

# Advanced Techniques in Wastewater Treatment: A Comprehensive Review

**Abstract:** The growing global need for uncontaminated water in the face of escalating pollution levels has emphasized the urgent requirement for efficient wastewater treatment. This comprehensive review explores advanced techniques in wastewater treatment, addressing the necessity for effective wastewater management due to increasing water scarcity and pollution from various sources such as households, industries, and agriculture. Despite their widespread use, conventional wastewater treatment methods frequently fail to adequately address complex and emergent contaminants. This review covers innovative approaches such as membrane filtration processes, advanced oxidation processes (AOPs), electrochemical treatments, and adsorption using novel materials such as carbon nanotubes. The advanced techniques demonstrate superior capabilities in removing complex contaminants including metals, organic and inorganic chemicals, and pathogens. It also highlights the environmental benefits and potential for resource recovery and conservation offered by these advanced methods. Furthermore, it underscores the potential of these advanced techniques to improve treatment efficiency, reduce operational costs, and achieve higher water quality standards, thereby contributing to sustainable water management practices.

**Keywords:** Wastewater Treatment, Membrane Filtration, Membrane Bioreactors, Advanced Oxidation Processes, Carbon Nanotubes, Aerobic Granulation, Electrochemical Treatment

## INTRODUCTION

Wastewater is defined as water that has had specific substances added to it that have altered its physical, chemical, or biological characteristics and made it unfit to drink. The daily activities of humans are primarily reliant on water, and as a result, they discharge "waste" into the water. "Body wastes (feces and urine), hair shampoo, hair, food scraps, fat, laundry powder, fabric conditioners, toilet paper, chemicals, detergent, household cleansers, dirt, and microorganisms (germs) are among the substances that can cause illness and harm the environment. It is widely recognized that a significant portion of the water that is supplied is disposed of as effluent, which underscores the significance of its treatment" (Amoatey *et al.* 2011). "Wastewater treatment refers to the systematic use of processes and technologies aimed at eliminating the majority of pollutants present in wastewater, with the ultimate goal of safeguarding the environment and promoting public health" (Metcalf and Eddy 1991). "The primary objective of wastewater treatment is to extract pollutants, remove coarse particles, eradicate toxicants, and kill potential pathogens. This process is intended to allow the remaining clean water, which is referred to as effluent, to be discharged back into the environment for a variety of purposes" (Alagha *et al.* 2020). According to World Vision, over 770 million individuals worldwide lack access to clean and secure water for domestic and drinking purposes (Villarín *et al.* 2020). Wastewater treatment is also designed to increase the availability of water for human consumption and alleviate the strain on natural water resources. Wastewater treatment is one of the most viable alternatives

for improving water sustainability as water scarcity intensifies due to increased demand and encroaching drought conditions (Tortajada 2020). According to Al-Juaidiet *al.* (2014) “the increasing human population will continue to place a greater burden on natural resources, such as pure water, for industrial and domestic purposes. The world is at risk of experiencing acute water shortages and diseases associated with polluted water in the absence of a sustainable water source. There are numerous sources of water

contamination, including households, industry, mines, and irrigation”. However, the largest source of water contamination is the extensive use of water by industry (Hai *et al.* 2007). The types of treatment of wastewater rely on its nature and the required quality of water after the treatment.

In general, the process of wastewater treatment consists of five successive stages: (1) preliminary/pre-treatment (physical and mechanical); (2) primary treatment (physicochemical and chemical); (3) secondary treatment or purification (chemical & biological); (4) tertiary or final treatment (physical and chemical); and (5) treatment of the sludge formed (supervised tipping, recycling or incineration). Generally, “the initial two stages are referred to as the pre-treatment or preliminary step, contingent upon the circumstances” (Anjaneyulu *et al.* 2005; Crini and Badot 2010). “Pre-treatment is crucial in removing solid particles and suspended substances from effluent before secondary treatment, as particulate pollution can hinder efficiency or damage decontamination equipment. Primary chemical treatment, such as oxidation, reduction of Cr(VI), pH adjustment, and pre-reduction of high organic load, may also be necessary” (Pokhrel and Viraraghavan 2004; Sharma 2015). “Prior to its release into the environment or its reuse, the pre-treated effluent must undergo a secondary purification treatment utilizing the most suitable biological, physical, or chemical methods to eliminate the chemical contamination. In specific instances, a final or tertiary treatment

may be necessary to eliminate the residual contaminants or the compounds generated during the secondary purification process (such as the elimination of salts formed by the mineralization of organic material)” (Crini and Lichtfouse 2018).

While there are different types of conventional technologies that have been acknowledged for the purpose of treating water in homes and industries, these approaches have their limitations, as indicated by research (Oller *et al.* 2011; Gil *et al.* 2009; Gavrilescu 2004; Fomina and Gadd 2014; Gleick and Palaniappan 2010). “Conventional methods exhibit a relatively high degree of automation. Typically, they necessitate power and stimulation. These systems necessitate specialized labour for their operation and maintenance. Further, the use of traditional methods has become restricted due to various challenges. These challenges include a growing public awareness of the negative effects of water pollution, a demand for higher quality water, a decrease in water resources due to rapid population growth and industrial development, and advancements in manufacturing industries that offer more advanced wastewater treatment processes. Eliminating contaminants such as diverse metals, organic and inorganic chemicals, and pathogens from water is more challenging. Therefore, researchers have introduced a range of innovative methods, including membrane filtration processes, Advanced Oxidation Processes (AOPs), UV irradiation, carbon nanotubes (CNTs), magnetic techniques, and numerous others. Water is a critical natural resource; consequently, it must be safeguarded. It is imperative to prevent contamination by organic and inorganic contaminants in order to preserve the reserve's prevailing flora and fauna. Nevertheless, the environment is further polluted by the discharge of secondary contaminants or byproducts by certain technologies

that are employed for this purpose” (Bartolomeu *et al.* 2018). Consequently, there is an imperative need for wastewater treatment technologies that are both cost-

effective and efficient (Bueno *et al.* 2017). Water scarcity is a global issue that underscores the urgent necessity for year-

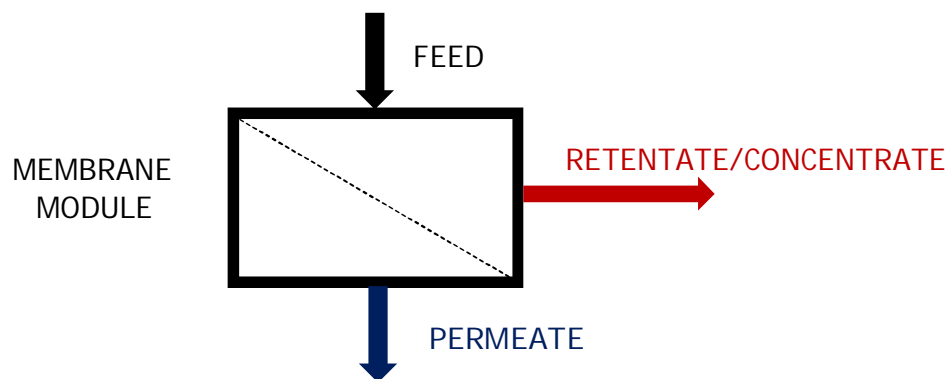
round food production to combat starvation, deprivation, and malnutrition. This necessitates the reuse of wastewater for irrigation purposes (Inyinbore *et al.* 2019). As individuals, communities, and industries seek to ensure that essential

resourcesareaccessibleandappropriate

for use, advanced wastewater treatment techniques have garnered global attention. This is essential as society addresses the consequences of urbanization, industrialization, population growth, and the depletion of potable water. Wastewater treatment is not always capable of effectively treating wastewater, which can result in a variety of issues, such as health problems and odours. New methods are employed to address these challenges in the treatment of wastewater. The quality of effluent can be enhanced beyond the constraints of conventional technologies through the implementation of these advanced treatment technologies, thereby achieving the objective of resource recovery or resource conservation. The available domestic water supply can be increased by recycling advanced wastewater treatment plant effluents, either directly or indirectly. The primary scope of this comprehensive review is to explore advanced techniques in wastewater treatment. Given the increasing water scarcity and pollution from various sources such as households, industries, and agriculture, there is a pressing need for effective wastewater management. The review addresses the limitations of conventional wastewater treatment methods, which are often insufficient in handling complex contaminants, and highlights innovative approaches that demonstrate superior capabilities. These approaches include membrane filtration processes, advanced oxidation processes, membrane bioreactors, aerobic granulation and electrochemical treatments.

## (I) MEMBRANE FILTRATION PROCESSES

A membrane is a selective barrier that restricts the passage of components through it, thereby separating two phases (Ravanchi *et al.* 2009). In the process of filtering impurities, salts, heavy metals, viruses, and other particles from water, scientific membranes function similarly to the cell walls in our bodies. The membranes are the selective barriers in wastewater treatment that permit the passage of water while preventing the passage of undesirable substances (Chadha *et al.* 2022). Membranes can be classified as either organic (polymeric) or inorganic (ceramic or metallic) based on their composition. The morphology of the membranes is determined by the characteristics of the material. Figure 1 illustrates a membrane separation system that divides an influent stream into two outgoing streams: the permeate and the retentate or concentrate. The permeate refers to the fraction of the fluid that has successfully traversed the membrane. The retentate, also known as the concentrate, comprises the components that have been excluded by the membrane (Chen *et al.* 2006).



