Water Practice & Technology

Water Practice & Technology Vol 17 No 12, 2598 doi: 10.2166/wpt.2022.147

The challenges and treatment of abattoir effluents: a South African perspective

Mabatho Moreroa[a,*] and Moses Basitere[b]

[a] Department of Chemical Engineering, University of South Africa, Private Bag X6, Florida, Roodepoort, Johannesburg 1710, Gauteng, South Africa
[b] Academic Support Programme for Engineering in Cape Town (ASPECT) & Centre for Higher Education Development, University of Cape Town, Rondebosch, Cape Town 7700, South Africa
*Corresponding author. E-mail: emorerms@unisa.ac.za

MM, 0000-0002-3042-2349

ABSTRACT

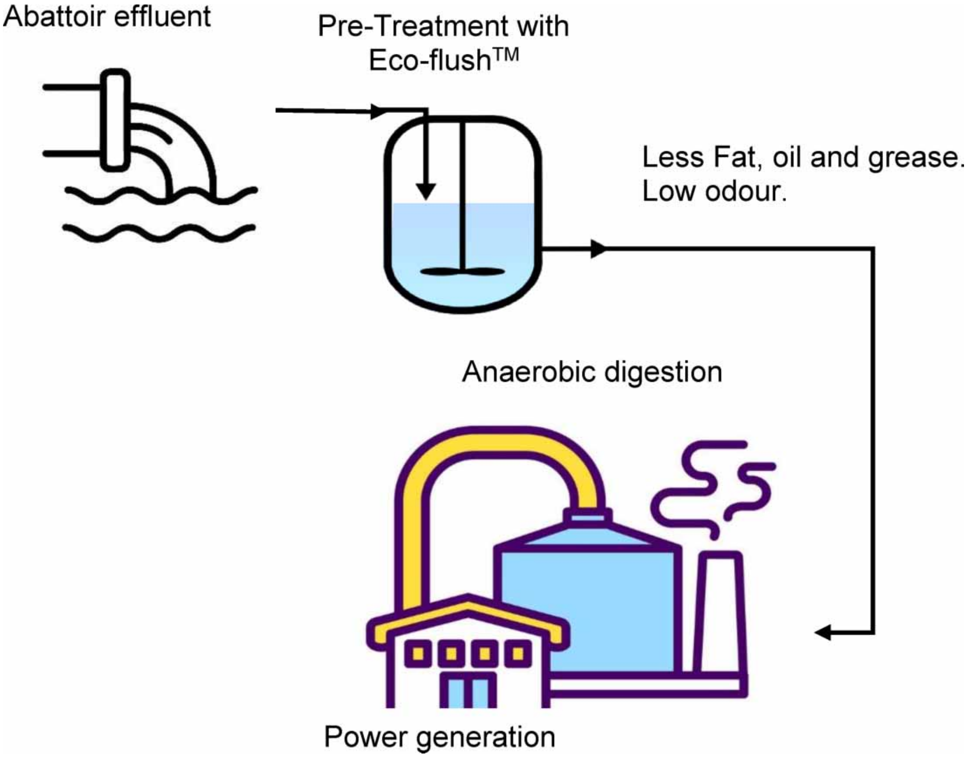
South Africa's (SA's) water resources have been severely affected by the demand for meat products. The growing population has resulted in an increase in food production, increasing the number of abattoirs from 25 in 1988 to 420 in 2021. Organic matter is abundant in abattoir effluent, with chemical oxygen demand levels reaching 9,000 mg/L. To reach permissible discharge limits, various methods such as sequential bed reactor, granular sludge bed, membrane bioreactor, and membrane filtration have been adopted. However, some abattoirs do not meet municipal regulatory requirements. As a result, practical and cost-effective approaches such as biofilm reactors were developed to encourage abattoirs to employ water treatment technology. Bioreactor-based technologies have proven to be successful, with more than 90% efficiency. Fat, oil, and grease (FOG) are problematic in abattoir effluents as they emit odours, attract insects, and impair the biodegradability of wastewater. For this reason, hydrolysis using a novel agent (Eco-flush™) has shown to be an effective technique for decreasing FOG. During treatment, biogas produced by anaerobic degradation may be utilized as an energy source to alleviate SA's energy problem. This review aims to outline the challenges related to abattoir wastewater in SA and highlight the gaps associated with abattoir wastewater treatment.

Key words: abattoir wastewater, biological treatment, FOG, pre-treatment

HIGHLIGHTS

- The study considers hydrolysis of solids arising from abattoir effluent.
- Production of biogas from anaerobic digestion of abattoir effluent is studied.
- Bioremediation of abattoir effluents using a biofilm reactor is studied.
- The South African abattoir industry is analysed critically.
- Integrated treatment systems for the bioremediation of abattoir effluents are suggested.

GRAPHICAL ABSTRACT



INTRODUCTION

A slaughterhouse, sometimes known as an abattoir, is a business that butchers animals for meat processing and other commercial goods. Dung for manure production, skin/hide for the leather industry, bones for poultry food, medications, cutlery, fats for tallow manufacture, and blood for blood meal production are some of the commercial items (GDARD (Gauteng Department of Agriculture and Rural Development) 2009; Tolera & Alemu 2020). The recovered fat may be used as a low-cost raw material in the production of animal feed, biodiesel, soap, grease, and candles, which is a significant raw ingredient in the steel rolling industry, providing the necessary lubrication for compressing steel sheets (Franke-Whittle & Insam 2013). Abattoir waste is described as waste or wastewater from an abattoir that may contain animal excrement, blood, fat, animal trimmings, urine, and paunch content. In numerous studies, abattoir waste has been highlighted as one of the most challenging types of food waste to handle globally and specifically in South Africa (SA) (Western Cape Government 2016). Essentially, the waste is toxic in nature (containing high chemical oxygen demand (COD) and pathogens (Tolera & Alemu 2020; Gufe *et al.* 2021)) and is likely to have negative implications for the environment and human health (Jabari *et al.* 2016; Western Cape Government 2016). Similarly, if not properly disposed of, the wastewater is a significant pollutant of water (Gufe *et al.*, 2021; Konneh *et al.* 2021). On a global scale, red meat abattoirs are well known for their excessive water use. Due to water shortage, SA concentrates its efforts on high-volume industrial customers to aid in water conservation (Müller 2017).

Although SA is a minor meat producer globally in comparison to Brazil, Europe, and the USA, the country is severely afflicted by slaughterhouse water pollution due to the country's water scarcity. The country's climate, with an average annual rainfall of 464 mm/year, varies from desert to semi-arid in the west to sub-humid along the eastern coastal plain (Oyebande 2010; Alexander 2021). For a country with high evaporation rates when compared with the rest of the world, the average rainfall of 464 mm/year is very low when compared to the global average of 860 mm/year and not enough to meet the water demands (Gray 2004). Thus, SA's limited water resources combined with its rapidly growing population have put unduly great stress on the water distribution system; a cause for concern (Alex & Pouris 2016).

There is an expected rise in red meat production and consumption, which will directly lead to an increase in slaughterhouse waste (Western Cape Government 2016). Statistics show that there were 25 registered red meat abattoirs in SA in 1988 (Müller 2017). The number increased to approximately 285 in the early 1990s (Müller 2017). The Gauteng Department of Agriculture and Rural Development estimates that there were over 470 abattoirs in SA by 2009 (GDARD 2009; AgriSETA 2020) as shown in Figure 1. However, due to the country's economic climate (such as increasing water scarcity; combined with the rising cost of energy and fuel (International Finance Corporation 2021)), the number has dropped to 432 in 2014 (Müller 2017) and 420 in 2020–2021 (AgriSETA 2020). The provincial breakdown is shown in Table 1 (Corporation 2020).

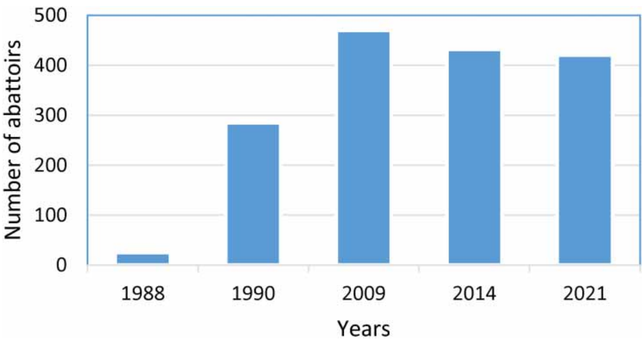


Figure 1 | The rise of abattoirs in SA over 33 years.

