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Advanced oxidation processes: a supplementary treatment option for recalcitrant organic pollutants in Abattoir wastewater

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Abstract: Animal production and meat processing generate large amounts of waste. Large amounts of water containing substantial quantities of biodegradable organic matter are produced because of the slaughtering of animals and the routine washing of leftover particles in the abattoir. Blood, fats, oil, and grease, undigested food, suspended materials, etc. are a few examples of the materials that typically contributed organic load to these effluents. Thus, regulatory agencies prohibit the direct discharge of the effluents and solid abattoir wastes into the environment. This is because these wastes are potential pollutants and can increase harmful ecological hazards, therefore, treatment is required before discharge into environment. The advanced oxidation processes (AOPs), tertiary water treatment group of methods are based on the production of hydroxyl radicals, which brings about its non-selective reaction with water contaminants, allowing mineralisation of contaminants and converting them into CO_2 and water. AOPs could be applied to oxidize pollutants in abattoir wastewater (AWW) and may be used as a supplementary treatment system. A combined process involving physical and biological treatments, and AOPs may be used as an alternate form of treatment with the potential for greater effectiveness and dependability. However, the properties of the wastewater, treatment time, influent concentration, type of treatment, and the best treatment technique currently available to comply with the standards will all have a significant impact on treatment efficiencies of AWW.

Keywords: slaughterhouse wastewater; animal production and processing; advanced oxidation processes; environmental pollution; water treatment

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1. Introduction

The reuse of industrial and municipal wastewater is essential due to the insufficient freshwater resources, population increase, and stringent laws on the quality of released effluents (Sun et al. 2016). To achieve a greater mineralisation rate with fewer detectable pollutants, researchers are faced with the task of creating and advancing breakthrough treatment technologies (Manna & Sen, 2023). Currently, a major environmental concern is the occurrence of emerging contaminants in water sources, including pesticides, endocrine disrupting chemicals (EDCs), persistent organic chemicals (POPs), pharmaceuticals, dyes, oil and gasoline by-products, etc. Several treatment techniques have been developed and applied to treat water based on different standards of living, economic variables, types of pollutant, and the extent of pollution of water bodies (Rajasulochana & Preethy, 2016). The most prevalent and economical way of treating practically all types of industrial wastewater is biological wastewater treatment. It involves the application of bacteria and other microorganisms to lower the contamination level of wastewater (Ahmed et al., 2021; Priya et al., 2021). Several types of wastewaters contain significant amounts of non-biodegradable organic compounds and are resistant to microorganisms even though the biological wastewater treatment methods are an affordable option (Buyukkamaci & Koken, 2010). These pollutants cannot be removed by traditional treatment facilities such as membrane processes (ultrafiltration, or reverse osmosis), biological wastewater treatment, or activated sludge, hence, the required standards cannot be met. Like that, the physical treatment methods are frequently used in wastewater treatment facilities. These methods work by removing substances from the wastewater stream. The separation procedure causes the contaminant to move from one phase to another. Considering this, further treatment is necessary to accelerate the second phase's breakdown of pollutants. Physical techniques are used to separate inorganic materials, clear turbid solutions, retrieve and recycle relevant compounds used in the primary processes, and separate big settleable and floating debris. Moreover, depending on the type and concentration of the influence as well as the operational circumstances, the physical treatment techniques can be used either before or after the chemical operations. The advanced oxidation processes (AOPs) have demonstrated effectiveness in contaminant mineralisation or degradation of stable, inhibiting, or hazardous compounds (Ganiyu et al., 2015). Most organic molecules are oxidized by AOPs, which produce extremely reactive intermediates such as hydroxyl radicals (•OH), which reduce them to intermediate products before converting them to inorganic ions, CO_2, and H_2O. Many studies have employed AOPs, including sonolysis, ultraviolet (UV), ozonation, Fenton process, among others, to remove different types of pollutants in the recent years (Bethi et al., 2016). Organic compounds become smaller and more biodegradable because of the breakdown. Although practically all organic molecules can be effectively treated by AOPs, various limitations hinder their commercial use. These drawbacks include but not limited to a high need for oxidant dose, high electrical power consumption, and precise pH correction, which raises the operational cost of AOPs (Coha et al., 2021). Therefore, to treat the recalcitrant components of wastewater such as AWW, combining AOPs with physical treatments or biological treatments might be a great choice (Hilares et al., 2021).

In a lot of nations, eating meat regularly is crucial. As a result, meat processing plants (MPPs) generate a lot of wastewaters, often referred to as slaughterhouse wastewater (SWW). The killing of animals for meat and cleaning of the abattoir facilities consumes up to 29% of the freshwater used by the global agriculture sector and 24% of the freshwater used by the food and beverage industry (Bailone et al., 2021). Blood, fats, oil, and grease (FOG), manure, loose meat, lard, paunch, colloidal particles, soluble proteins, grit, and suspended components make up the majority of SWW. Thus, the effluent must be treated before its release into the environment in an appropriate manner (Franke-Whittle & Insam, 2013). In Nigeria, large numbers of animals (cows, goats, sheep, and poultry birds) are slaughter in different abattoir. A typical example of a SWW discharge into rivers at Kara Abattoir, Ogun State, Nigeria is depicted in Figure 1. Kara Abattoir is the largest abattoir serving Lagos State, Nigeria. The blood wash and the process water from the abattoir are released onto-site directly into a river nearby without any prior treatment and are typically exempt from disposal charges.

Figure 1. Slaughterhouse wastewater discharge at Kara Abattoir, Ogun State, Nigeria (Kakulu, 2009).

SWW has been regarded hazardous globally because of high nutrients and organic contents. In addition, the treatment of wastewater onsite would be the ideal alternative to cleanse and decontaminate the effluents before dumping into receiving water bodies (Mittal, 2006; Nappier et al., 2020). The level of contamination of SWW are expressed in the form of chemical oxygen demand (COD), total organic carbon (TOC), total suspension solids (TSS), and biochemical oxygen demand (BOD). Due to the high COD levels in SWWs, anaerobic reactors are frequently used for treatment. Although anaerobic treatment is effective, total breakdown of the organic materials is not feasible. Aerobic or anaerobic-aerobic systems are better adapted to remove the soluble organic materials that remain in the effluent following anaerobic treatment (Chan et al., 2009). Anaerobic treatment techniques are unstable, thus adopting aerobic treatment is necessary to achieve the criteria (Show & Lee, 2017). The poor settling rate and the handling of ammonium ions (NH_4^+) and hydrogen sulfide (HS^-) in anaerobic treatment effluent are examples of this instability. The biological removal of nitrogen and phosphorus nutrients also calls for an appropriate blend of the two processes. It has been found that an effluent generated by anaerobic or aerobic processes alone did not adhere to discharge restrictions when treating wastewater with a high organic content (Chan et al., 2010). When compared to aerobic treatment alone, the adoption of integrated techniques can also result in lower operational costs.

AOPs are more appealing replacements to conventional treatment and can be utilized in conjunction with biological processes for SWW treatment. Additionally, AOPs can inactivate microorganisms without introducing extra chemicals into the SWW, preventing the production of dangerous by-products (Ahmed et al., 2021). When compared to the other procedures studied for the treatment of SWW, such as ozonation and gamma radiation, the UV/H_2O_2 approach has been found to be more effective (Bustillo-Lecompte & Mehrvar, 2017; Melo et al., 2008; Wang et al., 2023). The $UV/O_3/H_2O_2$ method degrades aromatic compounds and inhibits microorganism five times quicker than the other technologies (Fernandes et al., 2019). Total organic content, light source intensity, oxidant concentration, temperature, irradiation duration, pH, reaction time, and output power are a few of the characteristics that have an impact on AOP systems (Neboh et al., 2013). As a result, the characterisation of such systems necessitates considering both cross-factor and single-factor effects while employing experiment design to pinpoint the variables that affect the multivariable system.