**Figure 1. Diagram of a membrane separation system**

In recent decades, the utilization of membranes as a filtration technology has experienced advancements and has been adopted in several sectors, including large-scale enterprises, textiles, and domestic applications. A notable characteristic of membrane filtration is its compact spatial requirement. The chemicals employed in this procedure are very minimal, hence rendering it more desirable and feasible compared to traditional pre-treatment techniques.

### **Microfiltration (MF)**

Microfiltration (MF) is a method of filtering fluids using a membrane to eliminate particles that are in the micron size range. The MF membrane possesses hole diameters that span from 0.1 to 10.0  $\mu\text{m}$ , effectively preventing the passage of microbes. Microfilters are effective for sterilizing water solutions. For instance, the *Pseudomonas diminuta* bacteria, which has a diameter of 0.3  $\mu\text{m}$ , can be effectively disinfected using a microfiltration (MF) membrane that has hole diameters smaller than its size. However, both organic and inorganic molecules can permeate through MF membranes. The primary process for conventional depth filtration involves adsorption and trapping, whereas MF membranes utilize a sieving mechanism that relies on specific pore sizes to hold particles larger than the diameter of the pores. Therefore, this technique provides membranes that have an absolute rating, making them highly desirable for crucial tasks like filtering sterile parental fluids, filtering sterile air, and producing particulate-free, extremely pure water for the electronics sector. MF membranes are often composed of natural or synthetic polymers, including cellulose acetate (CA), polyvinylidene difluoride, polyamides, polysulfone, polycarbonate, polypropylene, and polytetrafluoroethylene (PTFE) (Mulder 1996). Several recently developed MF membranes include ceramic membranes made from alumina, membranes generated through the anodization of aluminum, and carbon membranes. Glass is employed as a membrane material. It is possible to apply zirconium oxide onto a carbon tube that has pores. Sintered metal membranes are produced using stainless steel, silver, gold, platinum, and nickel materials, in the form of disks and tubes. The characteristics of membrane materials are directly manifested in their final uses. The selection criteria include mechanical strength, temperature resistance, chemical compatibility, hydrophobicity, hydrophilicity, permeability, permselectivity, and the cost of the membrane material and production process. Microfiltration commonly employs two process modes: dead-end and cross-flow modes (UN.ECE 1990). In the dead-end mode, the entire solution is compelled to pass through the membrane. The compounds to be separated are accumulated on the membrane, resulting in an increase in the hydraulic resistance of the deposit. The membrane should be replaced promptly when the filtrate flux no longer meets the minimum values required at the maximum operating pressure. This mode is mostly utilized for solutions that have a minor level of contamination, such as in the creation of water that is extremely pure. In the cross-flow mode, the solution moves horizontally across the surface of the membrane at a velocity ranging from 0.5 to 5.0 m/s. This prevents the creation of a layer on the membrane surface. A circulation pump generates the cross-flow velocity or shear force required to regulate the thickness of the cover layer. The system is mostly utilized for periodic back flushing, a process in which a portion of the filtrate is forcefully directed in the opposite direction at specific intervals, thereby disrupting the cover layer. The standard operational pressure for this mode is 1–2 bars (Noyes 1994). A MF has a broad spectrum of uses in the treatment of water and wastewater. An extremely advantageous prospect for MF lies in the field of municipal water treatment, enabling the disinfection of water without the need for disinfectants such as ozone and chlorine. A recent study demonstrated that MF membranes have the capability to effectively eliminate viruses from surface water that is polluted. The reason for this discovery is that viruses are smaller than the pores in an MF membrane. It is believed that the viruses are being absorbed onto the clay particles, which are large enough to be trapped by the microfilter (Madaeni *et al.* 1995). MF has the potential to be

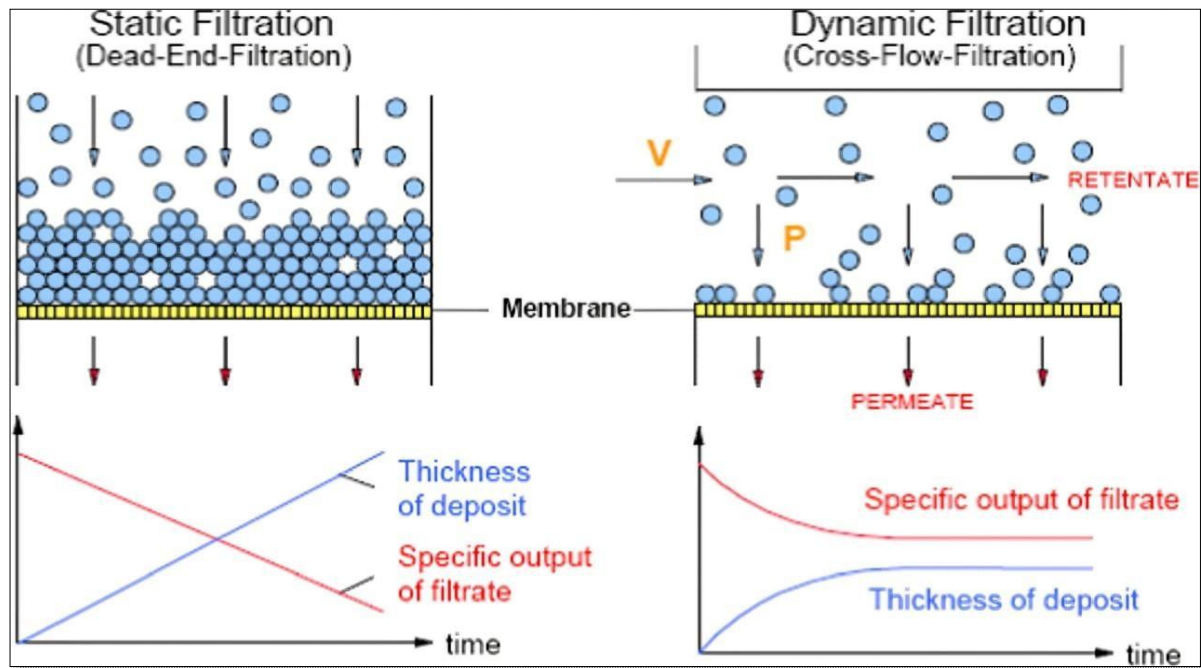
used in the treatment of municipal sewage. Engineers are investigating the implementation of distributed processing, which entails the utilization of multiple small sewage treatment plants. MF can effectively eliminate heavy metals from waste streams by employing pretreatment chemicals to induce the precipitation of the metals into particles that can be easily filtered. Although conventional wastewater treatment includes pretreatment, its use of gravity settling for solid/liquid separation is less efficient compared to membrane filtration. An effective technique for eliminating heavy metal ions entails the attachment of the metals to a specific agent, followed by the separation of the laden agents from the effluent. Blocher and co-workers (Blocher *et al.* 2003) have developed a unique hybrid process that combines flotation with MF. This process involves integrating specially built submerged microfiltration modules directly into a flotation reactor for these separation steps. This enabled the integration of the benefits of both flotation and membrane separation, while surpassing their constraints.

### **Nanofiltration (NF)**

In 1984, Dr. Peter Eriksson introduced a new type of membranes for commercial use, which he dubbed NF membranes. NF is characterized by its capacity to selectively isolate minute solutes from a solution through two distinct methods. The first mechanism, widely accepted in the scientific community, involves the separation of molecules depending on their charge in water, a process known as ionic separation of NF. The second mechanism involves the process of separating uncharged solutes based on their molecular weight by sieving. The NF membrane types are categorized based on the membrane structure and pore shape, including isotropic microporous, nonporous, dense, electrically charged, asymmetric, ceramic, and liquid membranes (Trivunac and Stevanovic 2006; Krantz 2008; Baker 2004). Nanofiltration (NF) is a filtration technique in which a portion of the feed solution is allowed to flow through a semi-permeable membrane (Figure 2).

### **Figure 2. Illustration of Nanofiltration process**

The incoming stream is separated into two parts: the permeate, which is the filtered fraction, and the retentate or concentrate, which is the non-filtered portion that is discarded. NF has demonstrated excellent elimination of organic matter. Chlorine disinfection is crucial for eliminating microbial growth that has been observed in NF distribution systems. In order to minimize the growth of microorganisms, the use of NF membranes that have a low capacity to retain inorganic elements and a high ability to remove organic materials can result in water of optimal quality. Membrane systems typically have two distinct flow configurations: Cross-flow with concentrate recycle (CFCR) and Flow system with a dead-end (Abdel-Fatah 2018) as depicted in Figure 3.



