Chapter

Available Technologies for Wastewater Treatment

Ifeanyi Michael Smarte Anekwe, Jeremiah Adedeji, Stephen Okiemute Akpasi and Sammy Lewis Kiambi

Abstract

During the last three decades, environmental challenges related to the chemical and biological pollution of water have become significant as a subject of major concern for society, public agencies, and the industrial sector. Most home and industrial operations generate wastewater that contains harmful and undesirable pollutants. In this context, it is necessary to make continuous efforts to protect water supplies to ensure the availability of potable water. To eliminate insoluble particles and soluble pollutants from wastewaters, treatment technologies can be employed including physical, chemical, biological (bioremediation and anaerobic digestion), and membrane technologies. This chapter focuses on current and emerging technologies that demonstrate outstanding efficacy in removing contaminants from wastewater. The challenges of strengthening treatment procedures for effective wastewater treatment are identified, and future perspectives are presented.

Keywords: anaerobic digestion, bioremediation, coagulation, expanded granular sludge bed, ion exchange, membrane technology, microfiltration, nanofiltration

1. Introduction

Wastewater is produced as a result of human and industrial activities. Different kinds of firms are emerging because of ever-changing needs and demands, and as a response, numerous new pollutants are deposited in wastewater, necessitating the development of advanced treatment techniques. To manage ever-changing wastewater discharges, advanced methods are essential, and there is always a connection between water and energy. Although it is impossible to completely eliminate wastewater formation because no business is 100% efficient, however, it is feasible to develop novel and improve existing wastewater treatment and reuse methods to satisfy water demand. Moreover, water reuse has an enormous prospective for replenishing water resource portfolios that are already overburdened.

Since wastewater treatment and reuse are linked to public health, they are extremely important. The existence of pathogenic organisms and polluted substances in wastewater presents the possibility of harmful health effects where contact, inhalation, or ingestion of substance or microbiological elements of health concern occurs. The impact of several factors (such as pH, temperature, colour, and particle matter) and chemical components (cations, anions, and heavy metals) on human health have already been proven, and acceptable thresholds have been set. However, if industrial emission comprises a major portion of the wastewater, the influence of organic elements in treated water utilized for non-potable activities requires investigation [1]. Furthermore, while modern technologies can assist in reducing energy consumption and improving reliability, the difficulties in human understanding can be even more worrisome. Past and contemporary proof of disease carried by water (such as cholera, typhoid, malaria, dengue fever, and anaemia) has sparked public debate about the safety of reusing water [2]. On-line sensors, membranes, and enhanced oxidation mechanisms are examples of sophisticated technology that can aid to alleviate this impression. Nevertheless, a clearer knowledge of the processes of reuse and the qualities of reused water in comparison to freshwater resources will lead to a more favorable public opinion.

Wastewater treatment is an eco-friendly process because it protects the ecosystem by releasing less contamination; it employs sustainable resources; it offers the opportunity for unused products to be recycled, and it manages leftover wastes in a more biologically acceptable manner. The features and kinds of contaminants contained in the water, as well as the anticipated use of treated water, influence the choice of treatment technique. Activated sludge mechanisms and anaerobic digestion are century-old methods that continue to work well and have become the treatment of choice [3]. Emerging pollutants in wastewater and rising wastewater loads in water bodies necessitate immediate studies in this field to provide safe and clean water while also ensuring freshwater supplies. With this goal in mind, this chapter focuses on research into the present and emerging wastewater treatment and reuse technologies while highlighting their limitations and prospects [4].

2. Wastewater treatment technologies

Physical, chemical, biological, and combined technologies are commonly used in wastewater treatment facilities. Primary, secondary, and tertiary treatment procedures make up a conventional wastewater treatment plant (WWTP). Primary processes consist of screening, filtration, centrifugation, sedimentation, coagulation, and flotation. Biological treatment, which can be oxic or anoxic, is the most common secondary procedure while oxidation, precipitation, reverse osmosis, electrolysis, and electrodialysis are examples of tertiary treatment. Advanced oxidation processes (AOPs), ion exchange, ultra and nanofiltration, adsorption/ biosorption, and advanced biological treatment combining algae, bacteria, and fungi are all emerging treatment methods that offer healthy and clean treated water [3].

2.1 Physical wastewater treatment technologies

Physical methods, in which physical forces are utilized to remove contaminants, were among the first wastewater treatment technologies used. They are still used in most wastewater treatment process flow systems. These methods are typically employed when water is heavily polluted. The most often used physical wastewater treatment methods are:

2.1.1 Screening, filtration, and centrifugal separation

The first phase in a wastewater treatment operation is screening. The purpose of screening is to eliminate solid waste from wastewater, and it is applied to remove items such as faecal solids, fibre, cork, hair, fabric, kitchen trash, wood, paper, cork, and so on. As a result, different-sized screens are utilized, the size of which is dictated by the requirement, i.e. the size of the particles in the wastewater.

In the filtering process, water is filtered in via a substance having fine holes. This is usually done with a set-up having pore diameters ranging from 0.1 to 0.5 mm. It is used to remove suspended particles, greases, oils, germs, and other contaminants. Membranes and cartridges are examples of filters that can be employed. Filtration can remove particles smaller than 100 mg l^{-1}, as well as oil smaller than 25 mg $l^{-1,}$ reducing it by up to 99%. For water purification, the filtering process is used. Filtration water is utilized in ion exchange, adsorption, and membrane separation processes. Furthermore, filtration devices create potable water [5, 6].