2. Abattoir wastewater

Abattoirs, sometimes known as slaughterhouses, are businesses that engage in the killing of animals for commercial purposes, and the preparation of the meat for consumption (Neboh et al., 2013). Most of the freshwater utilized by the global agriculture sector - about 29% of it - is consumed by the meat processing industry (Angelakis & Snyder, 2015; Gerbens-Leenes et al., 2013; Mekonnen & Hoekstra, 2012). Additionally, during the previous ten years, the output of chicken, beef, and pork has risen globally and there is expectation that the water used in the industry is projected to grow steadily until 2050. Likewise, the current trends from around the globe also showed that water consumed by abattoir industry has increase to a noticeable amount in the recent years (Dąbrowski et al., 2016) and due to the change in diet, certain other nations, such China and India, have seen a rise in the production of meat (Bustillo-Lecompte et al., 2015). Thus, as the number of abattoir facilities is increasing, it results in high expectation volume of AWW that needs to be treated (Valta et al., 2015). Numerous environmental problems, including soil degradation, water pollution, and the buildup of toxic compounds in plants and animals, are brought on by a rise in the amount and volume of effluents that are discharged (Matheyarasu et al., 2014; Oketayo et al., 2022). Therefore, facilities producing effluent with high total loads of organic contaminants like proteins or lipids as well as chemicals required to clean and sanitize processing equipment include meat, poultry, dairy, and other processing operations (Álvarez et al., 2011; Zhukova et al., 2010).

Consequently, an abattoir produces wastewater containing very high organic and inorganic waste. These wastewaters contain a variety of contaminants, both organic and inorganic. High levels of soluble and insoluble organic materials, including blood, FOG, inorganic and organic particles, paunch, grass, etc., are present in the organic waste. The largest source of pollution is the blood. Inorganic wastes such as phosphates, sulphates, nitrates, etc. with relatively high quantities of suspended solid, liquid, and fat make up most of the pollution load, followed by undigested feed (Liu & Haynes, 2011). The solid waste includes condemned meat, aborted foetuses, undigested food materials, hairs, and bones. Liquid waste is usually made up of dissolved solids, blood, gut contents, urine and water (Kenneth et al., 2019). Suspended material, blood, paunch, FOG, faeces, undigested food, urine, loose meat, soluble proteins, grit, excrement, manure, and colloidal particles all contribute to the organic load in these effluents, which has a polluting effect due to the high levels of organics and pathogens present in AWW as well as the detergents used for cleaning (Ragasri & Sabumon, 2023). These materials mostly consist of amino acids, possible pathogens, and other organic nitrogenous chemicals that, because of biodegradable processes, give unpleasant odours and colours (Sarairah & Jamrah, 2008; Eryuruk et al., 2018; Ozdemir et al., 2020).

Similarly, aquatic life is negatively impacted by biodegradable organic matter in receiving waters because it intensifies the struggle for oxygen in the environment, causing high levels of BOD and a drop in dissolved oxygen (DO) (Ilyas et al., 2019). By encouraging the growth of algae, nutrient enrichment in receiving water bodies can result in eutrophication. Due to aquatic DO depletion, the blooming and eventual collapse of algae may cause hypoxia/anoxia, which would cause a mass extinction of benthic invertebrates and fish across a vast region (Islam & Tanaka, 2004; Rabalais, 2002). These consequences include a detrimental influence on biodiversity, the potential extinction of sensitive species, significant ecological changes, and a variety of grave risks to human health (Yadav et al., 2023).

3. Characteristics and effect of abattoir wastewater

Abattoir effluents are regarded as detrimental on a global scale due to their complex composition of lipids, proteins, fibres, high organic content, pathogens, and pharmaceuticals. The effluents are often assessed using bulk characteristics because of the wide variety of SWW and pollutant loads. A typical feature of a real AWW are presented in Table 1.

It is important to sort and lower wastewater output at its source due to the various features of slaughterhouse effluent. Effluents from meat processing plants are growing to be one of the primary agricultural problems because of the enormous quantity of water consumed during slaughtering, processing, and cleaning of the slaughtering facilities.

3.1. Abattoir wastewater management and regulations

Stringent rules and regulations are required to lessen the environmental effect of slaughterhouses, and the primary regulatory need is the treatment procedures (Mogensen et al., 2016). Resource recovery from biogas produced utilizing high-rate anaerobic treatment may also offer some economic relief thanks to compliance with current environmental regulations and cutting-edge technologies. For a sufficient release to the environment, existing rules and nutrient and organic discharge restrictions for slaughterhouse effluent are described in Table 2 for various jurisdictions across the world. Canada does not have a special regulation for the meat processing business, even though it can be observed that Canadian requirements are stricter than those in other foreign jurisdictions, such as the European Union (EU), Australia and New Zealand, or the USA. Additionally, Australia, New Zealand, and the United States have been implementing an integrated approach to the regulation of MPPs, where industry and regulatory sectors are working together to achieve a common goal of minimizing the risks brought on by the hazardous and highly potent wastewaters produced in slaughterhouses. Finally, rising economies with less stringent regulations include China, India, and Colombia. However, their law focuses on certain businesses to achieve degrees of remediation based on the strength of wastewater. The qualities of the slaughterhouse effluent to be treated, the best technology available that is economically feasible, and compliance with legislation in various political jurisdictions determine which treatment technique is chosen.

Table 1. Typical characteristics of abattoir wastewater

Parameters	Range
Colour (mg/L Pt scale)	175-400
Turbidity	200-300
pH	4.9-8.1
BOD (mg/L)	150-8500
COD (mg/L)	500-16000
TOC (mg/L)	50-1750
TN (mg/L)	50-850
TP (mg/L	25-200
TSS (mg/L)	0.1-10000
K (mg/L	0.01-100

Table 2. Appraisal of the global standard limits for the discharge of Abattoir wastewater.

Parameters	World bank	EU	USA	CANADA	COLOMBIA	CHINA	INDIA	AUSTRALIA
BOD (mg/L)	30	25	16-26	5-30	50	20-100	30-100	5-20
COD (mg/L)	125	125	NA	NA	150	100-300	250	40
TN (mg/L)	10	10-15	4-8	1.25	10	15-20	10-50	10-20
TOC (mg/L)	NA	NA	NA	NA	NA	20-60	NA	10
TP (mg/L	2	1-2	NA	1.00	NA	0.1-1.0	5	2
TSS (mg/L)	50	35-60	20-30	5-30	50	20-30	100	5-20
pH	6-9	NA	6-9	6-9	6-9	6-9	5.5-9.0	5-9
Temperature (°C change)	NA	NA	NA	<1	NA	NA	<5	<2

The United States Environmental Protection Agency has designated AWW as one of the industrial wastewaters that are most detrimental to the environment (Barbera et al., 2018) due to the inadequate disposal or lack of treatment of the waste before discharge to the environments and this is one of the primary causes of groundwater contamination and river deoxygenation. As a result of inadequate waste treatment facilities (Ogbonna & Ideriah, 2014), waste from slaughterhouses is deposited on the land or channelled into water resource leading to pollution. Nigeria, which has a sizable population of more than 230 million, has one of the fastest increasing populations in the world. Studying the way, the Nigerian population disposes of their wastewater is important. Monitoring should be done to determine how effluent from abattoirs is released into the environment by the continuously expanding population. Many slaughterhouses in Nigeria are typically located near water, and they dump their waste directly into rivers without any kind of pre-treatment while also using that same water to wash the meat after it has been slaughtered (Elemile et al., 2019). The World Health Organization estimates that waterborne illness claims the lives of around 3.4 million people annually, many of them are young children. An estimated 50% of people worldwide, mostly in underdeveloped nations, are afflicted with a water-related illness at any one moment. The discharge of wastewater to the terrestrial and aquatic environments could result in the transmission of pathogens to humans, with the direct result being zoonotic diseases (Adelegan et al., 2002). Many abattoirs in developing countries, especially Nigeria, do not have the necessary facilities to treat abattoir effluents. Notably, rotaviruses, hepatitis E. virus, *Salmonella* spp., *E. coli*, *Yersinia enterocolitica*, *Campylobacter* spp., *Cryptosporidium parvum*, and *Giardia lamblia* are diseases linked to animal corpses (Sobsey et al., 2006). AWW in Nigeria has been related to significant concentrations of contamination by both *Escherichia coli* and *Enterococcus* spp. These water bodies are utilized by the populace as drinking water sources. Such infections can have a variety of negative effects, including temporary illness and even fatality, particularly in vulnerable people like the elderly and young children. As a result, the remediation and discharge of wastewater from slaughterhouses are a problem for both the economy and public health (Barrera et al., 2012), and AWW needs extensive treatment before it can be released safely and sustainably into the environment. Additionally, SWW treatment is crucial to preventing significant organic loading of water bodies and reducing or eliminating microorganisms linked to degrading processes. Thus, it is crucial to regularly monitor, pre-treat, and treat water bodies to preserve environmental sustainability (Khan et al., 2016; Nkansah et al., 2019; Tyagi et al., 2013).