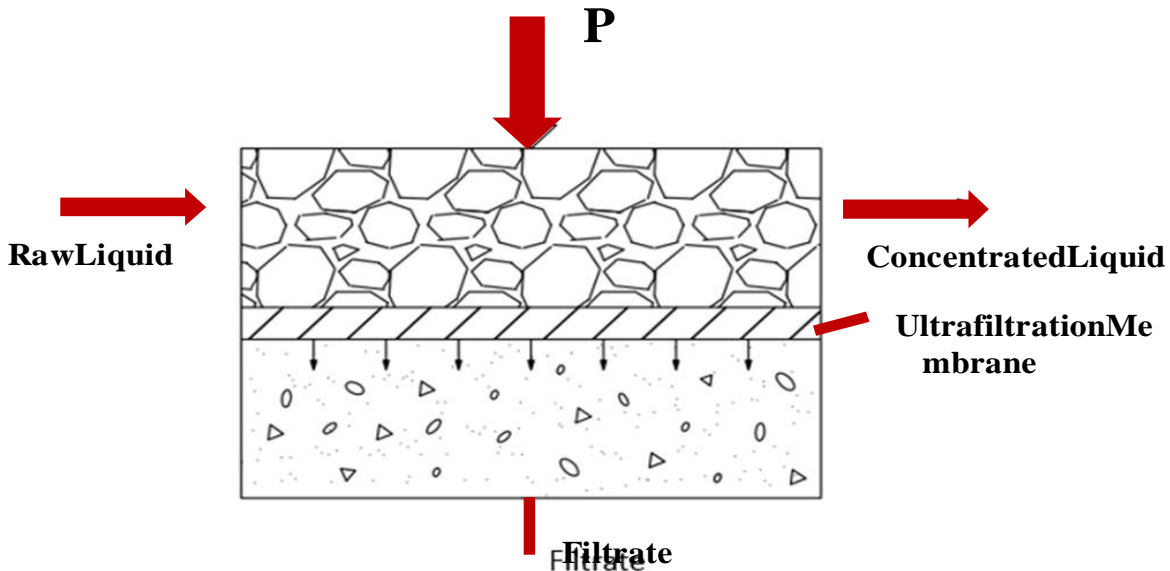
**Figure 3:** Membrane flow configurations

Cross-flow filtration, also known as tangential flow filtration, involves the use of a high-pressure flow of feed water over the membrane. The solution is separated into two components: the permeate, which passes through the membrane and is filtered, and the reject or concentrate, which flows along the membrane surface without undergoing separation or filtering. The concentrate consists of all discarded salts and is typically concentrated with all unwanted substances. The flow system that includes a terminal unit with no outlet is being run by accumulating refuse until the process of backwashing becomes necessary. The backwashing procedure eliminates and removes all the collected concentrate by utilizing a washing liquid volume that is 2-5% of the total inflow solution. The cross-flow mechanism maintains a consistent flow rate of permeate and extends the lifespan of the membrane by preventing irreversible fouling.

### **Ultrafiltration (UF)**

Ultrafiltration (UF) is a membrane-based separation technique that effectively separates, filters, and concentrates fluids with a size range between microfiltration and nanofiltration. The defined range of molecular weights for this domain is from 500 to 500,000 Daltons. The diameter of the corresponding aperture is approximately between 0.001 and 0.1 micrometers. The working pressure difference typically ranges from 0.1 to 0.8 megapascals, and the diameter of the separated component is roughly 0.005 to 10 micrometers. Figure 4 displays the schematic diagram of the ultrafiltration process. The technique can be conceptualized as utilizing the pressure difference between the two sides of the membrane as the impetus. Driven by static pressure, the ultrafiltration membrane acts as the filtering material to allow the solvent and small-molecular-weight solute, which have a smaller pore diameter, to pass through from the high pressure side to the low pressure side. Meanwhile, the large molecular weight solutes are retained on the high pressure side. When water passes through the membrane surface, only water, inorganic salts, and small molecules can go through the membrane. This prevents large molecules like suspended solids, colloids, proteins, and microorganisms from passing through. The objective is to purify, separate, and concentrate the solution.

(Taotao *et al.* 2008; Liu *et al.* 2016; Bray *et al.* 2021). Ultrafiltration membranes are mostly retained by physical screening. Nevertheless, the pore size of ultrafiltration membranes may occasionally exceed that of solvents and solute molecules. Despite its intended purpose of not trapping, it surprisingly exhibits a noticeable effect of separation. The chemical properties of the membrane surface, such as electrostatic effects, may be the cause. In conclusion, the retention of ultrafiltration membranes is facilitated by three primary mechanisms: adsorption on the membrane's surface and in the pores, retention in the pores, and the elimination of mechanical pores on the membrane's surface (Polyakov *et al.* 2013).



**Figure 4.** Illustration depicting the ultrafiltration process

### **Reverse Osmosis**

“Reverse osmosis (RO) is acquiring global acceptance in both water treatment and desalination applications. The process is pressure-driven, and a semi-permeable membrane is used to reject dissolved constituents that are present in the feed water. This rejection is the result of physical–chemical interactions between the solute, solvent, and membrane, as well as size exclusion and charge exclusion” (Radjenovic *et al.* 2008; Bellona and Drewes 2005). “A pressurized feed solution is passed over one surface of the membrane during the procedure. The water will migrate from the more concentrated solution to the more dilute solution through the membrane as long as the operation pressure, which varies from 10 to 70 bars depending on its application, is greater than the osmotic pressure of the feed solution. In a typical procedure, the semi-permeable membrane allows solvent (e.g., water) to flow from a dilute concentration to a more concentrated solution until equilibrium is achieved” (Noyes 1994). This process will be reversed by applying high pressure to the concentrated side. A higher concentration of solute is left behind as a result of the solvent flowing away from the concentrated solution. In application, the waste stream passes through the membrane; however, the solvent (e.g., water) is driven through the membrane, while the remaining solutes (e.g., organic or inorganic components) do not pass through and become progressively concentrated on the feed side of the membrane. The majority of RO membranes are composed of polymers, including cellulose acetate and matric polyamide varieties, and are

rated for NaCl rejection at 96–

99%. Two varieties of RO membranes are typically used: thin film composite membranes and asymmetric or skinned membranes. The thin film is composed of a variety of polyamines and polyureas, while the support material is typically polysulfones. The pore structure of RO membranes is the tightest, with a pore diameter that ranges from approximately 5 to 15 Å (0.5 to 1.5 nm). This semi-permeable membrane permits only the smallest organic molecules and unchanged solutes to pass through, with the water. This is due to the extremely tiny size of RO pores. The membrane will also reject a greater than 95–99% of inorganic compounds and charged organics as a result of the charge repulsion set up at the membrane surface. The primary benefit of RO for the treatment of process effluents is its capacity to concentrate diluted solutions for the recovery of salts and compounds with minimal power consumption. The primary energy requirement for separations is a high-pressure pump; no latent heat of vaporization or fusion is necessary. Additionally, it necessitates comparatively limited floor space for compact, high-capacity units and demonstrates favorable recovery and rejection rates for a variety of conventional process solutions.

### **Activated carbon filtration (ACF)**

Activated carbon, first used for water purification and medicinal purposes in Ancient Egypt, has been utilized in the industry for its decolorizing properties since the late 18th century (Bull 1980). Several plants have been developed to produce activated carbon for wastewater treatment, effectively removing contaminants like heavy metals and sediments without leaving any residual taste or odor (Junohet *et al.* 2016). ACFs are a hybrid technique of chemical treatment and membrane filtration) (Abdulrahman *et al.* 2012). Activated carbon is a substance that is produced by heating coal and other fossilized organic materials in the presence of specific compounds (Ismadji and Bhatia 2001). This process is initiated at temperatures exceeding 600°C; however, it can be induced at lower temperatures by employing specific catalysts and conditions. As long as particles are not entrapped, activated carbon generates pores on its surface, which facilitate the departure of gases (Spellman and Drinan 2012). The pores function as a filter to capture and eliminate contaminants from the water as it flows through by the process of adsorption. ACFs typically include many layers of activated carbon, designed to enhance the absorption of various types of contaminants: heavy metals such as lead, mercury, and cadmium; inorganic compounds such as proteins or hormones; and bacteria (Marshall and Rodríguez-Reinoso 2006). Also, salts, organic compounds, bacteria, and particulate matter like rust and iron oxide can be removed from water, as well as protozoan cysts. Activated Carbon, with a fine structure and large pore surface area, offers powerful adsorptive properties and is available in powder, granular, or pellet forms, and can be activated physically or chemically (Stevenson 1997; Janos *et al.* 2009). Zeolite, a common ACF, is a naturally occurring mineral with small pores that effectively remove bacteria, viruses, and pathogens from water, leaving only beneficial minerals behind. An other prevalent form of activated carbon filter is derived from polysaccharides, including sugar cane bagasse and coconut husks. The removal of suspended particles within the water column by polysaccharides has the potential to decrease turbidity levels, therefore enhancing the taste and purity of water (Nuithitikul *et al.* 2010). Studies show the use of agricultural wastes, tropical wood pulp, and non-agricultural sources like automobile tires to create ACFs (Heidarinejad *et al.* 2020). Rice husk, jujube seeds, sawdust, walnut shells, watermelon husks, tobacco stems, and bean hulls have been used, while other non-agricultural materials like automobile tires are being explored (Rahman *et al.* 2013; Ioannidou and Zabaniotou 2007; Kumar and Porkodi 2009). ACFs are simple to design, operate, and scale up, selective to certain substances, and capable of removing pollutants from even dilute solutions. They can reduce chemical odors and tastes, particularly hydrogen sulfide gas, which can cause rotten egg odor in water (Boopathy *et al.* 2013). According to Leimkuehler (2010), the ACF can be used in several types of applications, including industrial or commercial applications as well as in home or household-related situations.