Table 1 | Provincial breakdown of red meat abattoirs in South Africa (Corporation 2020)

Province	Total number
Eastern Cape	67
Free State	80
Gauteng	40
KwaZulu-Natal	50
Limpopo	34
Mpumalanga	33
North West	35
Northern Cape	38
Western Cape	46
Total	423

According to the Western Cape Department of Agriculture, the poultry business is the largest generator of slaughterhouse waste, followed by sheep and ostrich (Western Cape Government 2016). However, red meat abattoirs, which butcher cattle, sheep, ostriches, and pigs, use the most water in the slaughterhouse industry (Müller 2017).

Abattoirs require potable water for the processing of carcasses and other associated items for human consumption, yet approximately 70–85% of that water is discharged as effluents into the environment (Muller 2005; GDARD 2009; Jabari *et al.* 2016). Statistics indicate that about 76,102.65 tonnes of abattoir waste was produced in the Western Cape province from 2015 to 2016 (Western Cape Government 2016). Freshwater is utilized in abattoirs for continual cleaning during the slaughter process, cleaning stock enclosures, washing down carcasses, and transportation of solid waste (Muller 2005). This effluent generally comprises blood, meat, fat, and intestines, as well as urine and faeces (Adamu & Dahiru 2020). These factors result in high COD, with values up to 9,000 mg/L observed (GDARD 2009), across different types of abattoirs.

The SA government has enacted legislation to restrict the discharge of slaughterhouse effluent (and other wastewaters) into water resources or municipal sewage systems. These laws specify criteria for wastewater composition, as stipulated by the South African Water Act of 1997. COD, total suspended solids (TSS), nitrogen, and pH levels are examples of such factors (DWA 1999; GDARD 2009). The government is attempting to protect natural water resources such as lakes, ponds, and rivers from contamination and ultimate destruction. In this review, the use of a novel hydrolysis agent (Eco-flush™) for the pre-treatment of abattoir wastewater is advocated in order to biologically reduce fat, oil, and grease (FOG). The usage of Eco-flush™ is expected to minimize problematic FOG, suspended particles, and odour, and to increase the biodegradability of wastewater. Furthermore, it is envisaged that using anaerobic biodegradation technologies during the (Basitere *et al.* 2017; Rinquest *et al.* 2019) treatment of such wastewater will aid in the generation of biogas, which is envisaged to be utilized as an alternative energy source in SA.

Water usage in abattoirs

Abattoirs require high-quality water that conforms to South African National Standards (SANS) (Department of Agriculture Forestry and Fisheries 2006). The water is used for cleanliness and sanitation, putting a burden on the country's scarce water supplies. Water is a very affordable commodity in SA; hence, there appears to be a lack of interest in water conservation. Table 2 gives a breakdown of the amount of water used per unit of animal in different abattoirs within SA.

Table 2 | The breakdown of water usage in abattoirs (Kist *et al.* 2009; Müller 2017; Gutu *et al.* 2021)

Water usage breakdown	Cattle	Sheep	Pigs	Poultry
Lairage (L/unit)	180	26.6	80	
Slaughter and dressing (L/unit)	180	26.6	80	14
Offal processing (L/unit)	225	33.3	100	
Heating water (L/unit)	225	33.3	100	0.2
Producing steam (L/unit)	45	6.7	20	
Cooling/chilling (L/unit)	72	10.6	32	3.0
Feather removal (L/unit)	–	–	–	1.0
Ablution and laundry (L/unit)	63	9.31	28	
Total per unit (L)	800–900	133	400	26

With around 420 registered abattoirs in the country, it is apparent that a significant volume of fresh water is consumed in abattoirs. Given proper water management skills, strategies may be implemented to reduce water usage and wastewater generation in abattoirs. These include reducing water usage, removing particles before they reach waste streams, reducing the amount of waste generated, minimizing spills, and implementing dry-cleaning regimes prior to wash-down.

Water management in abattoirs

Owing to the lack of awareness of the impact of abattoir wastewater on the environment, SA is suffering from the impact of poor waste treatment and disposal. Apart from wastewater, abattoirs generate solid waste that arises from hair, stomach content, fat and oil skimming, blood solids, and hides and hooves (Müller 2017). This waste is frequently disposed of in poorly managed and unpermitted landfills, converted into animal feed, or buried in trenches and then covered with dirt (Western Cape Government 2016). Other frequent waste disposal methods used by South African abattoirs include municipal sewage systems, waste disposal facilities, private dumping, farm burial, incineration, decomposition, burning, anaerobic digester, septic systems, and alkaline hydrolysis (Western Cape Government 2016; Bingo *et al.* 2021). Often, these methods of waste disposal are done with the limited or lack of knowledge of the waste disposal method and the lack of accountability. This often leads to environmental harm and undesirable consequences, such as the emission of greenhouse gases from open degradation and the spread of pathogens. When releasing their wastewater into municipal sewage systems or natural water resources, abattoirs usually do not comply with national by-laws that prescribe wastewater to have values as shown in Table 3 (DWA 1999; GDARD 2009).

According to the Government of the Western Cape in SA, there is a paucity of statistics on abattoir waste due to the absence of record-keeping within abattoirs. In addition, the National Environmental Management Act (NEMA) was enacted with minimal engagement of the slaughterhouse industry and scant information on the

Table 3 | Permissible levels of wastewater discharge parameters into South African water systems versus the actual abattoir wastewater (DWA 1999; GDARD 2009)

Variable	Municipal sewers	Water resource	Abattoir wastewater
COD (mg/L)	3,000–5,000	75	2,380–9,000
TSS (mg/L)	500	25	198–4,992
Nitrogen (mg/L)	200–300	3–15	25–215
pH	6–10	5.5–9.5	4.9–7.5

volume of abattoir waste produced in SA. This has made it rather challenging to report waste generation and management statistics (Western Cape Government 2016). This can be minimized by conducting physical research, in which several abattoirs are visited for quantitative waste analysis. However, there have been some reports on the general observation, revealing that large abattoirs generated wastewater with COD values of 1,217 and 5,025 mg/L have been reported for small abattoirs (Müller 2017). Larger abattoirs appear to have higher water consumption and wastewater treatment procedures than smaller abattoirs. This is because larger abattoirs often have well-trained management staff and comprehensive income/expenditure records. Smaller abattoirs often employ a professional health official to operate as a 'jack of all trades' in plant management (Muller 2005). In addition, because of their large capacity and revenue, large abattoirs can often afford to hire professional and trained personnel with the relevant skills and experience of handling different parts of the operation (Muller 2005).

In addition, authorities are frequently accommodating toward abattoirs in areas where sewage infrastructure is non-existent. Often, the abattoir will discharge its effluent into an in-house septic tank, which septic collectors would visit to drain and deposit straight into the nearest municipal sewage system. As a result, abattoirs are relieved of the need to build systems for wastewater treatment. Furthermore, because of the high levels of COD in slaughterhouse wastewater, the release of raw abattoir wastewater into municipal drainage results in high organic loadings in the treatment system (Adamu & Dahiru 2020). Due to this, the municipal treatment plant spends large amounts of capital in treating heavily populated water. On the other end of the spectrum, some abattoirs discharge polluted water into bodies of water such as rivers and natural wetlands (Emmanuel *et al.* 2016). This behaviour is harmful to the ecosystem because excessively contaminated water stresses aquatic animals and plants, generates foul odours, and serves as a breeding ground for deadly viruses and infectious microorganisms (Tuttle-raycraft *et al.* 2017).

Changes in waste management in abattoirs may have a favourable influence on the abattoirs' operating costs, which abattoir management is frequently unaware of. The wastewater produced might be utilized to produce biogas, which could be used as an alternative energy source within the slaughterhouse. The facility may use the gas for lighting and heating, lowering its electricity bill. The treated wastewater can be utilized for non-sterile purposes such as toilet flushing. This will also help to maximize earnings because the water cost will be decreased. Following wastewater treatment, the proceeding sludge may further be used as an organic fertilizer/compost, which the abattoir may sell and generate income. Additional methods of how to manage waste from abattoirs and their potential end products are outlined by Western Cape Government (2016).