AWW treatment is like current technologies used in municipal wastewater treatments, this includes pre-treatment, primary and secondary treatment, tertiary treatment and management of the sludge formed. As a result, the main subgroups of slaughterhouse management techniques that may be separated after preliminary treatment are land application, physical treatment, chemical treatment, biological treatment, AOPs, and combination process. The effluents that are disposed from wastewater treatment systems are one of the main sources of pollution on a global scale, and studies at both the national and international levels have shown how harmful substances found in them have an ever-increasing negative impact on aquatic habitats and people. The wastewater treatment sector has recognized current trends in the discharge of heavy metals, hydrocarbons, organic and inorganic anions such as nitrates and phosphates into waterways as causing a major risk and challenge to the natural environment and proving hazardous to humans which is nowadays a matter of concern because of water scarcity. In addition to chemical accumulation and magnification at higher levels of the food chain, some of these effects include respiratory issues, childhood blood diseases, adult gastro-intestinal cancers, the death of aquatic life, algal blooms, habitat destruction from sedimentation and debris, increased water flow, short- and long-term toxicity from chemical contaminants, and contribution to high level of diseases in humans (Kosamu et al., 2011). There are several laws and regulations that have been designed and enacted for usage to optimize the health and environmental advantages connected with the use and wastewater discharge, both at international and national levels. Because the supply of high-quality water resources is becoming more and more scarce, reclamation and reuse of treated wastewater have become crucial concerns in the sustainable management of water. Although there are many contaminants in abattoir effluent, the main chemical pollutants include hydrocarbons, nitrates, phosphates, nitrogen, heavy metals, and pesticides. The two substances that are most nutrient limiting among them are nitrogen and phosphorus. When dumped into water bodies without treatment, nitrates and compounds containing phosphates cause major problems. The two main nutrients that microorganisms require for their physiological functions are nitrates and phosphates. However, if their concentration exceeds the permissible limit, they are regarded as pollutants.

Waterbodies with a high concentration of nutrients encourage the growth of aquatic plants while having a detrimental impact on water quality by speeding the formation of algal clumps, foul odours, and a high concentration of nutrients. These conditions make it difficult to use the water for recreational and aesthetic purposes. On the other hand, the recovery of these inorganic anions from wastewaters is essential to curtail the future global nitrogen and phosphorus paucity that is likely to be one of the greatest challenges of the 21st century. It is necessary to find appropriate methods to remove these excess pollutants from wastewater as well as recover it so that it can be used in the production of fertilizers and to compensate for the global exhaustion of high-grade phosphate ores. Recently, in line with rising environmental concern, scientists and researchers are now using nanomaterials for wastewater treatment methods. As environment related climate changes have become national and international challenges, effective AWW treatment should be pursued, from alternative extraordinary sources that offers less adverse impact on the environment with low-cost effectiveness, non-toxic, biologically safe, no secondary pollutants, materials renewability, biodegradability, higher photocatalytic activity, effective synthesis and easy recycling. Scientist all over the world in the last two decade have been involved in intensive research for the alternative way of treating AWW with good hygiene and sustainability practices, this research and development efforts have concentrated on reducing the impact of environmental problems of abattoir waste using various approaches which includes but not limited to the use of nanotechnology and AOPs. Therefore, it has become necessary to study the effect of AWW disposal on the environment with the aim to removing inorganic pollutants in this wastewater using cheap and feasible treatment processes.

3.2. Health hazards and sources of nitrates in water

Nitrate is an essential nutrient for plants and animals. Because it is a key nutrient for microbial life, nitrogen is crucial in determining how it affects the environment. Nitrate is the most prevalent type of nitrogen-containing molecules in water. Over time, nitrate is converted to nitrate from all other dissolved forms of nitrogen, including nitrite, ammonia, and organic nitrogen. Several anthropogenic sources also contribute to the environment's nitrate levels, and nitrates are present in both ground and surface water because of the natural decomposition of biological matters. The main sources of nitrates in surface and ground waters are industrial, domestic, and agricultural wastewater (Zhang et al., 2014). Agricultural operations are a well-researched source of nitrate pollution of soil and ground water globally (Brouwer, 2001; Evans et al., 2019; Merrett & Walton, 2005).

Nitrate concentrations have rapidly grown in both surface and ground water during the past ten years. Nitrate pollution is brought on by an increase in the usage of nitrogen fertilizers in agriculture. Additional factors that contribute to water pollution include untreated wastewater disposal, sewage, urban and agricultural runoffs, industrial wastewater, agricultural fertilizer, septic system leachate, waste disposal site leachate, and nitrogen compounds that are released into the air by industry and vehicles (Mukate et al., 2018). Nitrate is the most likely component of ground water pollution and a significant danger to water resources because of its high solubility, numerous studies connected the rising eutrophication in aquatic environments to the high nitrates concentration in water (Boeykens et al., 2017; Hekmatzadeh et al., 2012), which refers to an excessive development of algae in the water that kills fish and other aquatic life and disturbs the ecological balance of the creatures present in the water by consuming the oxygen gas contained in the water, and then creates a number of health problems in human that consumes the water (Rezaei & Sayadi, 2015). When combined with haemoglobin, nitrate converts to nitrites in infants to produce methaemoglobin (metHP). The reaction of nitrite with haemoglobin (oxyHb) to produce methaemoglobin (metHb) and nitrate is its most well-known effect. MetHb production has the effect of impairing oxygen supply to tissue. Because it cannot mix with oxygen, methaemoglobin reduces the amount of oxygen that the blood can carry from the lungs to body tissues causing the blue baby syndrome (methemoglobinemia) (Babaei et al., 2015). In adults, nitrate contaminated water is hazardous. The body converts nitrate to nitrite, which causes nitrate to be hazardous to humans. Human saliva of all ages and newborns' gastrointestinal tracts undergoes this response and directly affects the oesophagus and pharynx and cause adverse reproductive outcomes by causing abortion due to deficiency of oxygen in the foetus in pregnant women. It also increased the risk of specific cancers due to the likelihood that nitrosamine, which is known to cause cancer, will be produced in the body when nitrate reacts with amines or amides (Chatterjee et al., 2009). Literature studies have shown that the surge in the amount of nitrate in drinking water would possibly result to stomach cancer in adults, goitre, malformed child, increased infant mortality and hypertension (Mishra & Patel, 2009). In animals, when ruminants feed with high nitrate levels, the nitrate could be converted to nitrite, which results in the accumulation of nitrate and nitrite in the rumen (Abu-Dayeh, 2006). These buildups in animal rumen result in both acute and chronic symptoms, including stunted growth, rapid heartbeat, decreased milk production, low appetite, vomiting, aborted breathing, blue mucus membrane coloration, abdominal pain, and premature death of calves. This is because nitrate is converted to nitrite in the rumen by bacteria, which causes death within a few hours of ingesting a high-nitrate feed. From an environmental perspective and in addition to causing unwanted issues like algal blooms and eutrophication, nitrogenous wastewater also has a negative impact on receiving water bodies. Accelerated algal growth may result from nutrient inflow into surface waters. Bacterial activity raises oxygen levels in the atmosphere as the huge algal blooms die off.

If nutrients and organic carbon sink into the aquatic environment, the DO level will be further decreased. Waters may turn hypoxic or anoxic, stressing aquatic life and perhaps resulting in its demise. The safety of individuals who depend on the source is also protected by monitoring nitrate intake to surface waters, in addition to the health of the water body. The WHO and USEPA have determined the maximum contaminant limit of 10 mg/L due to the substantial health issues linked to nitrate in drinking water (Bhatnagar et al., 2010). Consequently, it is imperative that high nitrate concentrations in solutions are reduced to below the allowable level before release into sources of water. Thus, nitrate-contaminated wastewater must be treated effectively before discharge into the ground or a stream.