## **(II) ADVANCED OXIDATION PROCESSES (AOPS)**

AOPs are a class of chemical treatment techniques that can be used to break down organic materials that are resistant to conventional methods. These techniques involve oxidation reactions with a strong, non-selective

hydroxyl radical (OH●), which can break down organic pollutants that are resistant to conventional methods and improve the biodegradability of wastewater (Rekhate and Srivastava 2020). AOPs have the potential to totally mineralize organic molecules into carbon dioxide and water (Eq.1).

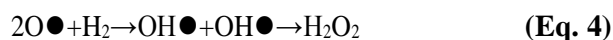
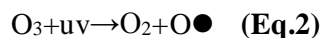


Hydroxyl Radical (●OH) is a very effective oxidizing agent that can be used to break down organic pollutants that are resistant to widely utilized oxidants like O<sub>3</sub>, O<sub>2</sub>, and Cl<sub>2</sub>. The hydroxyl radical plays a crucial role in the elimination of harmful compounds. The hydroxyl radical, formed through a chemical reaction, initiates a cascade of reactions that ultimately results in the full breakdown of organic contaminants (Munter 2001). "AOPs can lead to the complete mineralization of pollutants to CO<sub>2</sub>, water, and inorganic compounds, or at least their transformation into more benign products, through chemical wastewater treatment. In addition, the partial decomposition of non-biodegradable organic contaminants can result in biodegradable intermediates. Therefore, combined AOPs were implemented as pre-treatments, followed by biological processes are both cost-effective and highly economically viable" (Cañizares *et al.* 2009). "Despite the fact that AOPs employ a variety of reagents systems, such as photochemical degradation processes (UV/O<sub>3</sub>, UV/H<sub>2</sub>O<sub>2</sub>), photocatalysis (TiO<sub>2</sub>/UV, photo-Fenton reactives), and chemical oxidation processes (O<sub>3</sub>, O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub>, H<sub>2</sub>O<sub>2</sub>/Fe<sup>2+</sup>), they all generate OH radicals. These radicals are highly reactive, attack the majority of organic molecules, and are not highly selective" (Skouma *et al.* 2006; Rosenfeld *et al.* 2007).

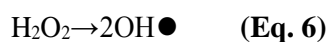
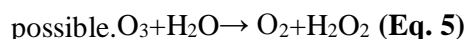
## OZONE BASED AOPs

### Ozonation and UV radiation (O<sub>3</sub>/UV)

The combination of ozonation and UV-radiation (O<sub>3</sub>/UV) is a highly effective catalytic system for breaking down persistent contaminants in wastewater. The process begins with the decomposition of ozone through photolysis, which is then followed by the generation of OH● radical through the reaction of O● with water (Emam, 2012). The combined impact of O<sub>3</sub> and UV light enhances the breakdown of ozone through direct mechanisms described in equations (2)-(4), as well as the indirect generation of hydroxyl radicals as described in equations (5) and (6). The hydroxyl radicals produced in a water-based solution react with the aromatic ring in the dye molecule, leading to the creation of smaller aliphatic molecules such as organic acids, aldehydes, and ketones (Khare *et al.* 2007). Ultraviolet (UV) light accelerates the breakdown of recalcitrant dyes by producing more free hydroxyl radicals (OH●), which in turn enhance the rate at which the dyes lose their color (Tichonova *et al.* 2017). The production of hydroxyl radicals can be illustrated using equations (2) to (6).



The indirect production of OH● by the following reaction is also

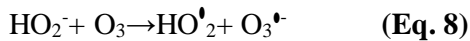


The combination of O<sub>3</sub> and UV increases the degradation of azodye at all pH levels (Wu 2008).

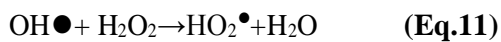
### O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub>

H<sub>2</sub>O<sub>2</sub> in conjunction with ozonation is a highly effective catalytic system for the degradation of refractory pollutants in wastewater. Peroxone AOP, which is also known as the O<sub>3</sub>/H<sub>2</sub>O<sub>2</sub> process, is characterized by a

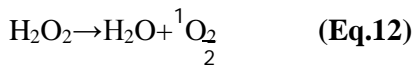
radical chain mechanism that is initiated by the ozone decomposition of the hydroperoxide anion HO<sub>2</sub><sup>-</sup>. The synthesis of OH● radicals is facilitated by the synergistic effect of O<sub>3</sub> and H<sub>2</sub>O<sub>2</sub>.



It is probable that O<sub>3</sub> reacts with the excess HO<sub>2</sub><sup>-</sup> that is produced from Eqs. (7)-(8), resulting in the production of OH● through Eqs. (9-11).



Nevertheless, the formation of the hydroperoxide ion (HO<sub>2</sub><sup>-</sup>) is a consequence of the scavenging of OH● by excess H<sub>2</sub>O<sub>2</sub>, as illustrated in Eq. (11). It is not advisable to have a hydrogen peroxide concentration that is too low, as H<sub>2</sub>O<sub>2</sub> effectively competes with hydroxyl radicals (Eq. (11)) and decomposes without oxidizing the pollutants, as demonstrated in Eq. (12) (Rodríguez *et al.* 2013).



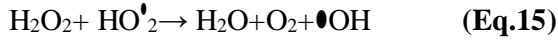
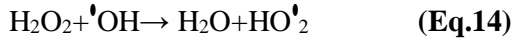
Below a certain level of ozone dosage, the addition of H<sub>2</sub>O<sub>2</sub> did not result in any significant increase in the rate of OH● formation (Barry *et al.* 2014). The initiators/promoters H<sub>2</sub>O<sub>2</sub> undergo a reaction with ozone until they cease to have an impact on ozone degradation. The researchers Barry *et al.* (2014) defined the ozone dose at which reactions with the initiators/promoters chemicals are completely depleted as the ozone dose threshold. Beyond this threshold, the addition of H<sub>2</sub>O<sub>2</sub> enhances the rate of OH● formation. The authors noted that the addition of H<sub>2</sub>O<sub>2</sub> does not significantly affect the exposure to OH● during ozonation, unless doses exceeding the threshold ozone doses are applied.

### UV/H<sub>2</sub>O<sub>2</sub> (Ultraviolet/Hydrogen Peroxide Processes)

In general, the combination of UV light radiation with hydrogen peroxide can effectively generate OH radicals. Additionally, UV light serves as a natural disinfectant for various organic contaminants and wastewater systems. The utilization of these systems has been documented in numerous sectors, ranging from the pharmaceutical business (Bobu *et al.* 2013; Jamil *et al.* 2017) to the textile industry, as well as in the removal of organic pollutants, and so on (Pandiset *et al.* 2022). Modeling the mechanisms and processes (Imoberdorf and Mohseni 2012) has allowed for an investigation into the chemistry of this technique. The results suggest that substituting expensive H<sub>2</sub>O<sub>2</sub> with chemicals like Cl<sub>2</sub> could be a beneficial alternative. This substitution is particularly effective at low pH levels and low UV doses (38). The primary chemical process taking place in these systems is outlined as follows (Zoschke *et al.* 2012):

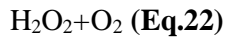
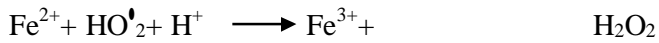
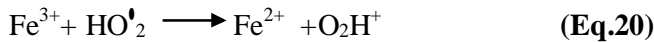
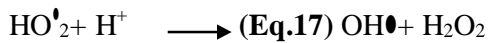
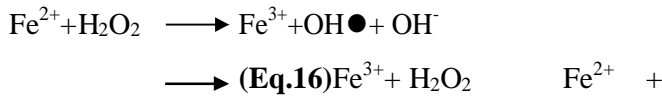


Under the influence of radiation, hydrogen peroxide molecules generate OH radicals. The decomposition is ascribed to a Haber-Weiss mechanism, which is triggered by the breaking of the O-O bond. The creation of additional OH molecules is initiated by the following chemical reactions (Oppenlaender 2007):



### FENTON-RELATED REACTIONS

Iron is the most commonly utilized metal among those capable of activating  $\text{H}_2\text{O}_2$  and generating hydroxyl radicals in water. The Fenton process involves the reaction of  $\text{H}_2\text{O}_2$  with  $\text{Fe}^{2+}$  to produce highly reactive species. The reactive species generated are commonly identified as hydroxyl radicals, however other compounds including ferryl ions are suggested. The Fenton-related chemistry for water and wastewater treatment has been extensively examined in previous literature (Pignatello *et al.* 2006). The Fenton radical processes predominantly encompass the subsequent reactions:



The generation of  $\text{OH}^\bullet$  is facilitated by electron transport, as described in Equation 16. Nevertheless, the  $\text{OH}^\bullet$  generated can be eliminated by either of the Fenton reagents, as seen in Equations 17 and 18. Hence, it is necessary to empirically establish the ideal molar ratio between iron ions and hydrogen peroxide in order to minimize the undesired scavenging. Despite the fact that Equation 17 suggests that the  $\text{Fe}^{3+}$  created from Equation 16 can be converted to  $\text{Fe}^{2+}$ , the iron cannot function as a catalyst in the Fenton system due to the significantly lower rate constant in Equation 17 compared to Equation 16. As a result,  $\text{Fe}^{3+}$  precipitates as iron sludge under normal water and wastewater treatment conditions. The sludge must be disposed of separately, which leads to increased complexity in treatment and higher operational expenses. It is important to mention that the production of hydroxyl radicals is most efficient during the Fenton reaction when the pH is acidic (Deng and Zhao 2015).