Environmental impacts

Often, a quick way to get rid of the heavily polluted water from abattoirs is through environmental discharge. When untreated, wastewater generated from abattoirs may have a wide variety of organic matter, including high COD values. COD is defined as the mass concentration of oxygen according to ISSO 6060, which is equal to the amount of dichromate absorbed by dissolved and suspended matter when that oxygen is treated with a sample (water or sludge) under defined conditions (Geerdink *et al.* 2017). Wastewater generated from abattoirs contains high organic matter with COD values between 2,380 and 9,000 mg/L being reported (GDARD 2009). With such high organic loads, the environment tends to be the hardest hit by the action.

The Blesbokspruit wetland in SA is one such natural water resource that suffers from the effects of industrial water pollution. The Blesbokspruit wetland, located on Johannesburg's eastern outskirts, is a recreational area that is home to a variety of aquatic creatures and birds. The catchment spans approximately 1,858 km^2 and roughly 21 km (Mckay *et al.* 2018a). The wetland receives many forms of wastewater from domestic sewage, acid mine treatment facilities, the paper and pulp industry, and surrounding urban and agricultural operations (Mckay *et al.* 2018b). Due to pollution and, more recently, an invasion of the water hyacinth, an invasive aquatic plant, the wetland is slowly degrading. The bulk of the water surface of the Blesbokspruit is now covered by invasive plant species, which has expanded rapidly (Badenhorst 2021). It is thought that water hyacinth rapidly grows because it absorbs nutrients from the organic material present in the sewage discharge. Additionally, the wetland's aquatic fauna and flora are declining as a result of the high organic load (OL) from sewage waste entering the water body (Robertson 2017). OL impacts the bacterial community makeup in a water treatment system and is one of the parameters that may determine the efficacy of a water treatment system. Szabó *et al.* (2017) reported that the organic loading rate (OLR) has an impact on sludge communities. This is because the nutritional content is among other factors, the determining factor for biodegradation and structure of the bacterial community, which are key players in the biological treatment of wastewater (Carrero-Colón *et al.* 2006; Koshlaf & Ball 2017; Szabó *et al.* 2017; Wu *et al.* 2018).

In addition, high concentrations of suspended solids (SS) and turbidity can alter the chemical, physical, and biological properties of a water body. High concentrations of SS have reduced feeding in freshwater mussels, thus disturbing aquatic life (Tuttle-raycraft *et al.* 2017). The presence of SS and high turbidity in water can restrict the amount of light that penetrates through the water, thus causing a change in temperature and affecting the aquatic life that relies on sunlight for their metabolic processes. When in high concentrations, these two parameters (SS and turbidity) affect plant growth in water, prevent proper egg and larval development, damage sensitive parts of fish (gills) and other organisms, and in turn, increase their vulnerability to disease (Fondriest Environmental, Inc. 2014). The establishment of this phenomenon has led to the legislation that regulate concentrations of SS in water bodies. The issue of SS should, therefore, be addressed during wastewater treatment processes and before the water can be discharged into water bodies.

Characterization

Several parameters may affect the treatment efficiency of abattoir wastewater. These include the wastewater source, or the type(s) of animals being slaughtered, which subsequently results in the wastewater characteristics as shown in Table 4. It is worth noting that wastewater properties vary greatly even among comparable types of slaughterhouse operations.

Table 4 | Characteristics of various abattoir wastewater as reported by other researchers

Slaughter type	COD (mg/L)	BOD_5 (mg/L)	pH	TSS (mg/L)	TDS (mg/L)	TKN (mg/L)	Nitrate (mg/L)	Phosphate (mg/L)	Ref.
Red meat	2,380–8,942	–	5.7–8.4	189–3,330	595–2,805	0.71–24	–	–	Haslett (2016)
Poultry	2,133–4,137	1,100–2,750	6.5–8.0	315–1,273	–	77–352	–	8–27	Basitere *et al.* (2017)
Pigs	465	575	5.7	610	–	13–86	13.5	5.9	Suceveanu *et al.* (2018)
Sheep and cows	2,200	1,060	6.62	1,130	2,000	250–500	500	6	Al Smadi *et al.* (2019)
Cows, goats, sheep and camels	1,421	718	8	946	3,353	–	51	17	Akan *et al.* (2010)
Cattle	4,502	2,350	7.1	–	–	154	–	–	Husam & Nassar (2019)
Cattle	5,817	2,543	7.31	–	–	137	–	–	Bazrafshan *et al.* (2012)
Poultry	5,280	–	6.61	1,207	–	–	–	–	Bingo *et al.* (2021)
Swine	1,239	556.45	8.13	751.3	–	–	–	–	Cruz *et al.* (2019)

COD: chemical oxygen demand; BOD: biochemical oxygen demand; TSS: total suspended solids; TDS: total dissolved solids; TKN: total Kjeldahl nitrogen.

Treatment of abattoir wastewater

With the increasing number of abattoirs worldwide, there will be an increase in the amount of wastewater to treat. Owing to its detrimental effect on the environment, high organic matter, and large production volumes, abattoir wastewater has become a great concern in the running and management of the facility. Several research studies have been carried out to find environmentally, cost-effective and easy-to-use methods to treat abattoir wastewater. Examples are shown in Table 5.

Table 5 | Treatment methods previously used for abattoir wastewater treatment

Treatment method	Abattoir	Treatment parameter	Influent	Effluent	Efficiency (%)	Ref.
SBR	Red meat	COD (mg/L)	4,000–6,000	200	90	Pereira *et al.* (2006)
EGSB	Poultry	COD (mg/L)	5,280	1,085	98	Bingo *et al.* (2021)
		FOG (g/L)	35	25	97	
		TSS (mg/L)	198	152	99	
MBR	Poultry	COD (mg/L)	1,085	100	–	Bingo *et al.* (2021)
		FOG (g/L)	25	8	–	
		TSS (mg/L)	152	7	–	
IMF	Poultry	Turbidity, colour, TSS, COD, and BOD	–	–	100	Meiramkulova *et al.* (2020)
Electrochemical	Poultry	Turbidity, colour, total suspended solids, total iron, aluminium, COD, and BOD	–	–	71–85	Meiramkulova *et al.* (2020)
		Free and total chlorine, nitrites, nitrates, phosphates, and ammonium nitrogen	–	–	4–45	
SGBR	Poultry	COD (mg/L)	5,216	–	>80	Rinquest *et al.* (2019)
SGBR	Poultry	COD (mg/L)	1,223–9,695	15–940	93	Basitere *et al.* (2017)
		TSS (mg/L)	734–4,992	21–111	95	
		FOG (g/L)	131–684	–	90	

SBR: sequential bed reactor; EGSB: expanded granular sludge bed; MBR: membrane bioreactor; IMF: integrated membrane filtration.

Parameters such as COD, TSS, and nitrogen levels are carefully monitored throughout the treatment of abattoir effluent. The primary goal in SA is to minimize the values of these factors, as specified in Table 3. COD and biochemical oxygen demand (BOD) are comparable in that they both assess the quantity of organic matter in wastewater; however, COD is preferred over BOD (Kayaalp *et al.* 2010). The BOD test is performed at certain temperatures (typically 20 °C), and the results are obtained in about 5 days (Attiogbe *et al.* 2011; Jouanneau *et al.* 2014). Because of the 5-day incubation time for BOD analysis, COD has become the preferred alternative over BOD.

Anaerobic treatment appears to be the ideal approach for treating slaughterhouse wastewater, owing to its efficacy in treating high-strength effluent while requiring less sophisticated equipment (Johns 1995; Bustillo-Lecompte & Mehrvar 2017). However, treated water frequently contains solubilized organic matter that requires further treatment via aerobic processes. Additionally, certain slaughterhouse effluents contain hazardous, non-biodegradable, bioresistant, and recalcitrant chemicals. Thus, advanced oxidation processes (AOPs) may be employed to enhance the biodegradability of slaughterhouse wastewater and inactivate harmful bacteria and viruses that remain after biological treatment (Kanafin *et al.* 2022). In general, it is more effective to integrate several treatment technologies in order to accomplish efficient slaughterhouse wastewater treatment.