To remove suspended noncolloidal particles, centrifugal separation is performed (size up to 1 mm). Solids (sludges) are separated and released after the wastewater is put to centrifugal devices and rotated at different speeds. Suspended solids segregate to a degree proportional to their densities. Furthermore, the centrifugal machine's speed is also important for the removal of suspended materials. Oil and grease separation, as well as source reduction, are examples of applications.

2.1.2 Sedimentation and gravity separation

This process removes suspended particles, grits, and silts by leaving water undisturbed/semi-disturbed in various types of tanks for varied time intervals. Under the pull of gravity, the suspended solids settle [5–8]. The size and density of the solids, as well as the velocity of the water if it is moving, determine the settling time. To speed up the sedimentation process, alums are occasionally utilized. Gravity separation alone can remove up to 60% of suspended particles. Sedimentation is normally carried out before the application of standard treatment methods. It's a cost-effective way to treat waste from the paper and refinery industries. Water is generated for membrane processes, ion exchange, industrial water supply, using this technology. Source reduction is another application of technology.

2.1.3 Coagulation

Non-settleable solids are allowed to settle when suspended solids do not settle down through sedimentation or gravity. Coagulation is the term for this process [5, 7]. It is possible to employ alum, starch, ferrous minerals, aluminum salts, and activated silica. Coagulants made of non-ionic polymers, anionic polymers, and synthetic cationic polymers are also effective, but they are usually more expensive than natural coagulants. The most essential governing parameters in the coagulation process are temperature, pH, and contact time. Specific coagulants are added to biological treatment units to remove bacteria and other organics that may be floating in the water. It's the most significant part of a wastewater treatment unit, and it's used for a variety of purposes, including wastewater treatment, recycling, and pollution removal.

2.1.4 Flotation

A conventional water treatment facility's flotation is a typical and necessary component. Flotation removes suspended particles, greases, oils, biological materials, and other contaminants by attaching them to air or gas [5, 9]. The solids bind to the gas or air and create agglomerates, which float to the water's surface and can be skimmed off easily. Alum, activated silica, and other substances enhance the flotation process. The flotation process is aided by compressed air flowing through the water. Electro-flotation (electro-flocculation) has been utilized for recycling and water treatment for a long time. This method may remove up to 75% of suspended particles while also eliminating up to 95% of grease and oil. It's a promising treatment method for paper and refinery sectors [5].

2.1.5 Membrane technologies of wastewater treatment

Over the last two decades, as an emerging wastewater treatment approach, membrane technology has evolved into a substantial separation technique. The water world has been looking for new solutions as regulatory limits and esthetic criteria for consumer water quality have continued to progress. Membrane technology is an example of a novel technology. Membranes are employed as filters in separation processes in a variety of applications in this technology. Adsorption, sand filters, and ion exchangers are just a few of the technologies they can replace. Water filtration (covering desalination) and purification (such as groundwater and wastewater) are major applications of this technology, as are sectors such as biotechnology and food & beverage [10, 11]. **Table 1** illustrates the pore size different membranes technologies ranges.

2.1.5.1 Ultrafiltration (UF)

Ultrafiltration has been utilized to remediate a wide range of waterways around the world. According to reports, surface waters, including lake waters, rivers, and reservoirs, have been employed in 50% of UF membrane plants. This technology has been used to treat municipal drinking water for over a decade [12]. UF pores are typically between 0.01 and 0.05 mm (roughly 0.01 mm) in diameter or less. Larger organic macromolecules can be retained by UF membranes. They used to be defined by a molecular weight cut-off (MWCO) rather than a definite pore size [13]. Since the osmotic pressure of the feed solution is low, hydrostatic pressures in UF are typically in the range of 2–10 bar. The operation of a pressure-driven UF process can be separated into three distinct pressure ranges based on the relationship of permeate flow on

Membrane process	Transmembrane pressure (kPa)	Pore size (nm)	Removable components
Microfiltration	100–200	100–1000	Suspended solids, bacteria
Ultrafiltration	200–1000	1–100	Macromolecules, viruses, proteins
Nanofiltration	1000–3000	0.5–5	Micropollutants, bivalent ions
Reverse-osmosis	3500–10,000	<1	Monovalent ions, hardness

Table 1.
Pressure-driven membrane process.

applied pressure (i) linearly increasing flux (sufficiently low), (ii) intermediate, (iii) and limiting flux (sufficiently high).

Even though its concentration polarization layer has not formed appreciably in the linearly increasing flux pressure range, the membrane is the only source of permeate flux resistance. Permeate flux in the limiting flux pressure range, on the other hand, is unaffected by the applied pressure. The process performance is primarily determined by these boundary layer phenomena, just as it is in MF [14]. Water and wastewater can be treated in a variety of ways using the UF process, including the manufacture of ultra-pure water for the electronics industry, COD levels are decreasing in maize starch plants, chemical treatment of groundwater combined with selective removal of dissolved hazardous metals, the dairy industry's whey treatment, wine, or fruit juice clarification.