3.3. Health hazards and sources of phosphates in water

When the amount of phosphate in water exceeds the allowable limit, it becomes pollution. Phosphorus is a necessary nutrient for plants and animals in the form of PO_4^{3-} and HPO_4^{2-}. Manure, sewage, organic waste in sewage, and industrial effluents all include phosphate as a component. Due to eutrophication in water, the release of phosphate ions poses major environmental hazards. As a result of reduced light penetration brought on by algal blooms, eutrophication has the consequence of eradicating fish and plant species (). Zohdi & Abbaspour, 2019 Phosphorus is often a limiting element in freshwater ecosystems; as a result, when unwarranted phosphates are discharged from city sewage and agricultural effluent, the water quality suffers significantly. Total phosphorus in wastewater is made up of both organic and inorganic species. The total organic phosphorus is composed of a variety of substances, such as phosphonate, adenosine triphosphate, and organic phosphates. In contrast, inorganic condensed phosphorus, polyphosphate, and orthophosphate make up the inorganic phosphorus component. Orthophosphate, sometimes referred to as reactive phosphorus, appears in a variety of forms and exhibits phosphorus's pH dependency. Orthophosphate may be produced chemically through the process of precipitation, but it can also be made biologically from organic phosphorus and polyphosphates. Both point and non-point sources of phosphorus can pollute ground water. Non-point sources include the natural breakdown of rocks and minerals, sedimentation, agricultural runoff, direct animal/wildlife input, and erosion, whereas point sources include sewage effluents and industrial discharges. According to the EPA, 5 mg/L of phosphorus is the acceptable level for drinking water. If it stays within the acceptable range, it is vital for human health; if it exceeds the acceptable range, however, it may harm the kidneys and lead to osteoporosis. Phosphorus is known to be the limiting nutrient in most aquatic environments. To avoid eutrophication and maintain the quality of the water, phosphorus intake must be limited (Kleinman et al., 2015). The eutrophication of the aqueous system may be caused by a tiny quantity of phosphorous enhancing the development of algae and aquatic vegetation, and phosphate in water causes the creation of algal blooms in water bodies. The flow of phosphate into bodies of water should not exceed 0.05 mg/L and should be kept between 0.01 and 0.03 mg/L to prevent algal blooms. Toxic toxins are byproducts of algae blooms, and such contaminated water is not advisable for irrigation. For home and industrial effluents in Nigeria to meet acceptable requirements before being disposed of into water bodies, it is necessary to offer a straightforward technique of phosphate reduction.

3.4. Effects of faecal wastes and microbes

Literature search has shown that most waterborne germs that infect humans come from faeces that are excreted by infected people or animals (Cabral, 2010). Many water-related illnesses, including cholera, campylobacteriosis, salmonellosis, giardiasis, cryptosporidiosis, typhoid fever, and hepatitis A, are spread by untreated water. Intense degenerative heart illnesses and stomach ulcers are two examples of the acute and chronic diseases that most pathogenic microorganisms may cause. One of the most important and maybe most hazardous contaminants in wastewater is viruses. They take fewer doses to yield infections and have higher infectiousness, resistance to therapy, and difficulty being detected (Speers, 2006). The most dominant microbiological pollutants in wastewater, for example, are bacteria. Bacteria are responsible for many different illnesses, including diarrhoea, skin and tissue infections, and dysentery. *Cryptosporidium* and *Giardia* are the two main harmful protozoans connected to wastewater. They are more common in wastewater than any other source of environmental pollution (Huang et al., 2023).

4. Wastewater treatment technology

It might be difficult to choose the optimum treatment strategy for a certain industrial water problem. The quality of the influence, treatment methods, potential uses of treated water, and the flexibility of the treatment process are the main factors that one considers when deciding on the wastewater technology to apply (Altowayti et al., 2022). Other important factors include the life cycle assessments for determining the compatibility of treatment technology, economic studies, facility decontamination capacity, and the final wastewater treatment system efficiency. Generally, most people are aware of the potential and capabilities of the traditional treatment options. Bench-scale and pilot-plant studies should, however, be carried out to evaluate the efficacy of novel technologies, such as AOPs. When combining several methods to reuse or decontaminate a specific industrial water source, such studies may be crucial. The meat processing industry uses a wide range of freshwater resources, and most of the meat processing factories produce a lot of wastewaters from the slaughtering process and cleaning of the slaughterhouse. Consequently, the primary focus of the agribusiness is on the reuse of water and the recovery of valuable byproducts from the meat processing effluents (Bailone et al., 2022). Primary, secondary, and tertiary treatment are among the AWW treatment techniques that are like those applied to municipal wastewater treatment. This does not, however, negate the necessity for preliminary treatment. After the preliminary treatment, there are several treatment options such as the physicochemical treatment, biological treatment, AOPs, and combination treatment techniques.

4.1. Preliminary treatment

The goals of preliminary treatment are to eliminate up to 30% of the BOD and separate big particles and solids from the AWW (Baker et al., 2021). Screeners, sieves, and strainers are some of the most often used unit activities for the first treatment of AWW. Large solids with a diameter of 10 to 30 mm are therefore kept in place when the AWW travels through. Homogenization, catch basins, settlers, equalization, and flotation are further first-step treatment techniques.

4.2. Primary and secondary treatment

The effluent should undergo primary and secondary treatment after the preliminary treatment. Dissolved air flotation (DAF) for the removal of FOG, TSS, and BOD is one of the most feasible initial treatment procedures for AWW (Rinquest et al., 2019). Coagulation-Flocculation, sedimentation, electrocoagulation, and membrane processes are a few other physicochemical treatment approaches.

4.2.1. Dissolved air flotation

The process of liquid–solid separation by air introduction is referred to as DAF technology. A sludge blanket is formed when the fat, oil, and light particles are transferred to the surface. As a result, scum scraping may be used to continually eliminate it. Furthermore, flocculants and blood coagulants can be added to boost the DAF treatment's efficiency and remove a higher proportion of COD and BOD. However, frequent DAF drawbacks include sporadic failure, poor TSS elimination, and modest nutrient removal.

4.2.2. Coagulation-flocculation and sedimentation

Colloidal particles in the AWW are organized into bigger particles known as flocs during the coagulation phase. The almost negative charge of the colloidal particles makes them stable and resistant to aggregation. To disrupt the colloidal particles and help the sedimentation process, coagulants containing positively charged ions are introduced. There are many different coagulant types, but inorganic metal-based coagulants with removal efficiency of up to 80% for BOD, COD, and TSS (Al-Hamadani et al., 2011) are the most popular. Examples of these include aluminium sulphate, poly-aluminium chloride, ferric chloride, aluminium chloralhydrate, and ferric sulphate.

4.2.3. Electrocoagulation

By producing an electric current without the use of chemicals, the electrocoagulation (EC) technique has been used as an economical approach to remove organic compounds, heavy metals, and pathogens from abattoir effluents. M^{3+} ions, mostly Fe^{3+} and Al^{3+}, are produced by the EC process utilizing a variety of electrode materials. In acidic or alkaline environments, Pt, SnO_2, and TiO_2 are some other electrode types that can interact with H^+ or OH^- ions. Therefore, removal efficiency of up to 80 to 96% for COD, BOD, TN, TSS, and colour is possible.

4.2.4. Membrane processes

Membrane methods are increasingly being used as an option to clean the wastewater from the meat industry. To remove macromolecules, particles, organic matter, colloids, and pathogens from SWW with overall efficiencies of up to 90%, several membrane techniques have been utilized, including ultrafiltration (UF), reverse osmosis (RO), nanofiltration (NF), and microfiltration (MF). In AWW, membrane techniques should be combined with traditional treatment processes to remove nutrients. The creation of biofouling layers on the membranes, which reduces the penetration rate, is another disadvantage of membrane processes. This occurs when treating high-strength wastewater.

4.3. Biological treatment

AWW is often not fully treated to the standards required by regulations, by primary treatment or physicochemical methods. As a result, after primary treatment, the residual soluble organic compounds are removed using secondary treatment. Lagoons containing facultative, anaerobic, or anaerobic microorganisms, trickling filters, activated sludge (AS) bioreactors, and CWs are examples of biological processes that may remove organic matter and nutrients with up to 90% efficiency.

4.3.1. Anaerobic treatment

Given that anaerobic bacteria decompose organic molecules into CO_2 and CH_4 in the absence of oxygen, anaerobic digestion is the preferable approach for AWW treatment. Low sludge generation, little energy needs with possible resource recovery, and high COD removal are all advantages of anaerobic systems. Anaerobic technologies such as anaerobic digesters, anaerobic filters, anaerobic lagoons, septic tanks, and up-flow anaerobic sludge blankets are frequently used to handle the waste products of the meat processing industry. Anaerobic treatment does, however, bare minimal compliance with current discharge restrictions. Due to the high organic strength of AWW, complete stability of the organic compounds is challenging. To get rid of the pathogens, nutrients, and organics that are still present following anaerobic treatment, a second step of treatment is advised. However, to obtain high overall treatment efficacy, anaerobic treatment needs a larger area and a longer residence period, which has an impact on the economic sustainability of anaerobic treatment alone. To treat AWW as effectively as possible, a mix of anaerobic and aerobic treatments is required (Irshad et al., 2016).