Fat, oil, and grease

Apart from the physicochemical properties of abattoir wastewater mentioned earlier, other parameters that contribute to the characterization of abattoir wastewater are FOG, which are a cause for concern when treating abattoir wastewater. The FOG arises from various stages of slaughtering, such as cutting and trimming the meat. There are various reasons why fats are cut-off from meat products, which include consumer preference.

With the increase in heart-related conditions that humans are suffering from, there is a need to reduce the amount of fats in one's diet. Consumers find themselves opting for lean meat as opposed to its counterpart. It has been reported that lean red meat, trimmed of visible fat, can reduce cardiovascular risk factors (Li *et al.* 2005). Due to this, meat processers find themselves having to remove as much fat as possible from meat to suit the needs of the market. The removed fats often solidify at lower temperatures, causing serious operational damage such as clogging and the eventual release of bad odour in water treatment facilities. The FOG float in the treatment reactor and thus form part of SS. The floating solids become a breeding ground for insects, flies, and pathogens, which are an undesirable factor. The problems related to FOG are so common; researchers have tried several techniques to mitigate the problem. These are shown in Table 6.

Table 6 | Techniques used for the treatment of FOG in abattoir wastewater

Abattoir type	Treatment method	Efficiency (%)	Ref.
–	Screening and scrapping	90	Muller (2005)
Pigs	Activated sludge	72	Suceveanu *et al.* (2018)
–	Hydrolysis	100	Pereira *et al.* (2006)
Poultry	Hydrolysis	99	Bingo *et al.* (2021)
Cattle	Chemical and thermochemical	3–8.5	Harris *et al.* (2017)
Poultry	Bioflocculant-supported dissolved air flotation and hydrolysis	91	Dlangamandla *et al.* (2018)
Poultry	Chemical dissolved air flotation	84	Dlangamandla *et al.* (2018)

In resolving the problem of FOG build-up, it was observed that screening and scraping are the most prevalent methods of removing solid particles such as fat, bone, hair, and meat that were lost during the slaughtering process. The screening strainers are made of metal wire and may catch particles of varying sizes depending on the mesh size of the strainer (Mittal 2006; EOH 2018). The screening and filtration methods are efficient in removing solids (up to 70% removal rates). However, they create another environmental challenge of disposal (Mittal 2006).

There is a link between solid removal and biodegradability of the preceeding wastewater. Due to this, it is recommended to remove the FOG and other solids before the biodegradation of the wastewater. This will form part of the pre-treatment of the wastewater. This phenomenon was investigated by Pereira *et al.* (2006). The study was aimed at understanding how different conditions affect the hydrolysis of fat and grease present in abattoir wastewater by a commercial *Candida rugosa* lipase. Biogas was used as a measure of biodegradabilition of the wastewater. It was revealed that pre-treatment of fat and grease resulted in four times more production of biogas than raw crude water. This proved that hydrolysis as a form of pre-treatment is an effective method to improve the biodegradability of abattoir wastewater.

The use of a developing bioremediation agent, which is an enzyme-based agent, called Eco-flush™, has recently been identified to be a novel hydrolysis approach, to validate the efficacy and practicality of adopting the hydrolysis process as a kind of fat pre-treatment (Bingo *et al.* 2021). Eco-flush™ is a cluster of naturally occurring bacteria that are isolated from soil, packaged in an inactive state, and activated when exposed to nutrient-rich wastewater. Eco-flush™ contains glaucids and essential amino acids that promote the natural proliferation of certain bacteria that produce enzymes capable of degrading hydrocarbon chains in FOG and oxidizing ammonia (NH_3) to nitrite (NO_2^-) and nitrate (NO_3^-), as well as the elimination of pathogenic bacteria and odour-causing bacteria. Additionally, it reduces the components of wastewater that contribute to COD and BOD levels (Ergofito 2012).

Although this technology has not been completely researched, it is expected to be a more cost-effective and superior alternative to pure commercial enzymes. The employment of the innovative Eco-flush™ achieved COD removal efficiencies of 98%, FOG removal efficiencies of 97%, and TSS removal efficiencies of 99% (Bingo *et al.* 2021; Gutu *et al.* 2021). Because of its efficacy, this review indicates the potential of using Eco-flush™ in a broader range of slaughterhouse wastewaters, such as red meat as a pre-treatment to hydrolyze FOG as well the odour.

Bacteria metabolizes the dissolved organic matter while producing methane, hydrogen, or carbon dioxide. The product of degradation relies on the degradation method used, such as aerobic and anaerobic biodegradation.

Taking into consideration the characteristics of abattoir wastewater such as high organic matter, anaerobic systems may be used during the first stages of treatment. Anaerobic systems are beneficial in that they reduce odour and pathogens and produce methane gas (biogas), which may be used as an energy source to power the treatment plant (Mittal 2011). The advantages and disadvantages of anaerobic degradation are shown in Table 7.

Table 7 | Advantages and disadvantages of anaerobic digestion (Chan *et al.* 2009; Mittal 2011)

Advantages	Disadvantages
High organic removal efficiency	Moderate to poor effluent quality
High OLR	Low nutrient requirement
Low sludge production	High temperature sensitivity
Low-to-moderate energy requirement	Long start-up time (2–4 months)
Bioenergy and nutrient recovery	Potential odour problems
	Essentially serves as pre-treatment

Following anaerobic degradation, an aerobic stage may follow, to further treat the wastewater. The expectations and outcomes of using aerobic degradation are shown in Table 8.

Table 8 | Expectations of aerobic treatment (Chan *et al.* 2009)

Parameters	Degree
Efficiency	High overall treatment efficiency
Sludge production	High
Energy requirement	High
Bioenergy and nutrient recovery	None
Effluent quality	Excellent
Nutrient requirement	High
Temperature sensitivity	Low
Start-up time	Short (2–4 weeks)
Odour problems	Less
Treatment level	Total mode of treatment, thus no pre- or post-treatment required

In an aerobic biological system, the floating fats found in abattoir wastewater may cause a decline in dissolved oxygen (DO) levels. DO levels in aerobic systems should be maintained between 0.5 and 2.0 mg/L to aid the completion of the digestion process and to avoid odour (Shammas & Wang 2007; Daskiran *et al.* 2019). Low oxygen levels in an aerobic system promote an anaerobic environment, which causes a fouling smell and the release of toxic greenhouse gases such as methane and H_2S that is a corrosion agent. Inadequate amounts of oxygen cause a change in the species present, enzyme activity, as well as death and reduction in microbial growth (Kazbar *et al.* 2019; Meng *et al.* 2019).

The role of microorganisms in wastewater treatment

Various living organisms that make up the food chain and, to some extent, the food web are known. By having these natural chains and webs, the natural processes that balance nature take place and make the earth what it is today. Bacteria play a major role of decomposition in the environment and wastewater treatment plants. Without decomposition, the earth would pile up with matter and most living organisms would die without decomposing. Bacteria decompose dead matter from the soil, food, and waste from our guts. Bacteria play a role in cleaning up the environment by degrading waste generated by human beings (Jenkins *et al.* 2004). Several types of bacteria exist in the environment, mammals, or other living organisms. To classify bacteria, taxonomic studies are performed in a sub-discipline of microbiology.

Taxonomic studies of bacteria began in the late 19th century when bacteria were classified based on phenotypic markers (Schleifer 2009). For the past decades, bacterial taxonomy has been used to identify new bacterial species. This approach involves a combination of genotypic, phylogenetic, and phenotypic techniques, which aids in the identification and description of bacteria (Morata de Ambrosini *et al.* 2014). This study is beneficial when studying a large population of bacteria in the environment where they occur in communities called consortia. A consortium is a community of bacteria comprising multiple species, living together in the same environment (Noszczyńska & Piotrowska-Seget 2018). Bacteria prefer to live as a consortium because it is usually difficult for a single microorganism/planktonic to degrade complex components in the environment. Bacteria living as a consortium are efficient at degradation due to several communication strategies that they employ during degradation (Jefferson 2004). This is because, in a consortium, several microorganisms with different metabolic capabilities are present. This difference in metabolic pathways is what enables bacteria to work together in a form of a consortium to degrade different materials found in the environment (Jamal *et al.* 2018). Since this discovery, researchers have been formulating and studying consortia for the degradation of complex organic wastes through quorum sensing (Maddela *et al.* 2019), wastewater polishing by consortia (Gonçalves *et al.* 2016), biodegradation mediated by bacterial communities (Noszczyńska & Piotrowska-Seget 2018), and microbial collaborative effects (Ji *et al.* 2019). Through taxonomy, several studies have investigated the common microorganisms found in various samples of abattoir wastewater as shown in Table 9.