The UF technology has several benefits such as perfect pore size range thus can be applied for the separation of most of the feed components, low energy usage owing to the unavailability of phase transition during separation, and simple and compact design makes it simple to use. In addition, for temperature-sensitive culinary, biological, and pharmaceutical applications, the most advanced membrane separation technology is UF. However, the application of this technology is faced with some drawbacks including an inability to desalinate saltwater because it cannot isolate dissolved salts or low molecular weight species. UF is ineffective at separating macromolecular mixtures; it can only be efficient if the species have a molecular weight difference of 10 times or more.

2.1.5.2 Microfiltration (MF)

Microfiltration is a pressure-driven membrane technology that can retain particles of molecular weight greater than 100 kDa and a diameter smaller than 1000 nm. The membrane pore size determines the separation or retention capacities. MF membrane pore size spans from 100 nm to 10,000 nm. Because the MF pore size is large, the separation pressure is low, ranging from 10 kPa to 300 kPa. Suspended particles, sediments, algae, protozoa, and bacteria are all separated with MF. Furthermore, the separation method is impractical since particles smaller than the pore size pass readily while larger particles are rejected. Darcy's law describes volume flow through MF membranes, where the applied pressure (ΔP) is directly proportional to the flux, $\boldsymbol{J}$ through the membrane:

$$J = A.\,\Delta P \tag{1}$$

Where permeability is a constant A containing structural elements like pore size distribution and porosity. MF can be utilized in a variety of industrial settings, where particles with a diameter > 0.1 mm must be controlled in a suspension. The most fundamental operations still rely on cartridge-based dead-end filtering. However, crossflow filtration will gradually replace dead-end filtering in larger-scale applications. Clarification and sterilization of all types of drugs and beverages are two of the most common industrial applications. Ultrapure water in semiconductors, drinking water treatment, wine, beer, and fruit juice clarification, pre-treatment, and wastewater treatment are some of the other applications.

Microfiltration has shown to be viable due to its low energy consumption, operating pressure, and maintenance which result in low operating cost, fouling is not as bad as it could be because of two factors: larger pore sizes and low pressures. The application of this technology is limited due to its sensitivity to oxidizing agents, bacteria and suspended particles can only be eliminated, particles that are hard and sharp can disrupt the membrane, and cleaning pressures of more than 100 kPa can damage the membrane.

2.1.5.3 Nanofiltration (NF)

Nanofiltration is a filtration technology that separates different fluids or ions using membranes. Due to its broader membrane hole structure than the membranes used in RO, "Loose" RO is a term used to describe NF. More salt can pass through the membrane as a result of this. NF is employed in conditions where strong moderate inorganic removal and organic removal are sought since it can function at low pressures, typically 7–14 bars, and absorbs some inorganic salts. NF may concentrate proteins, sugars, bacteria, divalent ions, particles, colors, and other compounds with a molecular weight of more than 1,000 [15]. NF membranes are constructed of aromatic polyamide and cellulose acetate, displaying salt rejection rates ranging from 95% for divalent salts to 40% for monovalent salts and a molecular weight cut-off (MWCO) for organics of 300 [16]. Organics of low molecular weight, including methanol, are unaffected by NF.

Although NF membranes have strong molecular rejection properties for divalent cations such as magnesium and calcium and may be used instead of traditional chemical softening to effectively remove hardness, they can also be utilized to generate drinking water. Organics with a higher molecular weight that cause odor and taste, or that mix with chlorine to produce trihalomethanes or other particles, can be rejected by NF membranes, boosting the effectiveness of downstream disinfection treatments [17]. Rai and co-workers [18] reported using NF for tertiary treatment of distillery effluent, that the NF membrane had a very high separation efficiency for both inorganic and organic chemicals (around 85–95%, 98–99.5%, 96–99.5% removal of TDS, cooler, and COD, respectively). The advantage of nanofiltration is the lower operating pressure, which results in lower energy costs and potential pump and piping investment savings. The most important drawback of NF membranes is the difficulty in controlling membrane pore size and pore size distribution repeatability. Furthermore, NF membranes are prone to fouling, which could result in significant flow reduction.

2.1.5.4 Reverse osmosis (RO)

Reverse osmosis (RO), in general, is the reverse of the osmosis process. When a semi-permeable barrier is established between two solutions, a solvent flows from lower to higher solute concentrations. Reverse osmosis occurs when an external force causes a solvent to flow from a higher to lower solute concentration. The driving force in the typical osmosis process is a drop in the system's free energy, which diminishes as the system seeks to achieve equilibrium. When the system reaches equilibrium, the osmosis process comes to a stop. An external force larger than the osmotic pressure of the system drives the RO process. RO is like other pressure-driven membrane processes; however, other processes employ size exclusion or straining as the mode of separation and RO employs diffusion.

RO membranes are usually dense membranes having pore sizes less than 1 nm. They are generally a skin layer in the polymer matrix. The membrane material (polymer) forms a layer and a web-like structure. The water follows a tortuous path to get permeated through the membrane. RO membranes can reject the smallest entities from the feed. These include monovalent ions, dissolved organic content, and viruses, almost everything that other membrane processes are not capable of. RO membranes can also be used in both cross-flow and dead-end configurations, but on the other hand, crossflow is frequently favored due to its low energy usage and low fouling qualities. Spiral wound modules, in which the membrane is wound around the inner tube, are the most prevalent. RO has several applications, of which desalination is the most important and widely used. RO is also used in wastewater treatment, and dairy and food products.