4.3.2. Aerobic treatment

After primary treatment, aerobic methods are typically used for nutrient removal and further treatment. It is insufficient as the main therapy of AWW but adequate following anaerobic treatment because the amount of oxygen required, and the length of the treatment are directly connected to the strength of the AWW. The use of aerobic wastewater treatment techniques has several benefits, including less odour creation, rapid biological development, and quick temperature and loading rate modifications. Contrarily, because of the running and energy needs for artificial oxygenation, the operational costs of aerobic systems are higher than those of anaerobic systems. For the treatment of AWW, many aerobic unit operations exist, including aerobic AS, rotating biological contactors (RBCs), and sequencing batch reactors (SBRs).

4.3.3. Constructed wetlands

Constructed wetlands (CWs) use biological and physicochemical processes from the interaction of vegetation, soil, microorganisms, and atmosphere for the adsorption, biodegradation, filtration, photooxidation, and sedimentation of organics and nutrients to mimic the degrading mechanisms of natural wetlands for water decontamination. Subsurface flow CWs in both horizontal and vertical orientations have been used to assess the efficacy of CW systems for the treatment of AWW. Intriguing maximum removals of 78–99% for BOD, COD, TSS, and TN have been found in the results, which reveal a broad range of organic and nutrient removal for various plants. Consequently, CWs are straightforward procedures with cheap operating and maintenance expenses and no adverse environmental effect, which makes them a desirable substitute for traditional wastewater treatment (Bottero et al., 2011).

5. Nanotechnology for wastewater purification

Water pollution continues to be the major source of disease and death in developing countries, as well as contributing to social and economic problems (Ebadi et al., 2020; Olutona et al., 2016). Hence, numerous strategies have been investigated to address this problem. Nanotechnology is one of the most modern techniques for cleaning up polluted water. Nanoparticles have distinctive features which are generally different from those of the bulk materials and as a result are appropriate for some applications. It focuses mostly on using materials in the nanoscale in applications that have a significant negative influence on the environment. Water and wastewater treatment have been advanced by nanotechnology to increase treatment effectiveness and expand water supplies by safely using unorthodox water sources. Numerous pieces of data point to the advantages of nanotechnology for treating wastewater. The size of the particles employed in nanotechnology is much less than 100 nm. Due to their tiny size and high concentration of atoms at the surface, nanoparticles have extremely high absorbing, interacting, and reacting capabilities. An increase in the synthesis and manipulation of nanoparticles is being used to enhance environmental quality of the air, soil, and water (Rafeeq et al., 2022). In contrast to macromolecules, reactive nanoparticles have many surfaces and are thus sought after for use as adsorbents. An essential component of nanotechnology is synthesis. Depending on the selection process, nanomaterials can have a totally new set of physical characteristics and uses. Achieving the required crystal size, shape, microstructure, and chemical composition has been made possible by remarkable advances in creative synthetic methods and crystal growth processes.

In contrast to solvothermal or hydrothermal methods, the co-precipitation approach has been used to create metal oxide nanoparticles since it promises to produce stable particles that are also smaller in size (Thangavelu et al., 2022). Many commercial and non-commercial technical advancements are used daily, but nanotechnology has emerged as one of the most cutting-edge techniques for water and wastewater treatment. As water quality requirements continue to rise, advances in nanoscale research have made it possible to develop wastewater treatment methods that are both ecologically safe and economically viable. Future generations now could have their freshwater needs met because to advancements in nanotechnology. It is believed that by utilizing various kinds of nanoparticles, nanotechnology might effectively handle many of the problems with water quality. Due to its structure and increased surface area-to-volume ratio, materials on a nanoscale are capable of water treatment and remediation, sensing and detection, and pollution control (Ayanda et al., 2023). These materials also have innovative and dramatically altered physical, chemical, and biological characteristics. Conventional methods often cannot totally treat polluted water or wastewater, whereas nanoparticles may penetrate deeper and enhance the treatment process. The reactivity with environmental pollutants is improved by the greater surface area-to-volume ratio of nanomaterials. The technique has the potential to eventually supply both enough water and a high-quality supply in the context of treatment and remediation.

6. Advanced oxidation processes

AOPs are characterized as procedures that generate and utilise large amounts of potent but generally non-selective hydroxyl radicals to oxidize the bulk of the complex compounds found in polluted water and wastewater (Ayanda et al., 2023). Hydroxyl radicals (•OH) have the greatest oxidation potential after fluorine radicals. The most potent oxidant, fluorine, which has an oxidation potential of 3.06 V, cannot be utilized to clean wastewater due to its high toxicity. These factors have caused most scientists and technology developers to pay attention to the development of •OH in AOPs. The two processes that make up the main and concise mechanism of AOPs are (a) the production of hydroxyl radicals and (b) the oxidative interaction of these radicals with molecules. The dissolved organic contaminants can then be transformed into CO_2 and H_2O by AOPs. AOPs are being viewed more and more as a very competitive water treatment method for eliminating contaminants with strong chemical stability or poor biodegradability (Hao et al., 2021). The cost of chemical oxidation for full mineralisation is widely known, even though these techniques are useful for treating contaminants with high chemical stability. AOPs are effective at oxidizing inorganic pollutants such cyanide, sulphide, and nitrite in addition to destroying dissolved organic pollutants. Depending on the source, wastewater frequently includes a range of contaminants. Since the makeup of wastewater from industrial sources differs from one industry to another, each type of effluent needs to be treated differently. The requirements for releasing industrial effluents into the public sewage network or surface watercourses are also based on several variables, but the most crucial ones are those related to toxicity and the presence of organic and inorganic materials.

The discharge of wastewater that hasn't been properly treated or hasn't been treated at all has frequently resulted in health issues and illnesses in various regions of the world. Many traditional physical, biological, and chemical methods are being employed for its treatment. Some toxins, however, are resistant to frequently used treatments and can be discovered in wastewater. In this situation, efforts are being made to use new and coupled technologies where the synergistic impact of the many decontamination procedures might offer a substitute that improves the efficacy of individual treatments. Generally, the AOPs provide an excellent possibility to lower the pollutants' concentration from several hundred ppm to ppb when applied correctly. They are referred to as the water treatment methods of the twenty-first century for this reason. AOPs are now being suggested as an option to the treatment of emerging contaminants in wastewater. These methods have recently provided an efficient and quick alternate option for treating newly emergent contaminants in wastewater. AOPs are suitable for effluents comprising hazardous, non-biodegradable, or refractory elements. The processes have several benefits over biological or physical processes, such as the capacity to manage varying flow rates and compositions, the lack of secondary wastes, and process operability. Because they are reactive electrophiles that react quickly and non-selectively with nearly all organic molecules that are electron-rich, hydroxyl radicals in AOPs are efficient in destroying organic substances. When compared to typical oxidations, their oxidation potential is 2.80V, which causes them to display quicker oxidation reaction rates. The organic compounds can be attacked by hydroxyl radicals once they have been produced by using radical combination, hydrogen abstraction, and electron transfer. Photolysis, photocatalysis, sonication, ozonation, electrochemical oxidation, and other processes fall within the general description of AOPs, which encompasses several techniques. With the help of chemical, photochemical, and photocatalytic reactions, these processes produce highly free radicals, mostly $^{\bullet}OH$. When traditional oxidants like H_2O_2 or O_3 combine with UV light or a catalyst, $^{\bullet}OH$ is produced. Organic compounds are gradually, and step wisely broken down by the generated radicals when they react with them. Numerous studies have examined how various AOPs have been used to treat refractory substances (Aremu et al., 2023; Jamil et al., 2011; Pera-Titus et al., 2004).

