Meknassi et al. (2005a) |
| AeP | 48 | – | 5155–5675 | – | 369–431 | – | 96.00 | – | 97.00–99.00 | Filali-Meknassi et al. (2005b) |
| AnaP-AeP | 249 | – | 3000 | – | – | – | 90–92 | – | – | Kuşçu and Sponza (2005) |
| AnaP | 24–48 | – | 7083 | – | 547 | – | 93.9 | – | – | Masse and Massé (2005) |
| AnaP | 18–27 | – | 1400–3600 | – | 13–179 | – | 70.60–92.60 | – | – | Miranda et al. (2005) |
| CC | – | – | 10,226–15,038 | 5042–8320 | – | – | 32.20–63.60 | 34.70–67.80 | – | Satyanarayan et al. (2005) |
| AOP | 0.13 | – | – | – | – | – | 10.70 | 23.60 | – | Wu and Doan (2005) |
| EC | 0.42 | – | 2600–2900 | 10,000–12,000 | – | – | 60.00–93.00 | – | – | Bayramoglu et al. (2006) |
| EC | 0.42 | – | 2600–2900 | 12,000–10,000 | – | – | 60.00–93.00 | – | – | Kobya et al. (2006) |
| AnaP-AeP | 249 | – | 3000 | – | 70–147 | – | 80.00–99.00 | – | 77.40 | Kuşçu and Sponza (2006) |
| AnaP-AeP | 24 | – | 6000–14,500 | – | 300–1000 | – | 99.00 | – | 46.00 | Ahn et al. (2007) |
| AnaP | – | – | 3102 | – | 186 | – | – | – | – | Amorim et al. (2007) |
| AnaP | 69 | – | 2360–4690 | 1190–2624 | 147–233 | – | 57.00–67.00 | 48.50–63.00 | 36.00–40.00 | Del Nery et al. (2007) |
| AnaP | 30–80 | – | 7148–20,400 | 3501–8030 | – | – | 62.00–96.40 | 93.96 | – | Saddoud and Sayadi (2007) |
| CW | – | – | 3188 | 2452–2500 | 494–500 | – | 97.40 | 99.90 | 78.20 | Soroko (2007) |
| AeP | 3.0–8.0 | – | 431 | 1320 | 5.6 | – | 72.00 | 99.00 | – | Al-Mutairi et al. (2008) |
| EC | 1.0–1.5 | – | 1290–1670 | 2700–3100 | – | – | 82.00 | 86.00 | – | Asselin et al. (2008) |
| AnaP | – | – | 1913–5157 | 1559–2683 | – | – | 21.00–58.00 | 14.00–64.00 | – | De Nardi et al. (2008) |
| GR | – | – | – | 3860 | – | – | – | 38.65–85.75 | – | Melo et al. (2008) |
| AeP | 42 | – | 6400–8320 | – | 260–306 | – | 95.00 | – | 97.00 | Lemaire et al. (2008) |
| AeP | 8.0 | – | 2850–4700 | 1000–2900 | 250–350 | – | 97.00 | – | 94.00 | Li et al. (2008) |
| AnaP | 10–3600 | 1030–3000 | 3000–4800 | 750–1890 | 109–325 | 15.00–86.00 | 18.00–80.00 | | | Rajakumar and Meenambal (2008) |
| AnaP | 60 | – | 4200–9100 | – | 565–785 | – | 72.20–98.60 | – | 45.90–63.70 | Debik and Coskun (2009) |
| AeP-AOP | 0.50 | – | 2800–3000 | 1400–1600 | – | – | 80.30–97.60 | 70.30–95.70 | – | De Sena et al. (2009) |
| AnaP | 48 | – | 5800–6100 | – | 530–810 | – | 80.00–92.00 | – | – | Gannoun et al. (2009) |