Using RO technology, desalination of the sea and brackish water is possible when compared to other membrane processes where separation occurs without a phase change. In comparison to other desalting systems, it is compact and hence takes up less space while ensuring low maintenance and easy scalability. High-pressure requirements, energy-intensive process, lower flux, fouling, and the need to pre-treat feed before use are some of the shortcomings of RO.

2.1.5.5 Forward osmosis (FO)

The FO process is a designed osmotic process in which the treated water is on one side of a semi-permeable membrane and a draw solution (DS) is on the other. Even though FO is built on the osmosis principle, the word "forward osmosis" (FO) was most likely coined to differentiate it from "reverse osmosis," which has been the term for membrane desalination technology for decades. Forward osmosis (FO) employs a concentrated draw solution to create high osmotic pressure, which extracts water from the feed solution across a semi-permeable membrane [19]. As a result, the volume of the feed stream drops, the salt concentration rises, and the permeate flux to the draw solution side reduces [20]. The general equation characterizing water movement over the RO membrane, according to Lee et al. [21], is:

$$J_W = A(\sigma\Delta\pi - \Delta P) \tag{2}$$

where J_W is the water flux, A is the membrane's water permeability coefficient, $\sigma\Delta\pi$ the effective osmotic pressure difference in reverse osmosis, σ is the reflection coefficient, and ΔP is the applied pressure; for FO, $\Delta P = 0$; for RO, $\Delta P > \Delta\pi$ [21]. Since the parameter A and the reflection coefficient are calculated using the pressure applied to the brine, this equation is not suited for FO operations; also, the driving force employed is the difference between osmotic pressure and the applied hydraulic pressure (ΔP) [22, 23]. **Figure 1** displays the principles of osmotic processes.

The primary benefit of FO is how little energy is required to extract pure water from wastewater or recycled feed, with just the energy needed to recirculate the draw solution requiring additional energy [18]. The ultimate flux reduction of concentration polarization is a fundamental limiting element impacting the performance of FO systems [25, 26]. Since forward osmosis is gaining attention as a viable method for lowering the cost of wastewater treatment and generating freshwater, many potential applications for FO membranes have been investigated, including desalination, dilute industrial wastewater concentration, direct potable reuse for enhanced life support systems, food processing, landfill leachate concentration, pharmaceutical industry processes, and concentration of digested sludge liquids [26].

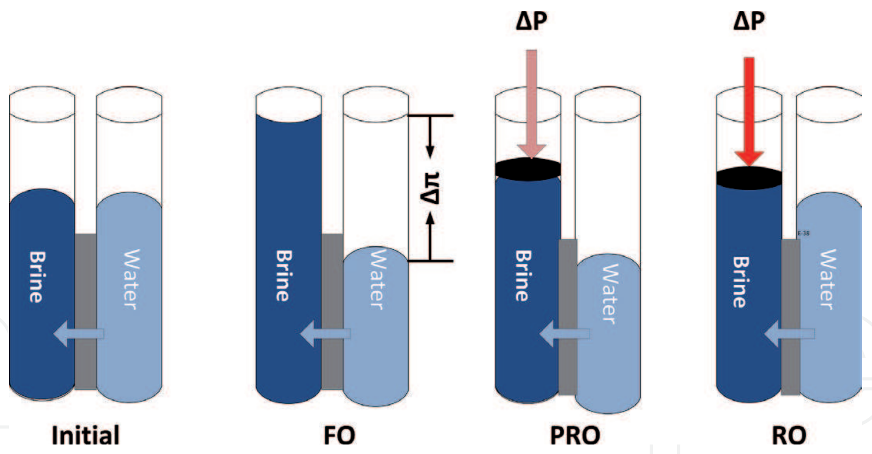

Figure 1.
Principles of osmotic processes: the initial state of the solutions, forward osmosis (FO), pressure retarded osmosis (PRO) and reverse osmosis (RO), adapted from Rao [24].

2.2 Chemical wastewater treatment technologies

Chemical methods employed in waste-water treatment are designed to create change through chemical reactions. They are always combined with physical and biological methods. Chemical methods, in comparison to physical ones, have an inherent disadvantage considering that they are additive processes. That is, the dissolved elements of wastewater usually increase. If the wastewater is to be reused, this is an important consideration. A brief description of chemical methods of wastewater treatment is given below.

2.2.1 Neutralization

The pH value of wastewater is adjusted through neutralization. Acids or alkalis are used to neutralize industrial wastewaters after operations such as precipitation and flocculation. Metal-containing acid wastewaters can be treated by adding an alkaline reagent to the acid waste, forming a precipitate, and collecting the precipitate. As a result, the pH of the input solution is adjusted to the optimal range for metal hydroxide precipitation. To meet the overall wastewater treatment objectives, the step is performed before the major phase of wastewater treatment [27].

2.2.2 Precipitation

By lowering their solubilities, dissolved contaminants become solid precipitates, which can be easily skimmed from the water's surface during precipitation [27]. While it effectively removes metal ions and organics, the accumulation of oil and grease may produce precipitation issues. Adding chemicals or reducing the temperature of the water reduces the solubility of dissolved pollutants. Adding organic solvents to the water could theoretically decrease the contaminant's solubility, however, this procedure is costly on a large scale. Precipitates form when these compounds react with soluble contaminants. The most used substances for this function include ferric chloride, lime, ferrous sulphate, sodium bicarbonates, and alum. The most critical moderating parameters for the precipitation process are temperature and pH. Precipitation can eliminate approximately 60% of pollutants [28]. This method can be used to recycle water and remediate wastewater from the chromium and nickel-plating industries. Among the applications are water softening and heavy metal removal and phosphate from water. The handling of the vast amount of sludge produced is the main issue related to precipitation [29, 30].