6.1. Electrochemical oxidation

The environmental compatibility, adaptability, simplicity, and ease of automation of the electrochemical techniques of AOPs (Figure 2) make them highly interesting options for the degradation of organic materials. The electrode material has a major impact on the electrochemical oxidation performance (Zhang et al., 2019). A variety of anodes with large overpotentials for oxygen potential, such as DSA-type, PbO_2, boron-doped diamond (BDD) electrodes, etc., can be used to electro oxidatively produce $^{\bullet}OH$ radicals. Recently, one of the most promising approaches for treating industrial effluents containing organics has been electrochemical oxidation using a diamond electrode doped with boron. Given the applied potential or current density, the BDD electrode's use in the electrooxidation of organics resulted in the total mineralisation of the organic material into CO_2. The high energy need for mineralisation is a significant disadvantage of electrochemical oxidation. Direct photoelectrochemical application or the presence of a catalyst in the electrical field can increase treatment effectiveness while using less energy (Wu et al., 2020). The anode material and the operating circumstances, such as the current density or voltage, affect how well electrochemical oxidation occurs. The effectiveness of photoelectrochemical degradation of organic pollutants depends not only on the choice of an appropriate supporting electrolyte and pH levels, but also on the electrode potential and processing conditions of the semiconductors involved. Under the influence of an applied electric field, photoelectrons and photoholes can be separated in a photoelectrochemical system. In photoelectrochemical systems, there is no problem with the separation of semiconductor particles from the treated solution, which is a concern in heterogeneous photolysis. Numerous semiconductors, including TiO_2, WO_3, SnO_2, ZnO, CdS, and others, can be employed as photoelectrocatalytic materials (Kusmierek, 2020).

Recalcitrant organics, suspended particles, and colour may be eliminated from a pre-treated abattoir effluent using the electrochemical AOPs developed by Alfonso-Muniozguren et al. (2020a). In terms of the technique's effectiveness for mineralisation, it was confirmed that electrochemical oxidation, electrochemical oxidation with hydrogen peroxide, electrochemical oxidation with ultraviolet C light, and electrochemical oxidation with ultraviolet C light/hydrogen peroxide could be used in that order. Anodic oxidation and electrocoagulation were compared in research by Sandoval et al. (2022) for the treatment of effluent from cattle abattoirs. According to the scientists, the electrocoagulation technique yielded the highest TOC removal efficiency (> 88%) at j = 20 $mAcm^{-2}$ with a 0.01 $kWhm^{-3}$ energy consumption. According to Fil and Günaslan (2023), the effectiveness of Ti/Pt anode in the electrooxidation treatment of wastewater from slaughterhouses] was examined. According to the authors, the ideal experiment had a supporting electrolyte type of 0.2 M, a current density of 4.06 mA/cm^2, and a stirring speed of 400 rpm. The COD, colour, turbidity, and suspended solids reductions were reported to be more than 80%, and the energy consumption was 210.7 kWh/m^3.

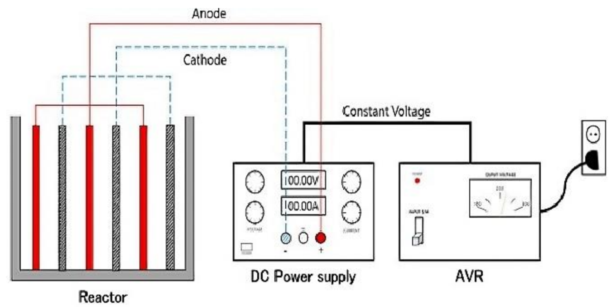

Figure 2. Schematic diagram of electrochemical oxidation apparatus (Jang et al., 2016).

6.2. Photochemical/photocatalytic methods

In the field of wastewater treatment, the photocatalytic or photochemical degradation procedures are gaining popularity (Akpotu et al., 2019) since they provide full mineralisation while operating under mild temperature and pressure conditions. In this method, semiconductor material is activated by electromagnetic radiation with energy sufficient to promote electrons from the valence band to the conduction band (Tahir et al., 2020). Chemical activity, stability, availability, affordability, and lack of toxicity are all factors that must be considered when choosing an appropriate catalyst. The catalyst's surface area and the photo-generated electron-hole pairs able to react with the contaminants are crucial factors. In photocatalysis, several catalytic materials (oxides like TiO_2, ZnO, SnO_2, WO_3, ZrO_2, CeO, etc., or sulphides like CdS, ZnS, etc.) have been investigated. TiO_2 is a significant semiconductor photocatalyst for environmental cleanup and energy conversion processes, distinguishing out from other semiconductors reported so far in terms of stability and oxidative power. However, there are two probable downsides to using TiO_2, namely (a) its potential harmful effects on human health (Skocaj et al., 2011) and (b) diminished activity because of the complexity of the water matrix.

The production of reactive species on the surface of the photocatalyst and the subsequent generation of •OH, which causes the mineralisation of most organic compounds, are two steps in the multistep process of photocatalytic degradation. The sun or artificial sources can provide the UV radiation needed for the photocatalytic activities. A large economic incentive exists for photocatalytic degradations based on solar light (Lu et al., 2022). Then, organic molecules can experience both oxidative deterioration through interactions with valence band holes, hydroxyl, and peroxide radicals and reductive cleavage through reactions with electrons, resulting in a variety of byproducts and finally mineral end products. Several research have employed the photocatalytic technique to remediate wastewater from wineries and distilleries, dairy industries, molasses industries, candy and sugar industries (Castro et al., 2019; Davididou et al., 2023; Sasidharan et al., 2023), etc. A schematic diagram for photocatalytic water splitting using a Z-scheme with an aqueous redox mediator is presented in Figure 3.

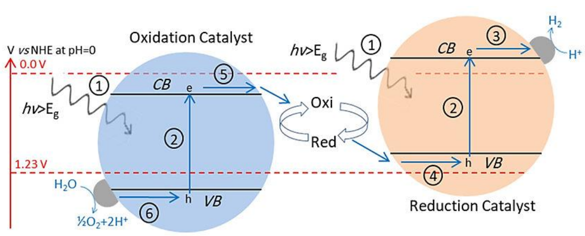

Figure 3. Schematic diagram for photocatalytic water splitting using a Z-scheme with an aqueous redox mediator (Nadeem et al., 2021).

The photocatalytic degradation of p-cresol and dibutyl-phthalate biorecalcitrant aromatic compounds in real AWW was conducted in a study by Aoyi and colleagues (Aoyi et al., 2017). It was reported that the photocatalytic process achieved degradation of 93% and 73% for p-cresol and dibutyl-phthalate, respectively, after ten hours of irradiation at a recirculation rate of 45 ml/min using a modified polyaniline, polyaniline/TiO_2/ZnO composite catalyst illuminated with 25 W UV-C lamps in an annular photoreactor. In addition, the decreases in COD and TOC were 88% and 78%, respectively. Bukhari et al. (2019) investigated the photocatalytic oxidation method for treating effluent from slaughterhouses. According to the scientists, process efficiency rose with an increase in catalyst dosage and reaction duration but declined with a rise in pH. Additionally, it was discovered that the choice of catalyst and its operation conditions significantly affect how well effluent from abattoirs oxidizes. The optimum catalyst for the degradation of AWW was determined to be Ag-TiO_2-H_2O_2 under UV (400 watt) irradiation, which produced 95% BOD, 87% COD, and 74% nitrogen elimination.

6.3. Ultrasound

An acoustic wave called ultrasound (Figure 4) has a frequency that is typically 20 kHz beyond the top auditory threshold of the ordinary individual. Cavitation is caused by bubble nuclei that already exist. These bubble nuclei expand and coalesce as the ultrasound pressure rises over the cavitation threshold, and when they achieve resonance size, the bubbles violently inertially collapse (Alfonso-Muniozguren et al., 2020b). The bubble core can reach temperatures of 10,000 K and pressures of up to 1000 atm during the inertial collapse. When a bubble bursts, the high temperatures that result cause the water vapour within to split, creating reactive radicals like •OH (sonochemistry) and emitting light (sonoluminescence). The localized microjets, which may travel at speeds of up to 120 m/s and are produced when bubbles burst asymmetrically close to a surface, can also produce mechanical effects in addition to chemical ones. This will then produce extremely high shear forces that aid in water treatment following the destruction of microorganisms and water disinfection (Ayanda et al., 2018).

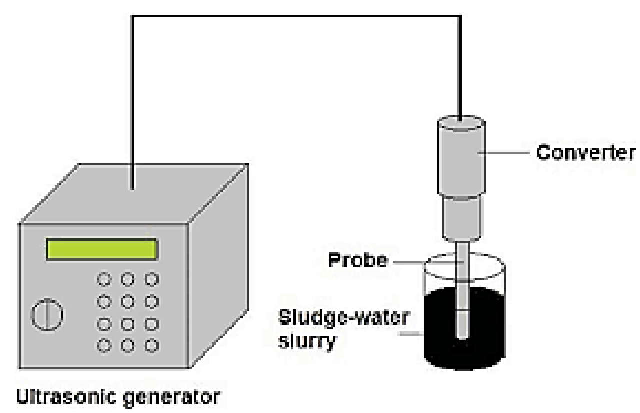

Figure 4. Schematic diagram of the ultrasonic irradiation set-up (Hu et al., 2014).