| AnaP | 48–240 | – | 2100–2425 | – | 250–260 | – | 88.00–99.00 | – | 76.00–78.00 | Kabdaşl et al. (2009) |
| AnaP | 10 | – | 2373–2610 | 900–2000 | 78–457 | – | 96.00–97.00 | 95.58–97.88 | 52.00–93.00 | Kist et al. (2009) |
| AnaP | 42 | – | 7460–9300 | – | 271–317 | – | 95.00 | – | 97.00 | Lemaire et al. (2009) |
| AOP | 5 | – | – | – | – | – | 18.00–95.00 | – | – | Luiz et al. (2009) |
| CC-AdP | 2 | – | 6605 | 5703 | – | – | 91.10–96.80 | 93.50–96.80 | – | Mahtab et al. (2009) |
| AeP | 29 | – | 9040 | 5242 | – | – | 89.03 | 89.73 | – | Pabón and Gélvez (2009) |
| CC-AeP | 0.33 | – | 2000–3000 | – | 100–200 | – | 80.00 | – | 90.00 | Wang et al. (2009) |
| AeP | 104 | – | 2800–3500 | – | 220–350 | – | 98.00–99.00 | – | 91.00–95.00 | Zhan et al. (2009) |
| AeP | – | – | 24,000 | 1198 | 139 | – | 90.00 | – | – | Al-Mutairi (2010) |
| AnaP-AeP-CC | 16–72 | – | 6363–11,000 | 5143–8360 | 46.6–138 | – | 50.10–97.42 | 97.76–98.92 | 73.48–92.72 | López-López et al. (2010) |
| AnaP | 30–97 | – | 8450–41,900 | 21,000 | – | – | 18.60–56.90 | – | – | Marcos et al. (2010) |
| UF | – | – | 3610–4180 | 1900–2200 | – | – | 94.52–94.74 | 97.80–97.89 | – | Yordanov (2010) |
| EC | 1.2 | – | 2171 | 1123 | – | – | 75.00–90.00 | – | – | Bayar et al. (2011) |
| AnaP-AOP | 76–91 | 80–950 | 2110–2305 | 1020–1143 | 80–334 | 89.90–95.00 | 97.70 | 96.60 | 1.00–6.00 | Cao and Mehrvar (2011) |
| AnaP-AeP-UV | 12 | – | 23–70 | 0.0–5.0 | 2.0–21 | 85.00 | – | – | 79.00 | De Nardi et al. (2011) |
| AnaP-AeP | 16 | – | 876–1987 | 12,000 | 84–409 | – | 90.60–97.60 | – | 81.50–95.60 | Fongsatitkul et al. (2011) |
| UF | 720–1344 | 50–328 | 114–1033 | – | 82–127 | 75.00–96.00 | 83.00–97.00 | – | 27.00–44.00 | Gürel and Büyükgüngör (2011) |
| AeP | – | – | 298–1115 | – | – | – | 53.65 | 84.32 | – | Mees et al. (2011) |
| AnaP | 12–48 | – | 6500 | 2900 | – | – | 75.00–83.00 | – | – | Méndez-Romero et al. (2011) |
| AnaP | – | – | 3437 | 2646 | 218 | – | 76–90 | – | 8.20–10.10 | Mijalova Nacheva et al. (2011) |
| AnaP | 12 | – | 3000–4800 | 750–1890 | 109–325 | – | 70.00–78.00 | – | – | Rajakumar et al. (2011) |
| EC | 0.83 | – | – | – | – | | 62.00–93.00 | 66.00–97.00 | 56.00–84.00 | Ahmadian et al. (2012) |
| AOP | 2.5 | 1000 | – | – | – | 57.60 | – | – | – | Barrera et al. (2012) |
| EC-CC | 25 | – | 4159–5817 | 2204–2543 | 92–137 | – | 80–98 | 75–93 | 75–80 | Bazrafshan et al. (2012) |