Table 9 | Common microorganisms found in various samples of abattoir wastewater

Origin of sludge	Common species	Dominant species	Ref.
Raw effluent	*Escherichia* sp., *Pseudomonas* sp., *Enterobacter* sp., *Klebsiella* sp., *Staphylococcus* sp., *Salmonella* sp., and *Streptococcus* sp.	*Escherichia* sp.	Emmanuel *et al.* (2016)
Anaerobic digestor	*Desulfovibrio*, *Clostridium*, *Desulfobulbus*, *Desulfotomaculum*, *Desulfomicrobium*, and *Bacteroides*	*Clostridium acetireducens* and *Segetibacter* spp.	Jabari *et al.* (2016)
Raw effluent	–	*F. streptococcus* and *Escherichia coli*	Nafarnda *et al.* (2012)
Raw effluent	*Escherichia coli*, *Bacillus cereus*, *Staphylococcus aureus*, *Salmonella* sp., *Klebsiella pneumonia*, *Seratia liquefasciens*, *Bacillus* sp., *Baccilus plegem*, *Aspergillus fimigatus*, *Aspergillus flavus*, *Trichoderma harziarum*, *Penicillum camberti*, *Aspergillus niger*, and *Rhizopus tolonifer*	Not specified	Sherifat *et al.* (2015)
Raw effluent	*Bacillus* sp., *Clostridium welchii* (*C. perfringes*), *Pseudomonas aeruginosa*, *Micrococcus luteus*, *Vibrio* sp., and *Lactobacillus plantarum*	Not specified	Adesemoye *et al.* (2006)
Abattoir receiving soil	*Escherichia coli*, *Pseudomonas aeruginosa*, *Bacillus* sp., *Staphylococcus epidermidis*, *Staphylococcus aureus*, *Alcaligenes* sp., *Klebsiella* sp., *Aspergillus flavus*, *Aspergillus niger*, *Penicillium* sp., *Geotrichum* sp. and *Mucor* sp.	*Bacillus* sp.	Akinnibosun & Ayejuyoni (2015)

As useful as microorganisms are in the biological treatment of wastewater, the discharged effluent (containing microorganisms) frequently ends up in water resources that humans may use for drinking and domestic purposes (Adesemoye *et al.* 2006). The existence of such microbes in bodies of water is cause for concern in this situation because the majority of them are harmful when taken in large quantities or on a regular basis (U.S. EPA 2014). This is reason enough to put in place robust water treatment systems that will prevent hazardous microorganisms from entering the environment.

Hybrid systems

Following biological treatment, the wastewater often contains pathogens, chemicals, and pollutants that must be removed from the raw influent. As a consequence, hybrid/integrated systems have been created, which are a combination of multiple treatment approaches to give the best treatment efficiency (Bingo *et al.* 2021; Zamani *et al.*

2021; Clem & Mendonça 2022). Several hybrid solutions for slaughterhouse wastewater have been devised, as it was assumed that combining biological and non-biological approaches would result in greater efficiency. A comparison of biological, non-biological, and hybrid methods is shown in Table 10. Although biological and non-biological techniques are widely utilized in hybrid systems, there are hybrid methods that solely use biological or non-biological approaches. Inorganic compounds, viruses, bacteria, and parasites are cleared during tertiary treatment, making the water suitable for reuse, recycling, and discharge into the environment. Chemicals are often utilized during tertiary treatment, making the process costly and unfriendly to the environment if not properly handled. The most often utilized tertiary treatment technologies, which look to have a good prospect, include chemical precipitation, neutralization, adsorption, disinfection (chlorine, ozone, and UV radiation), electrocoagulation, reverse osmosis (RO), ozone (O_3), and ultrafiltration ion exchange. However, recent research found encouraging outcomes of biological tertiary treatment employing hydroponic systems (Kaushal & Mahajan 2021). The hydroponic system, with COD removal efficiencies of up to 88%, was used as a tertiary treatment stage for sewage wastewater. With concerns revolving around the cost of tertiary wastewater treatment, such systems may be used to evaluate the environmental and economic aspects relating to such treatment, as this remains a gap in knowledge (de Boer *et al.* 2022). In an attempt to fill this gap, Ozgun *et al.* (2021) have studied 16 sewage wastewater treatment plants and reported that the unit total capital cost was found to be 0.054 ± 0.009 €/m^3 (thus R0.94/m^3) for tertiary treatment and 0.077 ± 0.021 €/m^3 (thus R1.34/m^3) for the operation and management of the tertiary treatment stages (Ozgun *et al.* 2021). While we agree that the costs indicated by Ozgun *et al.* (2021) are reasonable and make tertiary treatment accessible, we believe that further work is needed to evaluate the costs associated with various tertiary treatment options.

Table 10 | A comparison of biological, non-biological, and hybrid treatment systems for the treatment of abattoir wastewater

	Method	Abattoir type	Influent COD (mg/L)	Effluent COD (mg/L)	Efficiency (%)	Ref.
Biological	Membrane bioreactor	–	571	16	97	Gürel & Büyükgüngör (2011)
	Anaerobic baffled reactor	Cattle, sheep, and poultry	2,200–2,500	–	70–90	Al Smadi *et al.* (2019)
	Activated sludge	Pigs	465.5	399.2	15	Suceveanu *et al.* (2018)
	Static granular bed reactor	Poultry	5,216	–	80–95	Rinquest *et al.* (2019)
	Wetland	–	–	–	89	Gutiérrez-Sarabia *et al.* (2004)
Non-biological	Electrocoagulation	–	–	–	56	Nugroho *et al.* (2021)
	Electrochemical + UF + RO	Poultry	–	–	71–85	Meiramkulova *et al.* (2020)
	Electrocoagulation	Swine	1,239	41.67	90–97	Cruz *et al.* (2019)
Hybrid	EGSB + UF + RO	Poultry	5,280	101	98	Bingo *et al.* (2021)
	Chemical + electrocoagulation	–	5,817	13	99	Bazrafshan *et al.* (2012)
	AD + coagulation + flocculation	Bovine and sheep	5,136	–	76	Bazrafshan *et al.* (2012)

UF: ultrafiltration; RO: reverse osmosis; AD: anaerobic digestion; EGSB: expanded granular sludge bed.

As conveyed in Table 10, the treatment efficiency tends to vary depending on the kind of wastewater being treated, even within the same category. This means that the treatment efficiency is determined by the technology utilized as well as other elements such as residence time, OLR, suspended particles, temperature, agitation speed, and so on. Nonetheless, biological approaches appear to be chosen over other methods due to their simplicity of operation and lower capital expenditure. Some advantages and disadvantages of the treatment methods are outlined in Table 11.