The elimination of COD from effluent from chicken slaughterhouses by ultrasonic irradiation was studied by Abdelhay et al. (2022). After 180 minutes of radiation, the authors found that the COD elimination had achieved its maximum values. When the power density was raised from 160 to 1200 W/L at operating frequencies of 1142 and 578 kHz, respectively, the COD elimination percentage rose from 2% to 43% and from 2% to 49%. But when the pH was raised from 7 to 9, the COD removal decreased from 51% to 13%. They concluded that the removal of COD was improved using a technique that combines ultrasound and H_2O_2.

6.4. Ozonation

Strong oxidizing agents like ozone are well-known and often used for the treatment of both water and wastewater. Even at high pH levels, ozone is quite effective. Ozone interacts indiscriminately with all chemical and inorganic molecules present in the reaction media at these high pH levels (>11.0). Direct molecular reactions and indirect chain reactions of the radical type are the two main ways that ozone interacts with wastewater chemicals. However, the high cost of generating ozone might have created problem for is effective usage. Hammadi et al. (2016) presented a schematic diagram of a water treatment process using ozone (Figure 5). Other classification of AOPs based on source of radicals is presented in Figure 6.

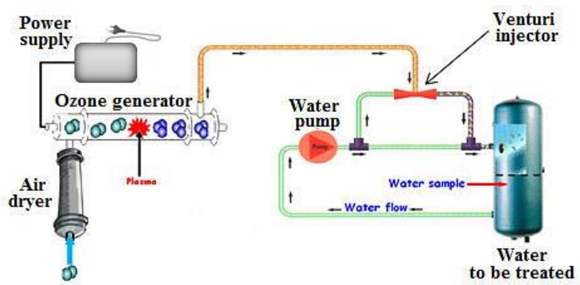

Figure 5. Representation of the water treatment process using ozone (Hammadi et al., 2016).

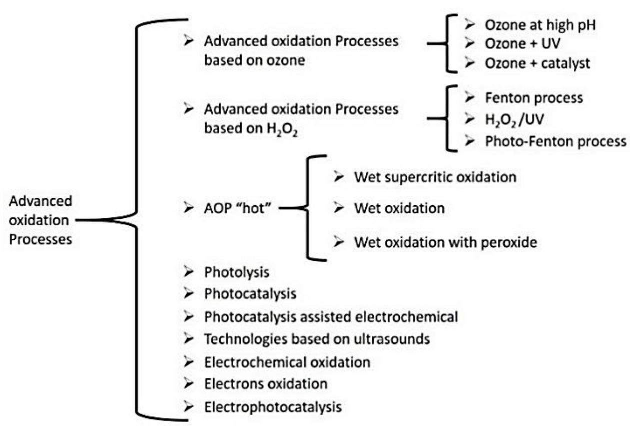

Figure 6. General classification of AOPs.

7. Combination of AOPs for wastewater treatment

Many researchers have developed and researched variously combined AOPs as solutions for treating wastewater that contains organic contaminants. This may frequently result in a decrease in the toxicity or removal of a particular pollutant, as well as a reduction in the reaction time and financial cost (Suryawan et al., 2019). Setting the objective is a crucial stage in combination studies since it aids in defining process efficiency, serves as a foundation for comparing various operating circumstances, and aids in process optimization. Wastewater refractory and high molecular organic contaminants can be removed using a variety of AOPs. AOPs could be employed singly or in combination $^{\bullet}OH$ are often produced during these procedures as the primary oxidants for pollutants elimination (Coha et al., 2021). It is crucial to offer suitable reaction conditions and generate adequate $^{\bullet}OH$ when using these AOPs. In many instances, the conventional oxidation of organic compounds with ozone or hydrogen peroxide does not entirely convert the organics to CO_2 and H_2O. The intermediate oxidation products that remain in the solution after the treatment process may be just as harmful as or even more so than the original substance. By adding UV light to the process, oxidation reactions can be completed as well as the oxidative destruction of substances resistant to ozone or H_2O_2 oxidation on their own. For effective ozone photolysis, UV lamps should have a maximum radiation output at 254 nm. Numerous organic pollutants that are exposed to UV light between 200 and 300 nm absorb the energy and either directly photolyze or become excited and more reactive in the presence of chemical oxidants. Water polluted with a wide range of contaminants has been effectively remedied using AOPs based on the utilization of UV light and oxidants like H_2O_2 and O_3. These procedures rely on the creation of reactive oxidizing species, which degrades the organic content of the wastewater. A combination of UV/H_2O_2, O_3/H_2O_2, O_3/UV and UV/H_2O_2/O_3 processes can accelerate the oxidation of organic molecules in water. Due to the creation of highly reactive $^{\bullet}OH$, the interaction of the combined processes produces a synergistic impact. The organic contaminants are attacked by the $^{\bullet}OH$, which sets off a chain of oxidation processes that eventually result in their complete mineralisation. The major justification for combining photochemical procedures is that, when employed independently, they frequently fall short of reducing pollutants in wastewater.

7.1. Ozone/Hydrogen peroxide process (O_3/H_2O_2)

Pollutants with complex oxidation and high oxidant consumption rates are treated using a combination of O_3 and H_2O_2 (Figure 7). These combinations enable the method to be economically viable despite the high cost of O_3 synthesis. Due to the production of the highly reactive $^{\bullet}OH$ in the presence of H_2O_2, the capacity of O_3 to oxidize various contaminants directly on various bonds (C=C bonds), aromatic rings, is further strengthened. When H_2O_2 dissociates, a hydroperoxide ion is created. This ion attacks the ozone molecule and produces $^{\bullet}OH$ consequently. Like other AOPs, the pH of the solution is essential for process efficiency. When H_2O_2 is added to an aqueous O_3 solution, higher pH conditions will cause more $^{\bullet}OH$ to be produced.

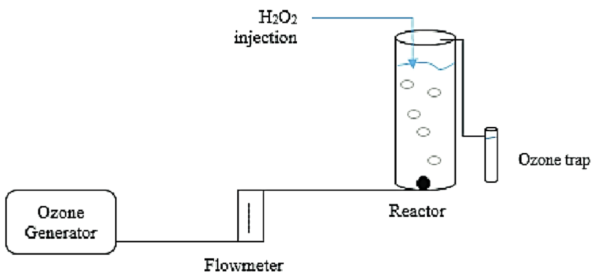

Figure 7. Reactor for ozone-hydrogen peroxide wastewater treatment (Suryawan et al., 2019).

7.2. Hydrogen peroxide/UV (H_2O_2/UV) process

This treatment procedure starts with the mixing of H_2O_2 to a reactor equipped with UV light. The O-O bond in H_2O_2 is broken during this process by UV light, which releases the $^{\bullet}OH$. This approach relies on a photon with a wavelength in the 200–300 nm range directly photolyzing the H_2O_2 molecule. As the predominant absorption band for H_2O_2 is between 220-260 nm, the low, medium, and high-pressure mercury vapor lamps can be employed for this procedure due to their strong emittance within this range. The use of low-pressure mercury vapour lambs might result in the need to use large amounts of H_2O_2 to generate enough $^{\bullet}OH$. A high H_2O_2 levels, however, may scavenge the $^{\bullet}OH$ and reduce the efficiency of the H_2O_2/UV process. Additionally, H_2O_2 has an optimal concentration; above this point, its scavenging effect makes its presence harmful to the degradative process. Furthermore, because the UV energy needed for the photolysis of the oxidizer is not present in the solar spectrum, this process cannot use solar light as the source of UV light. Due to peroxide's low UV absorption properties, much of the light entering the reactor will be lost if the water matrix absorbs a significant amount of UV light energy. The production of $^{\bullet}OH$ is influenced by several factors, including temperature, pH, H_2O_2 concentration, and the presence of scavengers (Ouahiba et al., 2023). The technique can be rationally enhanced by combining it with ultrasound or by ozone pretreatment.

7.3. Ozone/UV (O_3/UV) process

In many instances, conventional ozonation of organic molecules does not fully oxidize organics to CO_2 and H_2O. After oxidation, the remaining intermediate intermediates in some solutions may be just as harmful as or even more poisonous than the original molecule, and UV light may help to finish the oxidation reaction. For effective ozone photolysis, UV lamps must have a maximum light output of 254 nm. H_2O_2 may be produced by the photolysis of ozone in water using UV light with a wavelength of 200–280 nm. UV photons are used in the O_3/UV process (Figure 8) to activate ozone molecules and facilitate the production of $^{\bullet}OH$. O_3/UV was reported by Shu and Huang (1995) to be superior to UV or ozonation alone as a technique for decolorizing dyes. All types of UV light sources, aside from low pressure mercury vapour lamps, can be employed in this procedure. The effectiveness of the system is influenced by several factors, including pH, temperature, scavengers in the influent, turbidity, UV intensity, lamp spectrum features, and types of pollutant.