2.2.3 Ion exchange

An ion exchanger, a solid substance, exchanges hazardous ions in wastewater for non-toxic ions [31–35]. There are two types of ion exchangers: anion and cation exchangers, which can exchange anions and cations, respectively. Ion exchangers are resins with active sites on their surfaces, which might be natural or synthetic. The most used ion exchangers include metha-acrylic resins, zeolites, acrylic, polystyrene sulfonic acid, and sodium silicates. It is a reversible process that utilizes very little energy. Low amounts of inorganics and organics are removed using ion exchange (up to 250 mg l^{-1}). Concentrations of inorganic and organic compounds can be reduced by up to 95%. Potable water production, industrial water, pharmacy, fossil fuels, softening and other sectors are among the applications. It's also being utilized to cut down on pollution. If there is oil, grease, or large quantities of organics and inorganics in the water, it may be necessary to pre-treat it.

2.2.4 Oxidation/reduction

Redox reactions are commonly used in chemical wastewater treatment and potable water treatment. Chlorinated hydrocarbons and pesticides are effectively removed from drinking water using ozone and hydrogen peroxide oxidation methods. Oxidation techniques are utilized in wastewater treatment to remove problematic biodegradable chemicals. Photochemical purification, which uses UV light to create hydroxyl radicals from hydrogen peroxide or ozone, is very effective. These Advanced Oxidation Processes (AOP) destroy antibiotics, cytostatic medications, hormones, and other anthropogenic trace chemicals. Advanced Oxidation Processes (AOPs) are efficient methods to remove organic contamination not degradable through biological processes in water and wastewater. Ozone also helps with the oxidation of iron and manganese in well water. To convert heavy metal ions, for example, into easily dissolvable sulfides, reduction procedures are necessary [36].

2.2.5 Electrodialysis

Ion-selective semi-permeable membranes allow water-soluble ions to pass through them when an electric current passes through them [37, 38]. Ion-selective membranes are ion exchange materials that are selective. They can be anion or cation exchangers, allowing anion and cations to flow out of the system. The technique uses two electrodes to which a voltage is supplied in either a continuous or batch mode. The membranes are arranged in a series or parallel pattern, to obtain the required degree of demineralization [39, 40]. Factors such as pH, temperature, the type of contaminants, membrane selectivities, scaling and fouling of wastewater, the wastewater flow rate, and the volume and design of phases all affect dissolved solids removal. The creation of drinkable water from brackish water is one of the applications. Furthermore, this technology has been utilized to reduce water sources. Total dissolved solids (TDS) concentrations of up to 200 mg l^{-1} can be decreased by electrodialysis by up to 90% [41]. Membrane fouling happened in the same way that reverse osmosis does. Carbon nanotubes have been used in composite membranes to alleviate this problem and increase flow.

2.2.6 Disinfection

Disinfection in wastewater treatment aims to limit the number of microorganisms in the water that will be released back into the environment for later use as irrigation water, bathing water, drinking water, and so on. The quality of the treated water (pH, cloudiness, and other parameters), the type of disinfection used, the disinfectant dosage (time and concentration), and other external conditions all influence disinfection efficiency. Due to the obvious nature of wastewater, which contains several human enteric organisms linked to a variety of waterborne diseases, this technique is critical in waste-water treatment [42]. Physical agents such as heat and light, mechanical means such as screening, sedimentation, and filtration, radiation, primarily gamma rays, chemical agents such as chlorine and its compounds, bromine, iodine, ozone, phenol and phenolic compounds, alcohols, heavy metals, dyes, soaps, and synthetic detergents, quaternary ammonium compounds, hydrogen peroxide, and various alkali and acids are among the most used disinfection methods. Oxidizing chemicals are the most frequent chemical disinfectants, and chlorine is the most widely utilized of these.

2.3 Biological wastewater treatment technologies

Biological water treatment technologies are critical components of a wastewater treatment strategy since they are utilized to produce safe drinking water. Aerobic, anaerobic and bioremediation processes are the techniques employed for this. These operations are outlined below.

2.3.1 Aerobic processes

Aerobic and facultative bacteria cause biodegradable organic matter to break down aerobically when oxygen or air is freely accessible in wastewater in the dissolved form [43, 44]. Temperature, retention time, oxygen availability, and the biological activity of the bacteria all limit the extent of the process. Furthermore, the addition of specific compounds essential for bacterial development may increase the rate at which organic pollutants are biologically oxidized. This approach can remove phosphates, nitrates, volatile organics, dissolved and suspended organics, chemical oxygen demand (COD), biological oxygen demand (BOD), and other pollutants. It is possible to reduce the number of biodegradable organics in the environment by up to 90%. The method's downside is that it produces a huge number of bio-solids, which necessitates additional costly treatment and management. Oxidation ponds, aeration lagoons, and activated sludge processes are used to carry out the aerobic process [44]. The following Eq. (3) gives a simple depiction of aerobic decomposition.

$$\text{Organic matter} + \text{O}_2 + \text{Bacteria} \rightarrow CO_2 + \text{H}_2\text{O} + \text{Bacteria} + \text{Byproducts} \quad (3)$$

2.3.1.1 Oxidation pond

Oxidation ponds are aerobic systems in which the heterotrophic microbes consume oxygen that is supplied by both the atmosphere and photosynthetic algae. In this process, algae utilize the inorganic substances (N, P, CO_2) generated by aerobic bacteria to fuel their growth, which is powered by sunlight. They discharge oxygen into the fluid, which the bacteria then use to complete the symbiotic cycle [44].