Table 11 | Advantages and disadvantages of treatment methods

Treatment method	Advantages	Disadvantages	Ref.
Electrocoagulation	May be efficient when the correct electrodes are used. Less sludge formation.	Long run time. Efficiency depends on the type of electrodes used. It needs to be combined with other treatment methods. High cost of operation.	Obi *et al.* (2022); AlJaberi *et al.* (2022)
Ultrafiltration	Recovery of crude proteins.	–	Avula *et al.* (2009)
Reverse osmosis	Efficient in disinfection.	It can only be used in the tertiary treatment.	Bingo *et al.* (2021)
Anaerobic digestion	High overall treatment efficiency. High OLR. Low-to-moderate energy requirement.	High temperature sensitivity. Long start-up time (2–4 months). Essentially serves as pre-treatment.	Chan *et al.* (2009); Mittal (2011)
Expanded granular sludge bed	High treatment efficiency.	–	Bingo *et al.* (2021)
Membrane bioreactor	Effective in removing organic and inorganic contaminants as well as biological entities from wastewater.	–	Avula *et al.* (2009)

CONCLUSIONS

South African abattoirs have become negligent with regard to the usage and waste of water in their facilities. Currently, little information is available on the consequences of handling abattoir waste. The legislature must place strict restrictions on the flow of abattoir effluent into water treatment plants. Furthermore, the advantages of installing a water treatment system must be explained to abattoir management. Water reuse for toilet flushing and biogas production are two examples of such advantages. With SA experiencing an energy crisis, residents are encouraged to adopt alternative energy sources to reduce the demand for power. This goal will be reached by utilizing biogas from water treatment facilities as an energy source. To minimize the spread of infectious illnesses caused by improper waste management, abattoirs must employ methods based on low-cost and practical wastewater treatment technologies. This may be addressed by using biological treatment alternatives and incorporating emerging low-cost materials like enzyme-based pre-treatment such as Eco-flush™ to bioremediate the FOG and also can be used to decrease odour that attracts disease-carrying insects.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Adamu, M. & Dahiru, M. 2020 A review on abattoir wastewater treatment for environmental health improvement. *Journal of Environmental Bioremediation and Toxicology* **3**(2), 26–31. https://doi.org/10.54987/jebat.v3i2.548.

Adesemoye, A. O., Opere, B. O. & Makinde, S. C. O. 2006 Microbial content of abattoir wastewater and its contaminated soil in Lagos, Nigeria. *African Journal of Biotechnology* **5**(20), 1963–1968. https://doi.org/10.5897/AJB2006.000-5096.

AgriSETA 2020 *RED MEAT Sub-Sector Skills Plan.*

Akan, J. C., Abdulrahman, F. I. & Yusuf, E. 2010 Physical and chemical parameters in abattoir wastewater sample. *The Pacific Journal of Science and Technology* **11**(1), 640–648.

Akinnibosun, F. & Ayejuyoni, T. 2015 Assessment of microbial population and physico-chemical properties of abattoir effluent-contaminated soils in Benin City, Nigeria. *Agro-Science Journal of Tropical Agriculture, Food, Environment and Extension Volume* **14**(3), 1–6.

AlJaberi, F. Y., Alardhi, S. M., Ahmed, S. A., Salman, A. D., Juzsakova, T., Cretescu, I., Le, P. C., Chung, W. J., Chang, S. W. & Nguyen, D. D. 2022 Can electrocoagulation technology be integrated with wastewater treatment systems to improve treatment efficiency? *Environmental Research* **214**. https://doi.org/10.1016/j.envres.2022.113890.

Al Smadi, B. M., Al-Hayek, W. & Abu Hajar, H. A. 2019 Treatment of Amman slaughterhouse wastewater by anaerobic baffled reactor. *International Journal of Civil Engineering* **17**(9), 1445–1454. https://doi.org/10.1007/s40999-019-00406-5.

Alexander, M. (2021, July 16). South Africa's weather and climate. South Africa's Gateway. https://southafrica-info.com/land/south-africa-weather-climate

Alex, G. & Pouris, A. 2016 A 20 year forecast of water usage in electricity generation for South Africa amidst water scarce conditions. *Renewable and Sustainable Energy Reviews* **62**, 1106–1121. https://doi.org/10.1016/j.rser.2016.05.003.

Attiogbe, F., Glover-Amengor, M. & Nyadziehe, K. 2011 Correlating biochemical and chemical oxygen demand of effluents - A case study of selected industries in Kumasi, Ghana. *West African Journal of Applied Ecology* **11**(1), 1 –11. https://doi.org/10.4314/wajae.v11i1.45722.

Avula, R. Y., Nelson, H. M. & Singh, R. K. 2009 Recycling of poultry process wastewater by ultrafiltration. *Innovative Food Science and Emerging Technologies* **10**(1), 1–8. https://doi.org/10.1016/j.ifset.2008.08.005.

Badenhorst, J. 2021 *Special Beetle to Remove Hyacinth*. Springs Advertiser, Johannesburg, South Africa.

Basitere, M., Rinquest, Z., Njoya, M., Sheldon, M. S. & Ntwampe, S. K. O. 2017 Treatment of poultry slaughterhouse wastewater using a static granular bed reactor (SGBR) coupled with ultrafiltration (UF) membrane system. *Water Science and Technology* **76**(1), 106–114. https://doi.org/10.2166/wst.2017.179.

Bazrafshan, E., Kord Mostafapour, F., Farzadkia, M., Ownagh, K. A. & Mahvi, A. H. 2012 Slaughterhouse wastewater treatment by combined chemical coagulation and electrocoagulation process. *PLoS ONE* **7**(6), 1–8. https://doi.org/10.1371/journal.pone.0040108.

Bingo, M. N., Njoya, M., Basitere, M., Ntwampe, S. K. O. & Kaskote, E. 2021 Performance evaluation of an integrated multi-stage poultry slaughterhouse wastewater treatment system. *Journal of Water Process Engineering* **43**, 102309. https://doi.org/10.1016/j.jwpe.2021.102309.

Bustillo-Lecompte, C. & Mehrvar, M. 2017 Slaughterhouse Wastewater: Treatment, Management and Resource Recovery. In R. Farooq & Z. Ahmad (Eds.), Physico-Chemical Wastewater Treatment and Resource Recovery (p. 278). Intech Open. https://www.intechopen.com/books/6050

Carrero-Colón, M., Nakatsu, C. H. & Konopka, A. 2006 Effect of nutrient periodicity on microbial community dynamics. *Applied and Environmental Microbiology* **72**(5), 3175–3183. https://doi.org/10.1128/AEM.72.5.3175-3183.2006.

Chan, Y. J., Chong, M. F., Law, C. L. & Hassell, D. G. 2009 A review on anaerobic-aerobic treatment of industrial and municipal wastewater. *Chemical Engineering* **155**(1–2), 1–18. https://doi.org/10.1016/j.cej.2009.06.041.

Clem, V. & Mendonça, H. V. d. 2022 Ozone reactor combined with ultrafiltration membrane: a new tertiary wastewater treatment system for reuse purpose. *Journal of Environmental Management* **315**. https://doi.org/10.1016/j.jenvman.2022.115166.

Corporation, I. F. 2020 Benchmarking Study Resource Efficiency in Red Meat Abattoirs in South Africa (pp. 1–68). International Finance Corporation. www.ifc.org

Cruz, K. D., Francisco, J. T. J., Mellendrez, K. J. M. & Pineda, J. M. F. 2019 Electrocoagulation treatment of swine slaughterhouse wastewater: effect of electrode material. *E3S Web of Conferences* **117**(20), 1–5. https://doi.org/10.1051/e3sconf/201911700020.

Daskiran, C., Attiya, B., Altimemy, M., Liu, I. H. & Oztekin, A. 2019 Oxygen dissolution via pump-turbine – application to wastewater treatment. *International Journal of Heat and Mass Transfer* **131**, 1052–1063. https://doi.org/10.1016/j.ijheatmasstransfer.2018.11.130.

de Boer, S., González-Rodríguez, J., Conde, J. J. & Moreira, M. T. 2022 Benchmarking tertiary water treatments for the removal of micropollutants and pathogens based on operational and sustainability criteria. *Journal of Water Process Engineering* **46**. https://doi.org/10.1016/j.jwpe.2022.102587.

Department of Agriculture Forestry and Fisheries 2006 Poultry Regulation (Issue 28520). https://www.nda.agric.za/vetweb/Legislation/Meat safety/Poultry Regulations.pdf

Dlangamandla, C., Ntwampe, S. K. O. & Basitere, M. 2018 A bioflocculant-supported dissolved air flotation system. *Water Science and Technology* **78**(2), 452–458. https://doi.org/10.2166/wst.2018.324.

DWA (Department of water affairs) 1999 Discharge limits and conditions set out in the National Water Act (Issue 20526). http://hwt.co.za/downloads/NWA General and Special Authorisations.pdf

Emmanuel, T. O., Bawo, K. & Lawrence, I. E. 2016 Evaluation of bacterial profile and biodegradation potential of abattoir wastewater. *African Journal of Environmental Science and Technology* **10**(2), 50–57. https://doi.org/10.5897/ajest2015.1945.