### (III) ADSORPTION USING CARBON NANOTUBES (CNTs)

Since its discovery in 1991, carbon nanotubes (CNTs) have been widely recognized as an exceptional material for various environmental applications. Carbon nanotubes (CNTs) possess a cylindrical hollow structure, a large specific surface area, a high pore volume, a high aspect ratio (i.e., a high length-to-width ratio), hydrophobic walls, good electrical conductivity, stable chemical properties, and are more mesoporous than activated carbon (AC). These characteristics make CNTs an exceptional adsorbent for the removal of organic compounds (Kane *et al.* 2016; Wang *et al.* 2015). Furthermore, carbon nanotubes (CNTs) have been

demonstrated to possess significant adsorption capabilities for heavy metals, phenols, natural organic matter, methyl orange, and red dye (Joseph *et al.* 2011). In addition, carbon nanotubes (CNTs) are utilized as an adsorbent in water and wastewater treatment procedures to eliminate pharmaceuticals, personal care products (PPCPs), and endocrine disrupting compounds (EDCs) (Jun *et al.* 2015). CNTs have demonstrated significant potential as adsorbents for various organic pollutants, including 1,2-dichlorobenzene, polycyclic aromatic hydrocarbons (PAHs), dyes such as methylene blue, methyl orange, and rhodamine B, phenols, and isonicotinic acid. This is due to their porous structure, large specific surface area, and strong hydrophobicity. Several studies have confirmed their effectiveness in adsorbing these pollutants, as reported by Bhatia *et al.* (2019), Li *et al.* (2020), Saxena *et al.* (2020) and Pete *et al.* (2021). The organic pollutants can be

captured within the pores or adhered to the surfaces of carbon nanotubes (CNTs) through various types of interactions, including hydrophobic interactions,  $\pi$ - $\pi$  interactions, van der Waals forces, electrostatic attraction, and hydrogen bonding.

Typically, these interactions occur simultaneously (Pyrzynska 2008). CNTs can be classified into three basic types: single-walled CNTs (SWCNTs), multi-walled CNTs (MWCNTs), and functionalized SWCNTs. A single-

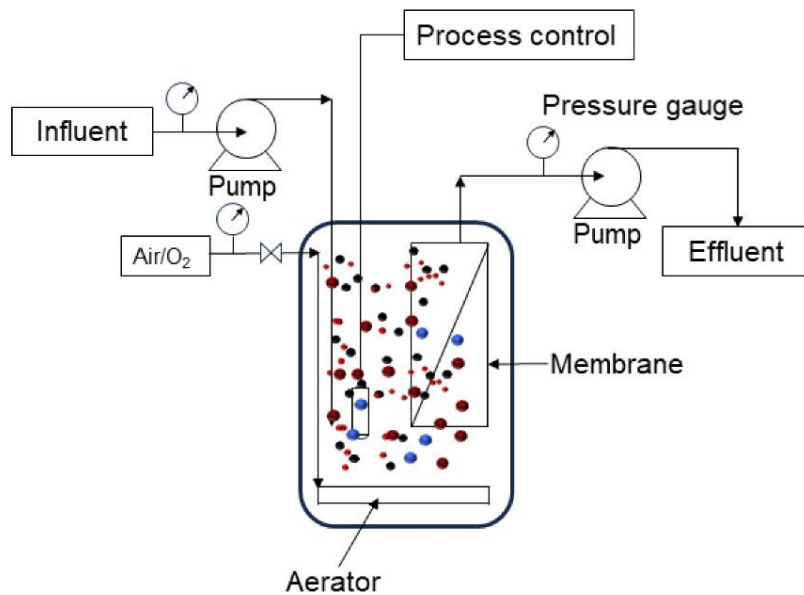
walled carbon nanotube (SWCNT) is composed of a single layer of rolled graphite sheet, while a multi-walled carbon nanotube (MWCNT) is made up of many SWCNTs with varying diameters arranged concentrically (Pan and Xing 2008). Functionalized carbon nanotubes (CNTs) possess oxygen-containing functional groups, including hydroxyl groups ( $-\text{OH}$ ), carbonyl groups ( $-\text{C}=\text{O}$ ), or carboxylic groups ( $-\text{COOH}$ ) (Jung Son *et al.* 2015). Acids, such as sulfuric acid ( $\text{H}_2\text{SO}_4$ ) and nitric acid ( $\text{HNO}_3$ ), can be utilized to oxidize CNTs, leading to the incorporation of functional groups (Celik *et al.* 2011). Heat treatment is frequently employed to reverse the process and eliminate the functional groups (Takagi *et al.* 2007). CNTs possess exceptional adsorption capacity and can be regenerated rapidly without any loss in their adsorption capability, making them a highly adaptable adsorbent.

“Undisturbed CNTs have a tendency to clump together because of their bundled structure, which is characterized by strong van der Waals forces. Aggregation decreases the accessibility of the external surface of the as-produced CNTs for the adsorption of contaminants and hinders the ability of the CNTs to be wetted. In order to address this difficulty, the technique of ultra-sonication is utilized to incorporate CNTs into water-based solutions” (Zhan *et al.* 2012). The modification of CNTs through oxidation procedures not only reduces their aggregation but also improves their dispersibility in water and other solvents by modifying the surface chemistry of the CNTs. Several techniques for oxidizing CNTs have been documented, such as wet chemical procedures (Andrade *et al.* 2013), photo-induced oxidation (Savage *et al.*, 2003), and plasma treatment (Ren *et al.* 2011). The predominant method used for oxidation of CNTs is wet chemical treatment, involving the use of acids or oxidizing agents such as nitric acid, sulfuric acid, and potassium permanganate, among others. Oxidation is used to eliminate metal impurities that remain on the surfaces of CNTs after their manufacture. The surface properties of CNTs have been altered through methods such as impregnation with metal/metal oxide (Mallakpour and Khadem 2016), introduction of heteroatoms (Yi *et al.* 2020), or attachment of functional molecules (Guo *et al.* 2019). “These modifications serve to selectively and synergistically capture specific pollutants. Magnetic material can be attached to CNTs to facilitate the separation of adsorption materials from water-based solutions by utilizing an external magnet” (Bhatia *et al.* 2019).

#### **(IV) MEMBRANE BIOREACTORS (MBRs)**

“The activated sludge process (ASP), which has been the conventional municipal wastewater technology for the past century, has been replaced by membrane bioreactor (MBR) technology as the preferred wastewater treatment technology. MBR is, in fact, one of the most significant innovations in wastewater treatment” (Meng

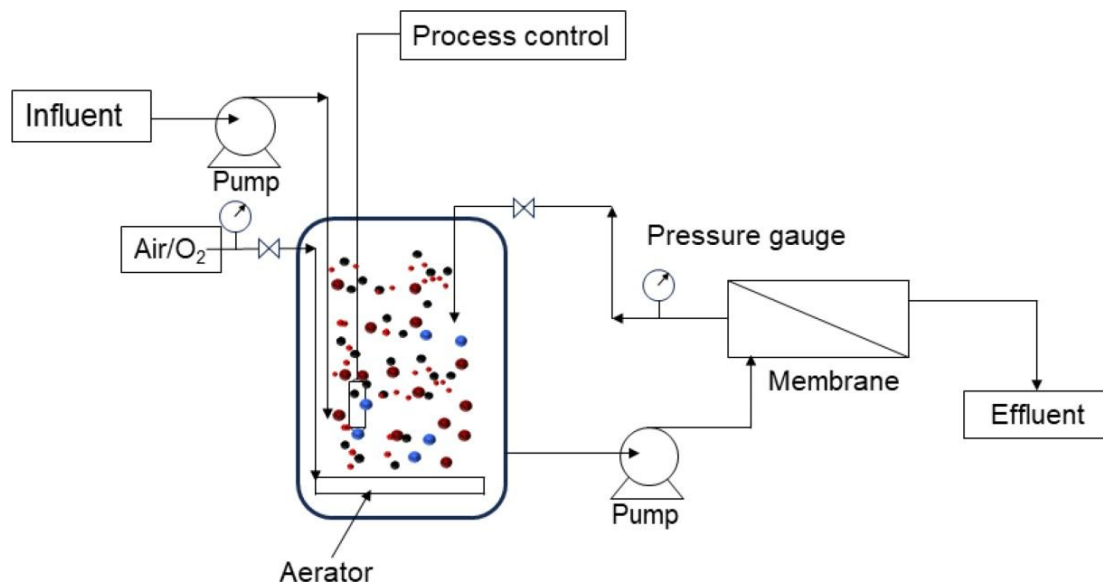
*et al.* 2009; Drews, 2010; Lin *et al.* 2012), as it address the shortcomings of the traditional ASP, such as the need for a significant amount of space for secondary clarifiers, the production of excess sludge, and the challenges associated with the removal of recalcitrants (Mutamimet *al.* 2013). MBRs have been employed for the treatment and reclamation of effluent in both municipal and industrial settings (Friha *et al.* 2014; Chuet *al.* 2006). MBR is a wastewater treatment process that integrates membrane technology with biological treatment (anaerobic, aerobic) (Eddy *et al.* 2014). In contrast to conventional biological procedures, which employ clarifiers for gravity settling, this process employs microfiltration or ultrafiltration to separate sludge generated by biological processes. MBR provides numerous advantages over the conventional activated sludge (CAS) procedure. An MBR typically consists of two primary elements: (1) the biological unit, responsible for the biodegradation of wastewater; and (2) the membrane module, which physically separates treated water from the mixed wastewater (Van Houghton *et al.* 2022; Chang *et al.* 2022). MBRs can be classified into two groups based on their configuration: integrated MBR systems and recirculated MBR systems. The first group of bioreactors, generally referred to as integrated MBR systems, includes those that are equipped with internal membranes (Figure 5). “The driving force across the membrane is generated by either generating negative pressure on the permeate side or pressurizing the bioreactor. The membrane is cleaned by regular back-pulsing and occasional chemical backwashing. A diffuser is placed right below the membrane module to aid in the cleaning of the filter surface. Simultaneously, the diffusers serve the dual role of mixing and aerating. Additional anaerobic or anoxic compartments can be incorporated to facilitate the concurrent biological degradation of substrates” (Li *et al.* 2018; Zhao *et al.* 2022).