2.3.1.2 Aeration lagoon

Aeration lagoons are deeper than oxidation ponds, because aerators supply oxygen rather than algal photosynthetic activity, as in oxidation ponds. The aerators maintain the microbial biomass afloat and supply enough dissolved oxygen for the aerobic process to be maximized. Although there is no deposition or sludge return, this process relies on properly mixed liquor formation in the tank/lagoon. As a result, aeration lagoons are appropriate for effluent that is both strong and biodegradable, such as wastewater from the food industry [44].

2.3.1.3 Activated sludge

The activated sludge method works by suspending a substantial bacterial colony in wastewater under aerobic conditions. Greater levels of bacterial proliferation and respiration can be achieved with limitless nutrients and oxygen, resulting in the conversion of accessible organic compounds to oxidized end-products or the formation of new microbes. The activated sludge system is comprised of five interconnected components: bioreactor, activated sludge, aeration and mixing system, sedimentation tank, and returned sludge [44]. The biological mechanism employing activated sludge is a widely utilized technology for wastewater remediation that has low operating costs.

2.3.2 Anaerobic processes or anaerobic digestion

Anaerobic treatment of waste is a biological process in which microorganisms degrade organic pollutants without oxygen. When there is no free dissolved oxygen in the wastewater, anaerobic breakdown or putrefaction takes place where anaerobic and facultative bacteria break down complex organic substances into sulfur-based organic molecules, carbon, and nitrogen. This sequence of biochemical events produces biogas such as methane, hydrogen sulfide, ammonia, and nitrogen. This approach minimizes the number of bacteria in wastewater [45–47]. Anaerobic technologies are generally used before aerobic treatment for streams with high organic material (measured as high BOD, COD, or TSS). Anaerobic treatment is a tried-and-tested low-energy way of treating industrial effluent. The following Eq. (4) represents the anaerobic process.

$$\text{Organic matter} + \text{Bacteria} \rightarrow CO_2 + CH_4 + \text{Bacteria} + \text{Byproducts} \tag{4}$$

The anaerobic digestion (AD) approach is appealing because it treats wastewater, provides renewable energy, and generates byproducts that may be utilized as farm fertilizers, making it an environmentally benign process [48]. When compared to the aerobic wastewater treatment process, the AD process offers the following advantages: fewer nutrients required and the creation of less biological sludge, which requires simply drying as further treatment [49]. It also necessitates a small reactor capacity and no oxygen, reducing the power needed to deliver oxygen in the aerobic approach, and the organic loading on the system is not restricted to an oxygen supply. Thus, a higher loading rate can be used in AD, allowing for a faster response to substrate addition after long periods without feeding and semi-feed strategies for a few months. This benefits the system, making AD a viable option for seasonal industrial wastewater treatment and off-gas elimination that causes air pollution. Examples of anaerobic treatment systems are upflow anaerobic sludge bed (UASB) reactor, expanded granular sludge bed (EGSB), anaerobic baffled reactor (ABR), anaerobic filter reactors and anaerobic Lagoons

2.3.2.1 Upflow anaerobic sludge bed (UASB) reactor

The Upflow anaerobic sludge blanket (UASB) technology is particularly effective for treating wastewater with a high carbohydrate content. As a result, the UASB reactor has become one of the most common designs for treating wastewater from agro-industrial processing companies because it can endure fluctuations in effluent quality and complete reactor shut down during the season [50]. In addition, wastewater containing carbohydrates are readily degraded by bacteria and acts as a nutrient-rich precursor for the anaerobic process. Because of its minimal sludge production and low energy and space requirements, the UASB technique has become well-known for treating wastewater. However, the most significant benefit of this technology is that it can generate energy rather than consume it while treating wastewater [51].

The treated wastewater enters the reactor from the bottom and runs upward through a blanket of biologically activated sludge, typically in granular aggregates. The anaerobic bacteria digest (degrade) the wastewater as it moves upward through the blanket. Under realistic conditions, the blanket is held by the upward flow coupled with gravity's settling action with the support of flocculants and does not wash off, resulting in better treatment efficiency. Intrinsic mixing is facilitated by anaerobic gas production, which aids in the creation and enhancement of biological granules. However, because some of the gas created in the sludge blanket is connected to the granules, a gas-liquid-solid separator (GLSS) is added to the reactor's top for effective gas, liquid, and granule separation. In GLSS, gas-enclosed particles collide with the bottom of degassing baffles, fall back into the sludge blanket, and treated water exits the reactor [52].