EOH 2018 *Draft Basic Assessment Report (Issue November)*.

Ergofito 2012 *Grease & Fats*. Available from: https://www.ergofito.co.za/application/Grease-Fats-Overview.

Fondriest Environmental, Inc. "Turbidity, Total Suspended Solids and Water Clarity." Fundamentals of Environmental Measurements. 13 Jun. 2014. Web. https://www.fondriest.com/environmental-measurements/parameters/water-quality/turbidity-total-suspended-solids-water-clarity/ .

Franke-Whittle, I. H. & Insam, H. 2013 Treatment alternatives of slaughterhouse wastes, and their effect on the inactivation of different pathogens: A review. *Critical Reviews in Microbiology* **39**(2) 139–151. https://doi.org/10.3109/1040841X.2012.694410

GDARD (Gauteng Department of Agriculture and Rural Development) 2009 *Guideline Manual for the Management of Abattoirs and Other Waste of Animal Origin*. Department of Agriculture and Rural Development, Johannesburg, South Africa, pp. 1–214.

Geerdink, R. B., Sebastiaan van den Hurk, R. & Epema, O. J. 2017 Chemical oxygen demand: historical perspectives and future challenges. *Analytica Chimica Acta* **961**, 1–11. https://doi.org/10.1016/j.aca.2017.01.009.

Gonçalves, A. L., Pires, J. C. M. & Simões, M. 2016 Wastewater polishing by consortia of *Chlorella vulgaris* and activated sludge native bacteria. *Journal of Cleaner Production* **133**, 348–357. https://doi.org/10.1016/j.jclepro.2016.05.109.

Gray, N. F. 2004 *Biology of wastewater treatment* (2nd ed.). Imperial College Press.

Gufe, C., Ndlovu, M. N., Sibanda, Z., Makuvara, Z. & Marumure, J. 2021 Prevalence and antimicrobial profile of potentially pathogenic bacteria isolated from abattoir effluents in Bulawayo, Zimbabwe. *Scientific African* **14**, 14–219. https://doi.org/10.1016/j.sciaf.2021.e01059.

Gürel, L. & Büyükgüngör, H. 2011 Treatment of slaughterhouse plant wastewater by using a membrane bioreactor. *Water Science and Technology* **64**(1), 214–219. https://doi.org/10.2166/wst.2011.677.

Gutiérrez-Sarabia, A., Villagómez, G. F., Martínez-Pereda, P. & Rinderknecht-Seijas, N. 2004 Slaughterhouse wastewater treatment in a full-scale system with constructed wetlands. *Water Environment Research* **76**(4), 334–343.

Gutu, L., Basitere, M., Harding, T., Ikumi, D., Njoya, M. & Gaszynski, C. 2021 Multi-integrated systems for treatment of abattoir wastewater: a review. *Water (Switzerland)* **13**(18). https://doi.org/10.3390/w13182462.

Harris, P. W., Schmidt, T. & McCabe, B. K. 2017 Evaluation of chemical, thermobaric and thermochemical pre-treatment on anaerobic digestion of high-fat cattle slaughterhouse waste. *Bioresource Technology* **244**(July), 605–610. https://doi.org/10.1016/j.biortech.2017.07.179.

Haslett, M. J. 2016 *Waste Water Management Plan for Salejee Red-Meat Abattoir Cato Ridge, Kwazulu Natal*, Durban, pp. 1–69.

Husam, A.-N. & Nassar, A. 2019 Slaughterhouses wastewater characteristics in the Gaza Strip. *Journal of Water Resource and Protection* **11**(07), 844–851. https://doi.org/10.4236/jwarp.2019.117051.

International Finance Corporation 2021 *Resource efficiency in red meat abattoirs in South Africa*. Agricultural Business Chamber. https://www.agbiz.co.za/blog/details/resource-efficiency-in-red-meat-abattoirs-in-south-africa.

Jabari, L., Gannoun, H., Khelifi, E., Cayol, J. L., Godon, J. J., Hamdi, M. & Fardeaub, M. L. 2016 Bacterial ecology of abattoir wastewater treated by an anaerobic digestor. *Brazilian Journal of Microbiology* **47**(1), 73–84. https://doi.org/10.1016/j.bjm.2015.11.029.

Jamal, M., Ahmad, W., Andleeb, S., Jalil, F., Imran, M., Nawaz, M. A., Hussain, T., Ali, M., Rafiq, M. & Kamil, M. A. 2018 Bacterial biofilm and associated infections. *Journal of the Chinese Medical Association* **81**(1), 7–11. https://doi.org/10.1016/j.jcma.2017.07.012.

Jefferson, K. K. 2004 What drives bacteria to produce a biofilm? *FEMS Microbiology Letters* **236**(2), 163–173. https://doi.org/10.1016/j.femsle.2004.06.005.

Jenkins, D., Richard, M. G. & Daigger, G. T. 2004 *Manual on the Causes and Control of Activated Sludge Bulking and Foaming and Other Solids Separation Problems*. Lewis Publishers, Washington DC, USA.

Ji, X., Li, H., Zhang, J., Saiyin, H. & Zheng, Z. 2019 The collaborative effect of *Chlorella vulgaris–Bacillus licheniformis* consortia on the treatment of municipal water. *Journal of Hazardous Materials* **365**, 483–493. https://doi.org/10.1016/j.jhazmat.2018.11.039.

Jouanneau, S., Recoules, L., Durand, M. J., Boukabache, A., Picot, V., Primault, Y., Lakel, A., Sengelin, M., Barillon, B. & Thouand, G. 2014 Methods for assessing biochemical oxygen demand (BOD): A review. *Water Res* **49**(1), 62–82. https://doi.org/10.1016/j.watres.2013.10.06.

Johns, M. R. 1995 Developments in wastewater treatment in the meat processing industry: A review. *Bioresource Technology* **54**(3), 203–216. https://doi.org/10.1016/0960-8524(95)00140-9.

Kaushal, J. & Mahajan, P. 2021 Design and evaluation of hydroponic system for tertiary treatment of STP wastewater: an eco-friendly approach. *Materials Today: Proceedings* **45**, 4914–4918. https://doi.org/10.1016/j.matpr.2021.01.365.

Kazbar, A., Cogne, G., Urbain, B., Marec, H., Le-Gouic, B., Tallec, J., Takache, H., Ismail, A. & Pruvost, J. 2019 Effect of dissolved oxygen concentration on microalgal culture in photobioreactors. *Algal Research* **39**, 101432. https://doi.org/10.1016/j.algal.2019.101432.

Kayaalp, N., Ersahin, M. E., Ozgun, H., Koyuncu, I. & Kinaci, C. 2010 A new approach for chemical oxygen demand (COD) measurement at high salinity and low organic matter samples. *Environ. Sci. Pollut. Res.* **17**(9), 1547–1552. https://doi.org/10.1007/s11356-010-0341-z.

Kanafin, Y. N., Makhatova, A., Meiramkulova, K. & Poulopoulos, S. G. 2022 Treatment of a poultry slaughterhouse wastewater using advanced oxidation processes. *Journal of Water Process Engineering* **47**(August 2021), 102694. https://doi.org/10.1016/j.jwpe.2022.102694.

Kist, L. T., Moutaqi, S. E. & Machado, Ê. L. 2009 Cleaner production in the management of water use at a poultry slaughterhouse of Vale do Taquari, Brazil: a case study. *Journal of Cleaner Production* **17**(13), 1200–1205. https://doi.org/10.1016/j.jclepro.2009.04.006.

Koshlaf, E. & Ball, A. S. 2017 Soil bioremediation approaches for petroleum hydrocarbon polluted environments. *AIMS Microbiology* **3**(1), 25–49. https://doi.org/10.3934/microbiol.2017.1.25.

Konneh, M., Wandera, S. M., Murunga, S. I. & Raude, J. M. 2021 Adsorption and desorption of nutrients from abattoir wastewater: modelling and comparison of rice, coconut and coffee husk biochar. *Heliyon* **7**(11). https://doi.org/10.1016/j.heliyon.2021.e08458.