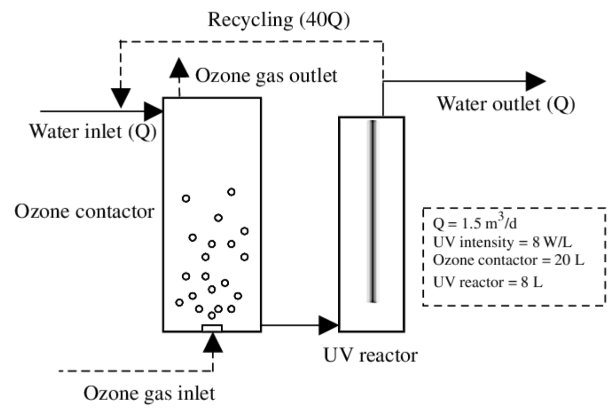

Figure 8. Schematic diagram of an ozone-UV system (Oh et al., 2007).

7.4. Ozone/Hydrogen peroxide/UV (O_3/ H_2O_2/UV) process

The O_3/ H_2O_2/UV technique is the most potent and successful one for quickly and completely mineralizing contaminants. The generation of $^{\bullet}OH$ is impacted by rising pH, just as other types of ozone and AOPs. Additional UV radiation use has an impact on the development of $^{\bullet}OH$. Through secondary reactions, the addition of H_2O_2 to the ozonation system increases the process's ability to oxidize. The breakdown of O_3 is initiated by H_2O_2 by an electron transfer. The optimal O_3/H_2O_2 molar ratio is 2:1, and the procedure is quick and effective in treating organic pollutants at extremely low concentrations (ppb), at pH levels between 7 and 8. The increase in ozone transfer in water caused by H_2O_2 has been hypothesized to be the cause of the acceleration of ozonation. This combined AOP can be used to treat water with a strong UV background since ozone has a greater absorption coefficient than H_2O_2. The treatment of oil sands process water with O_3/H_2O_2 and UV-C light irradiation is shown in Figure 9.

7.5. Ultrasound/Ozone (US/O_3) process

In addition to fulfilling drinking water regulations for microbiological disinfection, a combination of ozonation-sonication treatment might meet direct discharge restrictions for wastewater (Alfonso-Muniozguren et al., 2020b). Alfonso-Muniozguren et al. (2020b) examined the effects of ultrasound both on its own and in combination with ozone for the treatment of real AWW. According to the scientists, there was no change in the microbiological content for any of the frequencies (44, 300, or 1000 kHz), and only the frequency of 300 kHz of ultrasound alone caused a drop in COD (18%) and BOD (50%) levels. The elimination of COD (44%) and BOD (78%) for the three frequencies under study, however, significantly decreased when ultrasound and ozone were used together.

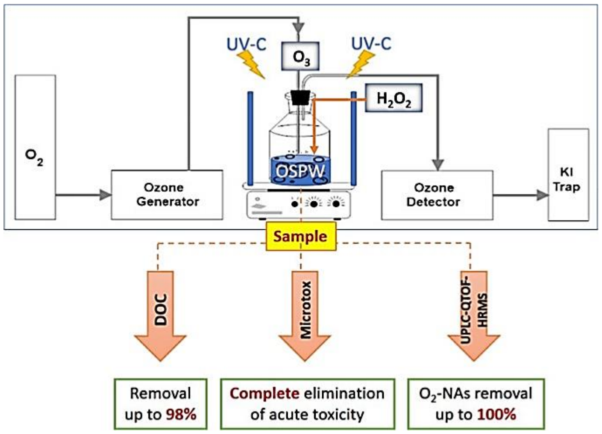

Figure 9. O_3/H_2O_2 and UV-C light irradiation treatment of oil sands process water (Demir-Duz et al., 2022).

8. Combined biological processes and AOPs for the treatment of AWW

AOPs have great overall treatment efficiency for water reuse, making them an intriguing additional treatment option for AWW's main or secondary treatment. In contrast to other disinfection techniques, such as chlorination, AOPs may inactivate microorganisms without the use of extra chemicals, preventing the generation of dangerous by-products (Barrera et al., 2012). This is another advantage of AOPs. High response rates and quick treatment times are two further key benefits of AOPs. The two AOPs for AWW treatment that are most often utilized are photocatalysis utilizing photo-Fenton-based techniques and photooxidation using UV/H_2O_2. AWW secondary effluents can be post-treated to obtain removal efficiencies of over 90% in terms of TOC and COD, even though these treatments are often costly if used alone. Therefore, it is advised for AWW to use both biological processes and AOPs. Since combined procedures combine the advantages of many technologies to treat high-strength wastewaters, they are advantageous for AWW treatment both operationally and financially. The properties of the wastewater, the length of treatment, the concentration of the influent, the kind of treatment, and the best available technology to meet standards (Oputu et al., 2015) all have a role in how well AWW is treated.

9. Conclusion

Untreated wastewater discharge not only seriously jeopardizes human health, but it also affects the aquatic life negatively. It produces eutrophication which depletes dissolved oxygen and may generate dangerous gas emissions. In AWW, blood and fat are significant issues. The COD of blood is quite high, and lipids in treatment plants can lead to physical issues including clogs, clogging, scum development, and even plant shutdowns. Therefore, to reduce the costs of pollution, governments have put rigorous restrictions on the release of water, with severe fines for noncompliance. Abattoirs are attempting to treat wastewater on-site with the prospect of reusing and recycling to lower plant running costs, have a smaller footprint, as well as updating to more cost-effective technology due to the high expenses involved with the efforts to minimize and handle waste. Chemical treatment has lost favour since it is more expensive, leaves onerous sludge disposal to be done, and is not ecologically friendly, making it an undesirable and uneconomical alternative. A benefit of anaerobic treatment is that it effectively removes organic matter in an environmentally benign manner, produces less sludge, uses less energy, can execute greater organic loading rates, requires less nutrients and chemicals, and has high COD and BOD removal efficiencies. The constraints of anaerobic digestion include lengthier start-up and operating times, susceptibility to higher temperatures, and the inability to efficiently remove nutrients like nitrogen and phosphates, which leads to low to moderate effluent quality. The process also frequently encounters operational issues because of the challenges associated with the handling of suspended solids, FOG collecting in the reactors, which results in reduced methanogenic activity, as well as sludge and biomass washout. Due to these difficulties, hydrolysis must be started, solid particles and feathers must be removed, and pre-treatment for FOG removal is necessary. According to some reports, aerobic treatment is preferable than anaerobic treatment for treating water with a high organic content since it degrades pollutants more quickly and effectively. Nevertheless, aerobic digestion is not without drawbacks. For example, it requires more energy to aerate than anaerobic digestion, which raises operating expenses. Therefore, to address this situation and successfully remove the nutrients and organic debris, a mix of both anaerobic and aerobic methods could be used. Due to their sluggish rate of hydrolysis, the proportion of lipids present in AWW represents a concern. Before aerobic-anaerobic digestion, the oils and grease are typically removed via dissolved and induced air flotation. The expenses of the air and reagents utilized, if chemical assistance is employed, however, can render this procedure unprofitable and costly. Additionally, the removal efficiency is poor and occasionally results in challenging sludges to treat.

When recalcitrant substances are present that cannot be removed or changed by traditional technologies into less harmful chemical compounds, AOPs appear as highly powerful and significant technologies to be used in such setup. Most wastewater treatment methods are physicochemical in nature, meaning they include either physical or chemical processes or a mix of the two. The efficiency of AOPs is based on the formation of extremely reactive and non-selective hydroxyl radicals, which are capable of degrading refractory, poisonous, or non-biodegradable pollutants. They provide a successful method of managing pollution in animal production and meat processing factories. This review emphasizes the significance of using a combination of biological processes and AOPs for AWW treatment. Using the synergy of concurrent technologies or increasing the degradation at the lowest possible cost by applying subsequent technological steps, the combination of these technologies appears to be the most practical application.

Conflict of interest

The authors have no conflict of interest to declare.

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