2.3.2.2 Expanded granular sludge bed (EGSB)

An improved anaerobic treatment system based on an up-flow anaerobic sludge blanket is the expanded granular sludge bed (EGSB). The differentiating feature is that the wastewater passing through the sludge bed has a faster rate of upward flow velocity. In addition, the enhanced flux allows for partial expansion (fluidisation) of the granular sludge bed, boosting wastewater-sludge interaction and enhancing sludge bed segregation of small inactive, suspended particles

2.3.2.3 Anaerobic baffled reactor (ABR)

McCarty and colleagues created the anaerobic baffled reactor (ABR) at Stanford University in the early 1980s. It is a simple linear reactor with a simple operational design that has widespread use in wastewater treatment. The ABR primarily treats wastewater through sludge and scum retention as well as anaerobic degradation of particulate and dissolvable organic substances. As a result, any factors impacting these processes impact ABR treatment. Baffles guide the flow within the reactor in an ABR reactor under the force of the pressure head at the influent. There is no need for mechanical mixing because the flow directly touches the biomass as it is driven through the sludge bed. As a result, no electricity is required during regular operation for an underground ABR design, while ABR above ground design necessitates pumping energy. In ABR, byproduct sludge is recirculated, discharged, or used as manure.

According to Reynaud and Buckley [53], a long solid retention time is required for anaerobic treatment of low-strength wastewater, and the required reactor capacity is influenced by the hydraulic load instead of the organic load. The upflow velocity of the wastewater inside the reactor compartments containing sludge influences solid retention in the ABR design. Low-strength applications, on the other hand, have negligible solid flotation as well as carry-over due to gas production.

2.3.2.4 Anaerobic filter reactors

In 1969, Young and McCarty invented the upflow anaerobic filter. An anaerobic filter was the first high-rate bioreactor that excluded the separation and effluent recycling requirement. In addition, it offers the advantages of eliminating the mechanical mixing stage, having improved stability even at loading rates higher than 10 kg/m^3 day COD, enduring hazardous shock loads, and being inhibitor-resistant. Because the upflow anaerobic filter is loaded with inert support material such as gravel, pebbles, coke, or plastic media, it works similarly to an aerobic trickling filter. As a result, there is no need for biomass separation or sludge recycling in the system. The reactor's designation is to trap particles in the wastewater as it runs through it, while active biomass connected to the surface of the filter material degrades the organic matter [43]. The anaerobic filter reactor can be used as a downflow or upflow filter reactor, with an OLR range from 1 kg/m^3 to 15 kg/m^3 day COD and separation efficiencies ranging from 75 to 95%. The treatment temperature ranges from 20 to 35.8°C, with HRTs varying from 0.2 to 3 days. The main disadvantage of the upflow anaerobic filter is the possibility of blockage due to undegraded sewage sludge, mineral precipitates, or bacterial biomass [43].

2.3.2.5 Anaerobic lagoons

An anaerobic lagoon is a deep earthen basin with enough volume to allow sedimentation of sedimentable solids, digestion of residual sludge, and anaerobic reduction of some soluble organic substrate [54]. Anaerobic lagoons are typically designed to store and treat wastewater for 20–150 days. They're deep (normally 8–15 feet) and function similarly to septic tanks, where anaerobic microorganisms break down contaminants in the absence of oxygen. Solids in wastewater segregate and settle into strata inside an anaerobic lagoon. Grease, scum, and other floating debris make up the top layer. The layer of sludge that settles at the bottom of an anaerobic lagoon gradually accumulates and must be removed if septic tanks are not used first. The effluent from an anaerobic lagoon will need to be treated further [55].

2.3.3 Bioremediation

Bioremediation is a biological treatment process that uses biological resources to convert environmental pollutants into less hazardous forms. For example, the innate ability of microorganisms, plants, bacteria, algae or fungi to survive, adapt and thrive in unseemingly harsh conditions has been exploited to treat contaminated water bodies or soils. Like any other biological treatment process, bioremediation is preferred because it does not require chemicals or a lot of energy. This technology can be applied both in-situ (on-site) or ex-situ; for example, the wastewater can be treated on-site where the pollution takes place or transported to an external site for proper manipulation of the operating condition if it cannot be achieved at the contaminated site. Bioremediation can occur in either aerobic or anaerobic environments. Living organisms require ambient oxygen to thrive in aerobic environments. There is no oxygen in anaerobic situations. Microbes in this situation decompose chemical molecules or ions like sulfates in the wastewater to obtain the required energy [56].

Bioremediation is broadly classified into the following;

i. Microbial bioremediation—employs microorganisms as food sources to break down contaminants.

ii. Mycoremediation—breaks down contaminants using the digestive enzymes of fungi.

iii. Phytoremediation—employs plants to extract, break down and clean up contaminants.

Microbial remediation and mycoremediation can be classified further based on the strategy used as bioattenuation (natural attenuation), biostimulation (use of organic or inorganic nutrients for remediation), and bioaugmentation (use of genetically engineered microbe).

3. Limitations and prospects of wastewater treatment technologies

3.1 Physical and chemical technologies

Conventional wastewater treatment methods are currently beset by several issues, including increased chemical usage, sludge disposal, and increased energy and space needs. Furthermore, effective elimination of recalcitrant organic components, the inability to handle more wastewater than the limited design capacity, and a scarcity of experienced labour are all major operational issues in these systems. Because of all of these operational and technological limitations in traditional wastewater treatment methods, researchers are working to establish novel categories of advanced wastewater treatment techniques to address the aforementioned issues. Advanced wastewater techniques must integrate membrane technology, Advanced Oxidation Processes, Less sludge formation and if sludge is formed, how to use the sludge rather than disposing of it at the dumpsite, adsorption materials with a low cost, fewer chemical or bioflocculant usage, a new group of nanoparticles for wastewater treatment. Although there is a large body of study on the aforementioned topics, there are still areas that need improvement in the open literature to tackle the concerns of developments in wastewater treatment methods. The employment of modern wastewater technologies in conjunction with traditional methods may lead to more efficient wastewater treatment as well as increased reuse and recycling of treated water.