Li, D., Siriamornpun, S., Wahlqvist, M. L., Mann, N. J. & Sinclair, A. 2005 Lean meat and heart health. *Pub Med* **14**(2), 113–119.

Maddela, N. R., Sheng, B., Yuan, S., Zhou, Z., Villamar-Torres, R. & Meng, F. 2019 Roles of quorum sensing in biological wastewater treatment: a critical review. *Chemosphere* **221**, 616–629. https://doi.org/10.1016/j.chemosphere.2019.01.064.

Mckay, T. J., Mckay, T., Ndlopfu, V. W., Ahmed, A., Ahmed, Q. & Rubric, O. 2018a *The Blesbokspruit Wetland, South Africa: A High Altitude Wetland Under Threat Under Threat*. https://doi.org/10.13140/RG.2.2.12042.98244.

Mckay, T., Ndlopfu, V. W. & Ahmed, A. A. Q. 2018b *The Blesbokspruit Wetland, South Africa: A High Altitude Wetland Under Threat*. https://doi.org/10.13140/RG.2.2.12042.98244.

Meiramkulova, K., Devrishov, D., Zhumagulov, M., Arystanova, S., Karagoishin, Z., Marzanova, S., Kydyrbekova, A., Mkilima, T. & Li, J. 2020 Performance of an integrated membrane process with electrochemical pre-treatment on poultry slaughterhouse wastewater purification. *Membranes* **10**(10), 1–17. https://doi.org/10.3390/membranes10100256.

Meng, F., Yang, A., Zhang, G., Li, J., Li, X., Ma, X. & Peng, M. 2019 Effects of dissolved oxygen on key enzyme activities during photosynthetic bacteria wastewater treatment. *Process Biochemistry* **76**, 165–170. https://doi.org/10.1016/j.procbio.2018.09.025.

Mittal, G. S. 2006 Treatment of wastewater from abattoirs before land application – a review. *Bioresource Technology* **97**(9), 1119–1135. https://doi.org/10.1016/j.biortech.2004.11.021.

Mittal, A. 2011 Biological wastewater treatment. *Water Today* August, 32–44.

Morata de Ambrosini, V. I., Martín, M. C. & Merín, M. G. 2014 Bacteria: classification of the bacteria: traditional. *Encyclopedia of Food Microbiology: Second Edition* **1**, 169–173. https://doi.org/10.1016/B978-0-12-384730-0.00027-6.

Muller, J. 2005 *Approaches to Abbatoir Effluent Treatment*.

Müller, J. R. 2017 *Water and Wastewater Management in the Red Meat Abattoir Industry*. WRC Report, Pretoria, South Africa.

Nafarnda, W. D., Ajayi, I. E., Shawulu, J. C., Kawe, M. S., Omeiza, G. K., Sani, N. A., Tenuche, O. Z., Dantong, D. D. & Tags, S. Z. 2012 Bacteriological quality of abattoir effluents discharged into water bodies in Abuja, Nigeria. *ISRN Veterinary Science* **2012**, 1–5. https://doi.org/10.5402/2012/515689.

Noszczyńska, M. & Piotrowska-Seget, Z. 2018 Bisphenols: application, occurrence, safety, and biodegradation mediated by bacterial communities in wastewater treatment plants and rivers. *Chemosphere* **201**, 214–223. https://doi.org/10.1016/j.chemosphere.2018.02.179.

Nugroho, F. A., Arif, A. Z., Sabila, G. Z. M. & Aryanti, P. T. P. 2021 Slaughterhouse wastewater treatment by electrocoagulation process. *IOP Conference Series: Materials Science and Engineering* **1115**(1), 012037. https://doi.org/10.1088/1757-899x/1115/1/012037.

Obi, C. C., Nwabanne, J. T., Igwegbe, C. A., Ohale, P. E. & Okpala, C. O. R. 2022 Multi-characteristic optimization and modeling analysis of electrocoagulation treatment of abattoir wastewater using iron electrode pairs. *Journal of Water Process Engineering* **49**. https://doi.org/10.1016/j.jwpe.2022.103136.

Oyebande, L. 2010 Water problems in Africa –how can the sciences help? *Hydrological Sciences Journal* **46**(6), 947–962. https://doi.org/10.1080/02626660109492888.

Ozgun, H., Cicekalan, B., Akdag, Y., Koyuncu, I. & Ozturk, I. 2021 Comparative evaluation of cost for preliminary and tertiary municipal wastewater treatment plants in Istanbul. *Science of the Total Environment* **778**. https://doi.org/10.1016/j.scitotenv.2021.146258.

Pereira, E. B., De Castro, H. F., Spiller, V. R. & Furigo, A. 2006 Degradation of fat and grease in slaughterhouse wastewater by a commercial microbial lipase. *Brazilian Archives of Biology and Technology* **49**(Special Issues), 21–28.

Rinquest, Z., Basitere, M., Ngongang, M. M., Njoya, M. & Ntwampe, S. K. O. 2019 Optimization of the COD removal efficiency for a static granular bed reactor treating poultry slaughterhouse wastewater. *Preprints* 1–8. https://doi.org/10.20944/preprints201902.0036.v1.

Robertson, A. 2017 *Sewage in Blesbokspruit Pollutes Water*. Springs Advertiser, Johannesburg, South Africa.

Schleifer, K. H. 2009 Classification of bacteria and archaea: past, present and future. *Systematic and Applied Microbiology* **32**(8), 533–542. https://doi.org/10.1016/j.syapm.2009.09.002.

Shammas, N. K. & Wang, L. K. 2007 Aerobic digestion. *Biosolids Treatment Processes* **6**, 177–205. https://doi.org/10.1007/978-1-59259-996-7_6.

Sherifat.T, A., A, A. Wunmi., Bolatito.A, O., Oloruntobi, J., Olufemi.M, A. & Sammy.O, S.-W. 2015 Microbiological Assessment of Waste-Water and Soil in Ijebu-Igbo Abattoir, Southwest, Nigeria. *International Journal of Advancements in Research & Technology* **4**(10), 1–12.

Suceveanu, M., Suceveanu, I., Grosu, L. & Alexa, I.-C. 2018 Treatment of wastewater from swine and poultry slaughterhouses. *Journal of Engineering Studies and Research* **24**(2), 41–45. https://doi.org/10.29081/jesr.v24i2.60.

Szabó, E., Liébana, R., Hermansson, M., Modin, O., Persson, F. & Wilén, B. M. 2017 Microbial population dynamics and ecosystem functions of anoxic/aerobic granular sludge in sequencing batch reactors operated at different organic loading rates. *Frontiers in Microbiology* **8**, 1–14. https://doi.org/10.3389/fmicb.2017.00770.

Tolera, S. T. & Alemu, F. K. 2020 Potential of Abattoir Waste for Bioenergy as Sustainable Management, Eastern Ethiopia, 2019. *Journal of Energy* **2020**, 1–9. https://doi.org/10.1155/2020/6761328.

Tuttle-raycraft, S., Morris, T. J. & Ackerman, J. D. 2017 Suspended solid concentration reduces feeding in freshwater mussels. *Science of the Total Environment* **598**, 1160–1168. https://doi.org/10.1016/j.scitotenv.2017.04.127.

USEPA (United States Environmental Protection Agency) 2014 *Drinking Water What are the Trends in the Quality of Drinking Water and Their Effects on Human Health?* pp. 1–5.

Western Cape Government 2016 *The Mini Guide to the Management of Abattoir Waste*. Western Cape Government, pp. 1–52. Available from: https://www.westerncape.gov.za/red-tape-reduction/news/red-tape-reduction-mini-guide-managing-abattoir-waste.

Wu, Y., Liu, J. & Rene, E. 2018 Periphytic biofilms : a promising nutrient utilization regulator in wetlands. *Bioresource Technology* **248**, 44–48. https://doi.org/10.1016/j.biortech.2017.07.081.

Zamani, H., Golestani, H. A., Mousavi, S. M., Zhiani, R. & Hosseini, M. S. 2021 Applying the aerobic/membrane hybrid process for treatment of slaughterhouse wastewater. *Desalination and Water Treatment* **235**, 92–98. https://doi.org/10.5004/dwt.2021.27622.

First received 11 August 2022; accepted in revised form 8 November 2022. Available online 18 November 2022