**Figure 5.** An integrated (internal) MBR system (Song *et al.* 2018).

The second form is referred to as a recirculated (external) MBR system, where the membrane module is assembled externally to the bioreactor (Figure 6). This application can make use of membranes for both the inner and outer layers of the skin. A rapid cross-flow velocity of the feed across the membrane surface creates a pressure environment, which serves as a driving factor for the separation process. Currently, the utilization of MBRs for commercial purposes has been on the rise. This can be attributed to the advancements in polymeric membranes, such as polyvinylidene fluoride (PVDF), polyethersulfone (PES), polyethylene (PE), and polysulfone (PSF), which are now more affordable and durable. These membranes offer lower pressure

requirements and higher permeate fluxes (Erkan *et al.* 2018). A Membrane Bioreactor (MBR) system has several advantages compared to conventional activated sludge (CAS) and other wastewater treatment technologies. The bioreactor's capacity to effectively retain both suspended matter and a majority of soluble elements leads to a remarkable effluent quality that meets stringent discharge criteria and enables direct water reuse.



**Figure 6.** A recirculated (external) MBR system (Song *et al.* 2018).

## (V) AEROBIC GRANULATION

The selection of microorganisms with the appropriate metabolic capabilities and their efficient separation from the treated effluent are necessary for successful wastewater treatment. A substantial amount of research has been conducted to reduce the settling time of activated sludge. This is accomplished through the use of biofilm reactors or the formation of dense flocs. Biogranules, a condensed form of biofilm that is produced through self-immobilization, are a significant advancement in this field.

These granules are compact conglomerates of a variety of bacterial species, with each gram of biomass containing millions of organisms. (Lee *et al.* 2010). Aerobic granules are compact clusters of microbial cells that occur spontaneously in aerobic wastewater treatment systems. These objects are distinguished by their round shape, robust structural strength, and capacity to quickly sink. The formation of these granules occurs by a self-immobilization process, in which many microbial species come together to break down both organic and inorganic substances present in wastewater (Zeng *et al.* 2024). The mechanism behind microbial aerobic granulation is still a topic of considerable controversy due to the complex nature of aerobic granulation. Based on the concept outlined by Zeng *et al.* 2024, aerobic granulation initiates with the clustering of microbial cells. Fungi utilize glucose as their carbon source and release  $H^+$  ion to decrease the pH, so producing a favorable environment for their growth while inhibiting the growth of competing bacteria (Tay *et al.* 2002). Filamentous fungi undergo growth from spores to mycelia in response to shear stresses, functioning as a focal point for the attraction of other microorganisms and as a supporting framework. Certain bacteria adhere to inorganic precipitates located inside the granule's core, where these precipitates serve as a central point

for the bacterium's development and reproduction. Some bacteria utilize cations such as  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  to facilitate aggregation by decreasing electrostatic repulsion and increasing van der Waals forces. The application of shear pressures during the granulation process induces the release of extracellular polymeric substances (EPS), which then adhere to organisms and bind them together within the granule. The elevated cell surface hydrophobicity and intense hydraulic stress, along with the constrained settling time, promote the attachment of microorganisms to aggregates, resulting in the formation of aerobic granules. Granules are initially formed from small microbial clusters that expand through additional aggregation. These dense granules settle rapidly as a result of the selection pressure in the reactor, which favors biomass that settles quickly and eliminates biomass that settles slowly. Diverse microbial communities are able to contribute

to the structure and function of granules by establishing distinct aerobic and anaerobic zones within the granules due to the oxygen and nutrient gradients. Microbial proliferation, EPS production, and shear forces that could potentially cause disintegration are all balanced by the maturation and growth of granules. The reactor's operation, which encompasses the feed composition, aeration, and cycle management, is essential for the maintenance of granulation.

Aerobic granulation technique is a very adaptable and effective method for treating wastewater. It has advantages such as a high level of treatment efficiency, space optimization, energy conservation, and environmental sustainability. The application of this technology is used in municipal and industrial sectors to satisfy both typical and difficult wastewater treatment requirements (Layer *et al.* 2019; Chen *et al.* 2015). Moy *et al.* (2002) proved the effectiveness of applying aerobic granulation technology for the treatment of high-strength organic wastewater. These researchers discovered that aerobic granules demonstrated a remarkable ability to endure a maximum organic loading rate of  $15.0 \text{ kg COD m}^{-3} \text{ d}^{-1}$  when glucose was used as a substrate. Furthermore, they achieved a COD removal rate of over 92%. The granules' great effectiveness can be due to their compact form, which also improves their capacity to breakdown hazardous chemicals.

## (VI) ELECTROCHEMICAL TREATMENT

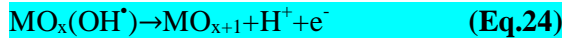
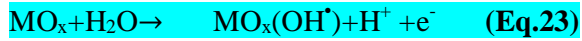
In an electrochemical system, the anode (positive side) undergoes oxidation, during which electrons are transferred to the cathode (negative side), where the reduction process takes place. Redox (reduction-oxidation) is the term used to describe these two chemical reactions, which result in the purification of water by removing metals. The type of electrochemical method and the removal efficacy towards specific metal ions are primarily determined by the selection of the anode and cathode.

### **Electrochemical Oxidation (EO)**

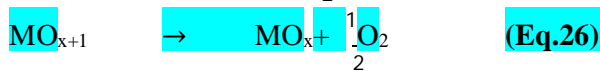
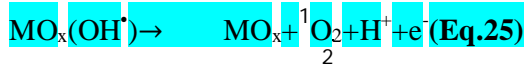
The electrooxidation process is an adsorption process that results in the oxidation of contaminants either directly on the electrode surface or indirectly through the production of oxidizing agents in the solution (Ozyurt and Camcioglu, 2018). In addition, direct electrooxidation is achieved through the production of physically adsorbed oxygen species (hydroxyl radicals,  $\bullet\text{OH}$ ) or chemisorbed oxygen species ( $\text{MO}_{x+1}$ ) (Comninellis 1994). Additionally, the selection of an anodic electrode is the primary factor determining the efficacy of the anodic oxidation process. Furthermore, an indirect electrooxidation occurs through the production of chloride or hypochlorite during anodic oxidation. This method is effective in the removal

of organic and inorganic contaminants from a high chloride concentration, ideally above  $3 \text{ g/L}$  (Szyrkowicz *et al.* 1994). Comninellis established a suitable mechanism for the breakdown of organic compounds on a metal

oxide anode in 1994. This process occurs in two sequential stages. During the initial phase, H<sub>2</sub>O is released from the anode surface, generating adsorbed Hydroxyl radicals (•OH), which are then absorbed by a metaloxide layer, as shown in Equations (23) and (24). Inhibition of the formation of the passivation layer is achieved by the oxide layer on the electrode (Gattrell and Kirk 1993).



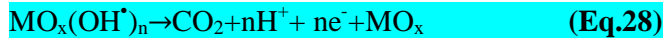
Oxygen is generated in the absence of any oxidizable organic compounds, as shown in Equations (25) and (26):



Combine reactions (23), (24), (25), and (26) to get the overall Equation



In the presence of the oxidizable organic compound R, the reaction will proceed as follows: R +