3.1.1 Membrane technologies

Membrane technology has several drawbacks, including greater energy consumption and fouling. Developing novel membrane materials, calculating hydrodynamics, incorporating modules, and exploring innovative modes of operation to reduce energy usage or application parameters to improve the treatment of water or wastewater are all examples of current advancements linked to membrane technology. All membrane processes have a minimal impact on the environment. There are no hazardous chemicals that must be disposed of, and no heat is generated in the operations. Future trends will include the recovery of valuable compounds, utilization of process waters, technological development including forwarding osmosis and pervaporation, real-time fouling monitoring, the advancement of existing fouling analysis techniques, the creation of custom-made novel membranes, and the development of membranes that can be applied in extreme circumstances. As these objectives are met, capacity, selectivity, and cost, as well as environmental effects including chemical consumption and concentrate handling should be addressed.

Membrane processes play an important role as well. As materials and membrane processes advance, new applications such as new MBRs (membrane bioreactor technologies), advanced osmosis, and pervaporation systems will be accessible. Anaerobic MBRs decompose organic compounds using anaerobic bacteria. In this configuration, biogas can replace the air in the submerged reactor. Due to their lower energy use, MBR systems outperform conventional systems. Since anaerobic MBR systems can retain high biomass concentrations, withstand high organic loadings, recover organic and energy acid, and generate little sludge, they are promising. Another promising technique is microbial fuel cells, a new form of MBR. Decentralized treatment systems can be utilized in wastewater systems to reduce costs and promote sanitation and reuse [57, 58].

3.2 Biological technologies

The biological treatment process is a well-known technique for dealing with problems associated with the treatment of industrial effluents and municipal wastewaters, where conventional technologies have proven to be prohibitively expensive, time-consuming, and ineffective. Though the aerobic technique has been successful in terms of industrial application, there are some drawbacks, such as greater capital costs for aeration facilities, increased operational costs (especially for energy for pumps or aerators), increased maintenance demands, and probably surveillance requirements for detecting the dissolved oxygen content in the liquid. While for the anaerobic treatment post-treatment of wastes generated because treated water does not meet standards, odor generation, fouling/clogging of the membrane, and a slower start-up time are some of the limitations. Bioremediation is only possible with biodegradable chemicals. Not all substances can be completely degraded in a short period. There are concerns that the biodegradation byproducts will be more persistent or dangerous than the main contaminant. Extrapolating some biological technologies from bench and pilot-scale to large scale operations is still challenging. Biological mechanisms are frequently very specialized. The availability of metabolically competent microbial communities, proper environmental growth parameters, and optimum quantities of nutrients and pollutants are all crucial site considerations.

Biological treatment technology is an innovative tool with significant future potential. As scientists understand more about its functionalities, it is possible to become one of the most effective methods for wastewater and environmental remediation. The tremendous improvement of molecular biological technologies has made it possible to analyze the organization of microbial communities without being influenced by cultivation. To achieve effective system operation with diverse functional microorganisms, careful management and modification of environmental parameters are required for system performance. The invention of innovative techniques and new concepts (e.g., new functional components and novel biological metabolism pathways) will facilitate the advancement of biological wastewater remediation systems. The best approach to achieving this goal is interdisciplinary collaboration.

4. Conclusion

The treatment of wastewater is crucial because of its effect on the environment. Due to increased urbanization and industrialization, wastewater generation and treatment have become a growing concern in the twenty-first century. Wastewater treatment ensures the long-term viability of the ecosystem. Many wastewater treatment options are employed to address the problem of growing environmental pollution, including physical, chemical, and biological (primary to tertiary treatment) technologies. The employment of some treatment strategies has the potential to produce secondary contaminants. The effective implementation of wastewater treatment options in water resource management necessitates planning, activity, design, storage, and operation. Advances in wastewater recycling have made it possible to produce water of virtually any quality. Water recovery systems incorporate a variety of safety precautions to reduce the environmental risks associated with various reuse applications. Continuous advancements have been made in the fundamental science of water treatment methods, as well as the innovation used in the process. However, based on the known treatment methods, attaining considerable wastewater treatment with a single treatment technology is difficult. Under the present conditions, improved or integrated wastewater treatment technologies are critically required to ensure high-quality water, reduce chemical and biological pollutants, and enhance industrial production operations. Integrated approaches, which may overcome the limits of single treatment techniques, seem to be viable options for efficient wastewater remediation. Regrettably, most viable treatment techniques are on the small scale and lack commercial application feasibility.

Author details

Ifeanyi Michael Smarte Anekwe[1]*, Jeremiah Adedeji[2], Stephen Okiemute Akpasi[3] and Sammy Lewis Kiambi[3]

1 School of Chemical and Metallurgical Engineering, University of the Witwatersrand, Johannesburg, South Africa

2 Department of Chemical Engineering, School of Engineering, University of KwaZulu-Natal, Durban, South Africa

3 Department of Chemical Engineering, Durban University of Technology, Durban, South Africa

*Address all correspondence to: anekwesmarte@gmail.com

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