(continued on next page)

**Table 6** (*continued*)

| Processes[a] | HRT[b] (h) | $TOC_{in}$[c] (mg/L) | $COD_{in}$[c] (mg/L) | $BOD_{in}$[c] (mg/L) | $TN_{in}$[c] (mg/L) | TOC removal (%) | COD removal (%) | BOD removal (%) | TN removal (%) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| AeP | 12–20 | – | 5220 | – | 4500 | – | – | – | – | Dallago et al. (2012) |
| AeP | 110–583 | – | 850–1400 | – | 50–100 | – | 93.50–97.20 | – | – | Hsiao et al. (2012) |
| AeP-UF | 48 | – | 1764–2244 | 1529–1705 | 435–665 | 91.00 | 98.00 | – | – | Keskes et al. (2012) |
| AnaP | 20–96 | – | 5659–9238 | 5571–6288 | – | – | 92.10–96.60 | 98.00–98.78 | – | Park et al. (2012) |
| CC | 3.0 | – | 6970 | 5820 | – | – | 85.46–92.00 | 85.40 | – | Tariq et al. (2012) |
| AnaP | 8.0–24 | – | 3000–4800 | 750–1890 | – | – | 70.00–86.00 | – | – | Rajakumar et al. (2012) |
| AnaP | 794–3948 | – | 70,673 | – | – | – | 54.00–98.00 | – | – | Affes et al. (2013) |
| AnaP-AeP | 24 | – | 418 | 117 | 169 | – | 95.00 | – | 76.00 | Barana et al. (2013) |
| AnaP-AeP-AOP | 75–168 | 941–1009 | – | 630–650 | 254–428 | 89.50–99.90 | – | 99.70 | 76.40–81.60 | Bustillo-Lecompte et al. (2013) |
| AeP | 240 | 0.10 | 150 | – | – | – | 68.00–77.00 | – | – | Carvalho et al. (2013) |
| AeP | 1.0 | – | 18,200 | 10,500 | – | – | 81.31–93.08 | – | – | Hossaini et al. (2013) |
| AeP | 48 | 1152–1312 | 2052–2296 | 1529–1705 | 435–665 | – | 89 | – | – | Keskes et al. (2013) |
| AOP | 0.42 | 2240 | – | – | 290 | 92.60 | – | – | 76.20 | Khennoussi et al. (2013) |
| AeP-AnaP | 8.0 | – | 6485–6840 | 3000–3500 | 1050–1200 | – | 95.00 | – | 97.00 | Kundu et al. (2013) |
| AeP | 23 | – | 5590–11,750 | 3450–4365 | 214–256 | – | 74–94 | – | – | Louvet et al. (2013) |
| AnaP | 39–72 | – | 1040–24,200 | – | 296–690 | – | 30 | – | – | McCabe et al. (2013) |
| AnaP | 172 | – | 1790–4760 | 834–3186 | 90–196 | – | 79.00–89.00 | 84.00–94.00 | – | Nery et al. (2013) |
| CW | – | – | 293–3141 | 79–87 | 52–64 | – | 28.28–75.03 | 9.27–71.40 | 5.20–25.40 | Odong et al. (2013) |
| AnaP | 24–36 | – | 2273–20,073 | – | 570–1603 | – | 51.00–72.00 | – | 3.50–21.60 | Siqueira et al. (2013) |
| EC | 1.0 | – | 2171 | 1123 | 148 | – | 69.00–83.00 | – | – | Bayar et al. (2014) |
| AnaP-AeP-AOP | 41–76 | 100–1200 | – | 610–4635 | 50–841 | 75.22–99.98 | – | – | – | Bustillo-Lecompte et al. (2014) |
| EC | 1.5 | – | 840 | – | – | – | 90.00 | – | – | Eryuruk et al. (2014) |
| EC | – | – | – | – | – | – | 55.00–60.00 | – | – | Hernández-Ramírez et al. (2014) |
| AeP | 3.0–96 | – | 6185–6840 | – | 1950–3400 | – | 9.42–80.11 | – | 8.81–93.22 | Kundu et al. (2014) |
| AeP-AnaP | 888 | – | 1400–2500 | – | 200–250 | – | 30.20–98.68 | – | 22.40–96.16 | Li et al. (2014) |
| AnaP | 24 | – | 49–137 | 30–76 | 6.1–27 | – | 13.90 | 11.30 | 42.30–77.20 | Manh et al. (2014) |
| AnaP | 46–72 | – | 12,000–15,800 | – | – | – | 60.00 | – | – | Martinez et al. (2014) |
| AnaP | 48–72 | – | 1014–12,100 | 1410–7020 | – | – | 83.62 | 94.23 | – | McCabe et al. (2014) |
| AOP | 0.04–1.0 | – | 3337–4150 | 1950–2640 | – | – | 76.70–90.70 | – | – | Ozyonar and Karagozoglu (2014) |
| AeP | 12–3360 | 1435 | 6057–6193 | 4214–4240 | 547–576 | – | 97.80–98.20 | – | 97.70 | Pan et al. (2014) |
| AeP | 12–16 | – | 356–384 | – | 143–175 | – | – | – | 80.76–91.09 | Mees et al. (2014) |
| AnaP | 24–480 | – | 88 | – | – | – | 67.00–80.00 | – | 90.00 | Stets et al. (2014) |
| AnaP | 2640 | – | 18,600 | – | 5200 | – | – | – | 28.00–65.80 | Yoon et al. (2014) |
| MF | – | 183 | 480 | – | 115 | 44.81 | 90.63 | – | 45.22 | Almandoz et al. (2015) |
| AnaP-MF | 48–168 | 470–2778 | 2084–13,381 | – | 108–295 | 86.36–95.11 | 97.17–98.90 | – | 78.00–90.00 | Jensen et al. (2015) |

[a] AC, activated carbon; AdP, adsorption process; AeP, aerobic process; AnaP, anaerobic process; AOP, advanced oxidation process; CC, chemical coagulation; CW, constructed wetland; EC, electrocoagulation; GR, gamma radiation; MF, microfiltration; RO, reverse osmosis; UF, ultrafiltration; UV, ultraviolet light.
[b] HRT, Hydraulic retention time.
[c] $TOC_{in}$; $COD_{in}$; $BOD_{in}$; $TN_{in}$, influent concentration of total organic carbon, chemical oxygen demand, biochemical oxygen demand, and total nitrogen, respectively.