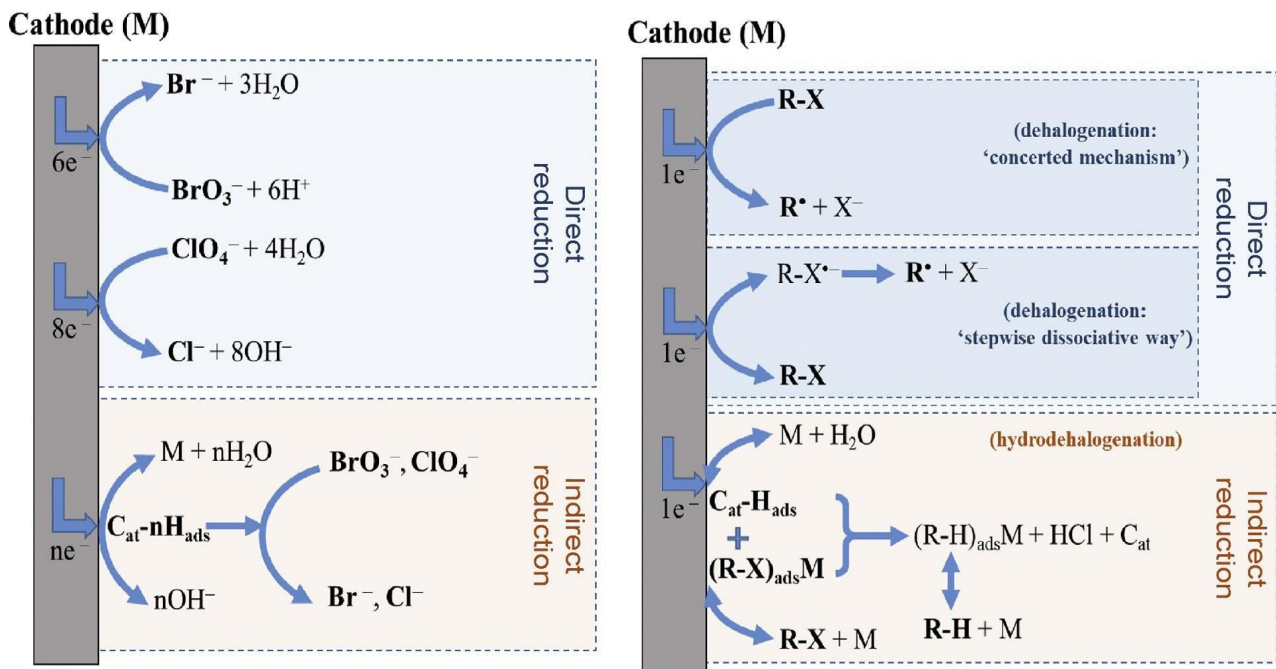


**Direct Anodic Oxidation:** This method of treating and destroying pollutants using electrons involves adsorbing pollutants on the anode's surface without incorporating other elements. This process requires more negative potential than water spitting and oxygen evolution, leading to catalytic poisoning of the electrode (Rodrigo *et al.* 2001; Chatzisymeon *et al.* 2009). This is particularly evident when using a platinum electrode for treating phenol, as phenol adsorbed onto the platinum electrode's surface in voltammetry and chronoamperometry, arresting catalytic activity due to irreversible adsorption. (Feng *et al.* 2016).

**Indirect Anodic Oxidation:** This method uses oxygen evolution as an intermediate, eliminating the need for an oxidizing agent and avoiding by-products. Both physically adsorbed (adsorbed hydroxyl radicals •OH) and chemisorbed active oxygen (oxygen in the lattice of a metaloxide anode) play crucial roles in electrochemically destructing species at the anode, either partially or completely. The hydroxyl radical OH, which is comparable to fluorine in terms of its oxidative capacity, exhibits an exceptionally high potential of E<sub>0</sub> = 2.80 V. Therefore, the generation of specific oxidation products is a consequence of the chemisorbed oxygen, also known as "active oxygen," when the complete destruction of organic compounds occurs (Johnson *et al.* 1999; Chang and Johnson 1990). Active anode materials like RuO<sub>2</sub>, IrO<sub>2</sub>, and Pt enable selective and partial oxidation with low oxygen evolution over potential, while non-active materials like SnO<sub>2</sub>, PbO<sub>2</sub>, and boron-doped diamond (BDD) enable complete combustion with high oxygen evolution over potential (Feng and Li 2003). The EO method has a significant drawback in treating water and wastewater with high suspended solid concentrations, necessitating the use of other techniques to remove the wastewater containing suspended solids (Chakchouk *et al.* 2017).

## Electrochemical Reduction

Electrochemical reduction, which is the counterpart of electrochemical oxidation, is a chemical reaction in which an atom or molecule at the cathode acquires one or more electrons when an electric current flows through the solution (Sillanpaa and Shestakova 2017). Analogous to electrochemical oxidation, electrochemical reduction can take place either directly on the cathode surface or indirectly in the bulk by the action of a reducing agent produced at one of the electrodes (Mousset and Doudrick 2020). This process is commonly employed to treat water contaminated with heavy metals, inorganic anions, or halogenated organic compounds by converting these species into more benign products (Yang et al. 2016; Garcia-Segura et al. 2018). The process of electrochemical reduction, shown in Figure 7, is a well-established technique employed for the treatment of oxidized pollutants, including both inorganic and organic halides (R-X). High-energy electrons or reactive species are generated through the method, which interact with contaminant either directly at the cathode surface (direct reduction) or indirectly in the bulk (indirect reduction). The abbreviation for the cathode material, which is the catalyst ( $C_{at}$ ).  $C_{at}-H_{ads}$ ,  $(R-X)_{ads}M$ , and  $(R-H)_{ads}M$  represent the hydrogen atom, organic halide, and dehalogenated organic molecule (R-H), respectively, adsorbed on the cathode (Alkhadra et al. 2022).



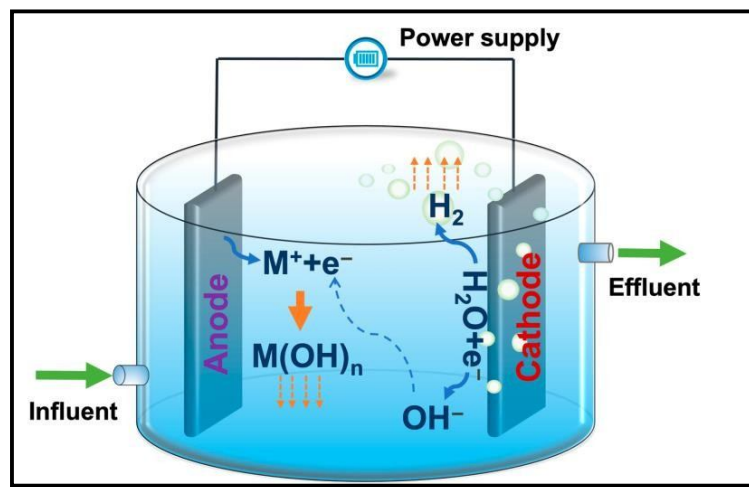
**Figure 7.** Schematic illustration of electro-reduction mechanisms (Alkhadra et al. 2022)

Catalyst loading, cathode potential, and water quality are factors that affect the efficacy of electrochemical reduction. Elevated catalyst loading often amplifies reduction activity, although, activity may decline as electron transfer distance progressively increases (Sun et al. 2014). Electrochemical reduction performance is influenced by feed quality and characteristics, with improved performance at lower pH, higher ionic strength, and the absence of certain species like organic matter, electrocatalyst poisons, and competing ions (Gennero et al. 1998; Yao et al. 2020). Electrochemical reduction is a very efficient technique used to

remediate contaminants such as volatile organic halides and chlorofluorocarbons, converting them into products with increased inherent value (Comninellis and Chen 2015). It involves the selective elimination of halogens and the carboxylation or carbonylation of organic molecules. The integration of electrochemical reduction and electrosynthesis can effectively treat wastewater to facilitate the synthesis of value-added organic products (Gutzet *et al.* 2015; Mohle *et al.* 2018).

### Electrocoagulation (EC)

Electrocoagulation is a process that utilizes electricity to eliminate contaminants from wastewater, neutralizing negative particles by forming hydroxide complexes in the water. It helps bridge, bind, and strengthen floc for sedimentation due to gravity force (Fagnekar Nilesh A 2015). This process agglomerates suspended solids in water without chemical coagulants and occurs when direct current is applied to the aqueous solution. Coagulants are generated in situ by electrical dissolution from respective metal electrodes (Al, Fe, Cu, or Stainless steel), with dissolved metal ions and hydrogen gas generated at the anode and cathode, respectively (Linares-Hernández *et al.* 2010). Various factors, such as electrode type, surface area, number of electrodes, electrode size, current density, charge loading, sample pH, operational duration, and electrolyte addition, influence the electrocoagulation process (Can *et al.* 2006). Iron, aluminum, stainless steel, and copper are among the most frequently used electrodes. The high coagulation efficiency of aluminum plates makes them the preferred choice for effluent treatment (Shen *et al.* 2003). The EC method integrates the advantages of coagulation, flotation, and electrochemistry into a single system (Ingelsson *et al.* 2020; Almukdad *et al.* 2021). Electrocoagulation is a water treatment process that involves an electrolytic cell with two electrodes (an anode and a cathode) submerged in a conducting solution and connected to an external power source (Figure 8).



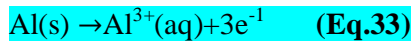
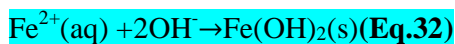
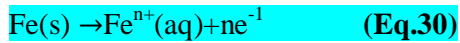
**Figure 8.** Schematic illustration of the electrocoagulation procedure (Mao *et al.* 2023).

The EC procedure consists of multiple steps, which are as follows:

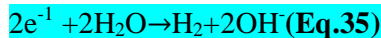
- 1) Electric current from an external power source causes the active coagulant cations (often aluminum or iron) to be released into the solution through electrolytic oxidation of a sacrificial anode. Equations (30) and (33).
- 2) Simultaneously, cathode hydrolysis generates hydroxyl ions. Equation (35).

- 3) Metallic cations undergo reactions with hydroxyls to produce both monomeric and polymeric species, as illustrated in Equations (31), (32), and (34).
- 4) The neutralization of the surface charge of contaminants, suspended particulate matter, and emulsions is accomplished through its reaction with metal hydroxyls.
- 5) In the aqueous phase, neutralized particles aggregate and their coagulation results in flocs.
- 6) Heavy flocs are precipitated by sedimentation by sweep coagulation.
- 7) Electrolysis of water at the cathode generates hydrogen bubbles, which cause flocs to float on the solution's surface through sweep coagulation Equation (35).

**Anode reactions:**



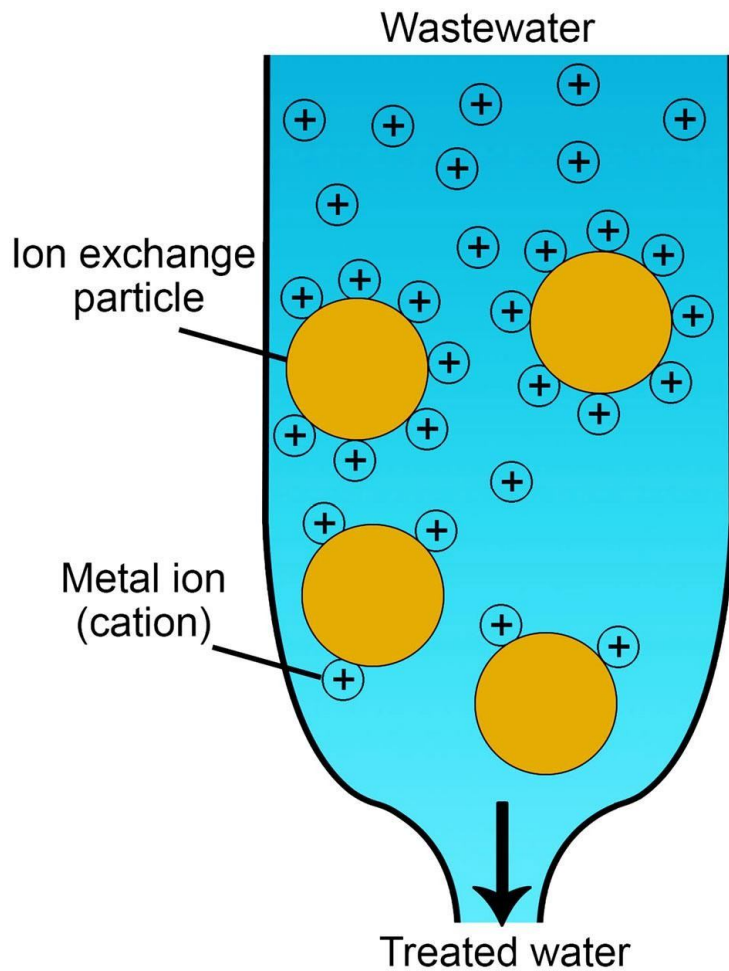
**Cathode reactions:**



The electrocoagulation method is a widely used and environmentally friendly wastewater treatment method due to its simplicity, ease of operation, short retention time, minimal chemical additions, and reduced sludge formation (Azarian *et al.* 2018).

**Ion exchange treatment**

Ion exchange is a chemical process characterised by the substitution of unwanted metal ions with harmless and eco-friendly ones (Dąbrowski *et al.* 2004). This process entails the attachment of a heavy metal ion to an immobile solid particle, therefore substituting it with a solid particle cation, as depicted in Figure 9.



**Figure 9.** Schematic illustration of the Ion Exchange Process (Qasem *et al.* 2021).

Solid ion-exchange particles, made from natural (inorganic zeolites) or synthetic materials (organic resins), can remove heavy metal ions like  $Pb^{2+}$ ,  $Hg^{2+}$ ,  $Cd^{2+}$ ,  $Ni^{2+}$ ,  $V^{4+}$ ,  $V^{5+}$ ,  $Cr^{3+}$ ,  $Cr^{4+}$ ,  $Cu^{2+}$ , and  $Zn^{2+}$  from wastewater. The ion exchange mechanism involves the particle having anion exchanger of  $M^{-}EC^{+}$ , which exchanges its cation ( $EC^{+}$ ) with the wastewater cation ( $WC^{+}$ ). In  $M^{-}EC^{+}$ ,  $M^{-}$  is the fixed anion and  $EC^{+}$  is the exchange cation.



Several varieties, including Amberlite (Kang *et al.* 2004) and Diaion CR11 (Cavaco *et al.* 2007), were examined for their ability to remove cations. Zeolite exhibits a high ion exchange capacity due to its negative charge provided by  $Si^{4+}$  ions, which are located in the centre of the tetrahedron and undergo isomorphous substitution with  $Al^{3+}$  cations.

## **(VII) COMPUTATIONAL METHODOLOGY IN WASTEWATER TREATMENT**

### **Bioinformatics and Genome Sequencing**

In wastewater treatment, computational methods are being employed more frequently, utilizing tools such as sequencing platforms, metagenome sequencing strategies, bioinformatics tools, and genome analysis of complex microbial communities (Schloss and Handelsman 2005; Foerstner *et al.* 2006; Raes *et al.* 2007; Marsh 2007). These instruments offer comprehensive information and assistance for future application in wastewater treatment-related research and development (Siezen and Galardini 2008). Studies have shown the capacity for micro-pollutant biodegradation using whole metagenome sequencing (WMS), and bioremediation of highly polluted wastewater from textile dyes by two novel strains identified as *Lysinibacillus sphaericus* and *Aeromonas hydrophila* through 16S rDNA analysis (Balcom *et al.* 2016; Kumar *et al.* 2016). Additionally, researchers are conducting research to enhance the safety and practicality of potable water reuse through the use of metagenomics for water quality analysis (Leddy *et al.* 2018).

### **Computational Fluid Dynamics (CFD)**

The field of biological wastewater treatment has seen the widespread implementation of CFD, a widely used methodology, in recent years. The internal flow structure that represents the hydraulic condition of a biological reactor has been revealed (Peng *et al.* 2014). CFD is the application of powerful predictive modeling and simulation tools. It is possible to calculate the numerous interactions between all of the water quality criteria and the process design criteria. CFD modeling technologies, which are extensively utilized in many sectors, have lately become prominently applied in the water industry for the purpose of water and wastewater treatment. They function mechanically by utilizing the hydrodynamic and mass transfer capabilities of reactors operating in single or two-phase flow (Do-Quan *et al.* 1998). The capability of CFD differs among process units, although it is widely utilized in some areas such as final sedimentation, activated sludge basin modeling, disinfection, primary sedimentation, and anaerobic digestion. These areas demonstrate a higher demand for CFD (Samstag *et al.* 2016). Now, scientists are augmenting the CFD modeling by using a newly created three-dimensional (3D) model of the anoxic zone in order to assess the hydrodynamic performance in greater detail (Elshaw *et al.* 2016).

### **Computational Artificial Intelligence Approach**

A computer-based artificial approach has been devised by researchers to automate the monitoring of water quality tests, encompassing BOD and COD. In their study, Nourani *et al.* (2018) investigated the application of feedforward neural network (FFNN), adaptive neuro-fuzzy inference system (ANFIS), and support vector machine (SVM) in wastewater treatment plants. Their measurements of effluent levels for BOD, COD, and total nitrogen in the Nicosia wastewater treatment plant demonstrated the exceptional performance of artificial intelligence.

### **Remote Sensing and Geographical Information System**

The identification and localization of water contaminated sites have been revolutionized by satellite technology using remote sensing and GIS applications (Kesari *et al.* 2021). Geographic Information System (GIS) analysis provides a rapid and cost-effective approach for atmospheric correction techniques. Furthermore, it offers a user-friendly interface for intricate spatial operations, facilitating the acquisition of high-quality data on water quality indicators via remote sensing (Ramadas and Samantaray 2018).

## CONCLUSION

In conclusion, the comprehensive review of advanced techniques in wastewater treatment highlights significant progress and innovative methods developed to address the limitations of conventional wastewater treatment technologies. Traditional methods, while effective to an extent, face challenges such as high operational costs, extensive energy requirements, and the inability to remove certain persistent pollutants. Advanced treatment technologies such as membrane filtration, advanced oxidation processes, carbon nanotubes, and membrane bioreactors offer promising solutions. Membrane filtration processes effectively separate contaminants with high efficiency, while AOPs utilize strong oxidizing agents to break down complex organic pollutants into less harmful substances. Carbon nanotubes demonstrate exceptional adsorption capacities for various organic and inorganic pollutants, enhancing the overall treatment process. MBRs combine biological treatment with membrane filtration, addressing the shortcomings of traditional activated sludge processes by offering higher effluent quality and better handling of sludge. The review underscores the importance of integrating these advanced techniques to achieve efficient, cost-effective, and environmentally sustainable wastewater treatment solutions. As water scarcity becomes an increasingly critical global issue, the implementation of these advanced methods is vital for enhancing water reuse and conservation efforts, thereby ensuring the availability of clean water for future generations. Overall, the continuous development and optimization of these advanced wastewater treatment technologies are essential to meet the growing demand for high-quality water and to protect public health and the environment. Implementing these technologies on a larger scale requires overcoming cost, operational complexity, and environmental impact, necessitating continued research for sustainable wastewater management.

## DATA AVAILABILITY STATEMENT

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

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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