ABR, AS, and UV/$H_2O_2$. Overall efficiencies reached 75.22, 89.47, 94.53, 96.10, 96.36, and 99.98% by the UV/$H_2O_2$, ABR, AS, combined AS-ABR, combined ABR-AS, and combined ABR-AS-UV/$H_2O_2$ processes, respectively. A CEA was performed at optimal conditions for the SWW treatment by optimizing the total electricity cost, $H_2O_2$ consumption, and HRT. The combined ABR-AS-UV/$H_2O_2$ processes reached a maximum TOC removal of 99% in 76.5 h with an estimated cost of 6.79 $/m$^3$ day.

The combined ABR-AS-UV/$H_2O_2$ system was proven to be the most cost-effective solution compared to other processes for the TOC removal under these conditions. Nevertheless, the selection of a particular treatment method for SWW treatment requires an analysis of the characteristics of the SWW being treated and the best available technology (BAT) in order to comply with current regulations and different jurisdictions worldwide.

## 5. Summary and conclusions

A summary of the most commonly applied technologies and combined processes during the last decade is portrayed in Table 6, with particular attention to treatment efficiencies in terms of organic and nutrient removal, highlighting commonly used parameters, such as COD, TOC, BOD, and TN. The treatment efficiency of SWW varies extensively, it depends on several factors including, but not limited to, the characteristics of the SWW, the HRT, and the pollutant concentration in the influent. Table 6 also reveals that several types of individual and combined processes have been used for the SWW treatment.

SWWs are commonly pre-treated by screening, settling, blood collection, and fat separation, followed by physicochemical treatment, including DAF, coagulation/flocculation, and/or secondary biological treatment. Although the organic matter and nutrient removal can achieve high efficiencies, the treated SWW effluent usually need further treatment by membrane technologies, AOPs, or other appropriate treatment methods as combined processes. AOPs may also provide high-quality treated water allowing water recycle in the meat processing industry. Therefore, combined processes have evolved into a reliable technology that is nowadays successfully used for many types of SWW effluents. However, the selection of a specific treatment mainly depends on the characteristics of the SWW being treated, the BAT, and the compliance with current regulations under different political jurisdictions.

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## Nomenclature

| | |
|---|---|
| ABR | anaerobic baffled reactor |
| AC | activated carbon |
| AdP | adsorption process |
| AeP | aerobic process |
| AF | anaerobic filter |
| AnaP | anaerobic process |
| ANN | artificial neural networks |
| ANZECC | Australian and New Zealand Environment and Conservation Council |
| AOP | advanced oxidation process |
| AS | activated sludge |
| BAT | best available technology |
| BOD | biochemical oxygen demand |
| $BOD_{in}$ | influent concentration of biochemical oxygen demand |
| CC | chemical coagulation |
| CCD | central composite design |
| CEA | cost-effectiveness analysis |
| CEC | council of the European communities |
| CM | composite membrane |
| COD | chemical oxygen demand |
| $COD_{in}$ | influent concentration of chemical oxygen demand |
| CSTR | continuous flow stirred-tank reactor |
| CW | constructed wetland |
| DAF | dissolved air flotation |
| DO | dissolved oxygen |
| EC | electrocoagulation |
| ECO | environmental commissioner of Ontario |
| FAU | formazine attenuation units |
| GR | gamma radiation |
| HFCW | horizontal flow constructed wetland |
| HRT | hydraulic retention time |
| IR | internal recycle |
| MBR | membrane bioreactor |
| MF | microfiltration |
| OLR | organic loading rates |
| OMAFRA | Ontario ministry of agricultural and rural affairs |
| PACl | Polyaluminum chloride |
| RO | reverse osmosis |
| RSM | response surface methodology |
| SBR | sequencing batch reactor |
| TKN | total Kjeldahl nitrogen |
| TN | total nitrogen |
| $TN_{in}$ | influent concentration of total nitrogen |
| TOC | total organic carbon |
| $TOC_{in}$ | influent concentration of total organic carbon |
| UAF | up-flow anaerobic filter |
| UAPF | up-flow anaerobic packed-bed filters |
| UF | ultrafiltration |
| US EPA | united states environmental protection agency |
| UV | ultraviolet light |
| $UV/H_2O_2$ | ultraviolet light and hydrogen peroxide |
| TSS | total suspended solids |
| VFCW | vertical flow constructed wetlands |
| VUV | vacuum-ultraviolet |

## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jenvman.2015.07.008.

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