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PROOF
REVIEW

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Advanced Techniques for Aquatic Ecosystem Treatment and Their Application in the Egyptian Lakes

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Abstract

This study aims to evaluate the effectiveness of advanced wastewater treatment strategies used to address pollution challenges in Egyptian lakes, focusing on how these methods improve water quality under pressures from industrialization, population growth, and agricultural expansion. The scope covers key technologies currently applied in wastewater treatment, including membrane filtration, activated sludge processes, chemical precipitation, advanced oxidation processes (AOPs), and bioremediation. These techniques have shown strong performance in removing contaminants such as heavy metals, organic pollutants, and excess nutrients that threaten both environmental and human health. The study also examines integrated treatment approaches, highlighting that combining biological and chemical methods:such as coupling bioremediation with AOPs can enhance removal efficiency and support more sustainable, resilient treatment outcomes. The main conclusions underscore that while advanced technologies significantly improve lake water quality, their long-term effectiveness depends on continuous monitoring, regular maintenance, and systematic evaluation to avoid secondary environmental impacts and maintain consistent performance. Overall, the findings indicate that well-designed, integrated advanced treatment systems offer a promising pathway for safeguarding the ecological integrity of Egypt's lakes.

Introduction

The rapid pace of global population growth and industrial development has undeniably improved living standards, yet it has also introduced profound ecological challenges. The intensification of industrial activities, in particular, has been accompanied by increased emissions of hazardous substances, leading to heightened levels of environmental contamination (Raghunandan et al., 2018). As noted by Ahuti (2015), industrialization exerts wide-ranging negative impacts, not only on public health, causing severe illnesses linked to chemical exposure, but also on ecosystems, through the depletion of natural resources, rising greenhouse gas emissions, and the accumulation of pollutants (Gouthaman et al., 2019).

Egypt faces an especially critical situation due to acute water scarcity, a challenge that necessitates the adoption of nontraditional water resources to meet the demands of its growing population. The reuse of treated wastewater (TWW) has emerged as a practical and cost-effective solution for addressing this gap. Beyond conserving limited freshwater reserves, TWW has been shown to improve the physicochemical characteristics of light-textured soils, thereby enhancing agricultural productivity and supporting food security.

Nevertheless, the application of TWW is not without risks. The reuse of inadequately treated wastewater can result in the transmission of pathogens and the accumulation of toxic substances in soils and crops. To mitigate these hazards, international and national guidelines recommend restricting the use of

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TWW primarily to non-edible crops, alongside the adoption of strict management practices that align with established water quality standards. Continuous monitoring of irrigation practices and treated effluent quality remains essential to safeguard public health and minimize ecological risks.

By 2015, Egypt's total available water supply was estimated at 76.4 × 10^9 m³, of which 8.9 × 10^9 m³ was allocated for domestic and health-related uses. This consumption generated nearly 5 × 10^9 m³ of wastewater annually. After undergoing primary, secondary, and tertiary treatments, approximately 3.7 × 10^9 m³ of TWW was recovered, accounting for 16.8%, 81.4%, and 1.8% of the treated wastewater volumes, respectively. These figures highlight the growing role of wastewater treatment and reuse as an essential component of Egypt's national water management strategy.

Wastewater management and reuse in Egypt are overseen by multiple organizations and governed by a framework of national laws, regulations, and environmental protection measures. The Egyptian Code for wastewater reuse further categorizes TWW into four grades (A, B, C, and D), based on the degree of treatment achieved. Despite these regulations, four main challenges hinder the broader application of TWW: social acceptance, management issues related to crop selection and irrigation practices, human health risks, and potential environmental impacts. Nevertheless, significant opportunities remain to optimize the benefits of TWW in Egypt, particularly given that less than 75% of collected wastewater currently undergoes treatment. Expanding the safe reuse of TWW in agriculture offers a highly viable strategy to alleviate water scarcity and contribute to the long-term sustainability of Egypt's water resources.

Water Pollution

Various organic and inorganic compounds find their way onto the Earth through manufacturing processes or accidental spills, posing a serious global threat, with water pollution being a significant concern. This pollution arises from multiple factors, such as the rapid global population increase, the expansion of industries, and urbanization. Water contamination occurs due to the presence of pollutants like poisonous heavy metals, and inorganic and organic substances, all of which pose significant threats to surrounding ecosystems (Nguyen-Sy et al., 2025). There are different of the water source pollution are listed in (Table1)

Across the globe, numerous metropolitan areas are grappling with, or are expected to encounter, critical shortages of potable water. This mounting challenge arises from a convergence of pressures, including rapid population growth, escalating pollution levels, climate variability, and deficiencies in water management systems.

Egyptian Lakes

Lakes in Egypt constitute indispensable water resources, underpinning agricultural irrigation, domestic consumption, and local economies. Beyond their utilitarian value, these aquatic systems play a fundamental ecological role, providing habitats for a wide array of species, from aquatic organisms to migratory birds, thereby contributing to the preservation of biodiversity (Abd Ellah, 2020). Many of these lakes also carry profound historical and cultural importance, with their presence interwoven into the fabric of ancient Egyptian civilization, where they served religious, economic, and social functions, including navigation, trade, and ritual practices (Al-Gorair et al., 2019).

In recent decades, however, the sustainable management and conservation of Egyptian lakes have emerged as urgent national priorities. Addressing the mounting pressures of pollution, overexploitation, and ecological degradation requires integrated strategies that combine advanced technological solutions, ecological restoration efforts, and active community participation (Ahmed, 2000). These aquatic systems,

Table 1. Sources of pollution and associated possible contaminants (Wong et al., 2019)

	Pollution sources	Potential pollutans
Domestic activites	Leakage from sewage system septic tanks, sewage water drains	Bacteria, Ammonium, phosphate and nitrate, Heavy metals and microorganisms
Agricultural activities	Excessive use of fertilizers Excessive use of pesticides Waste water irrigation	Nitrate, pesticides, Phosphate, Bacteria
Industrial activity	Food production Textile industry Wood, paper and graphica industry Chemical industry Oil and soap industry Metal and machine industry Energy production industry Construction industry Small scale services (like petrol station and garages)	Hydrocarbons as proteins Ammonia oil products heavy metals (Cd, Zn, Cu, etc.), Aromatic hydrocarbons, Mineral oil heavy metals (Cd, Zn, Cu, etc.), Phenols, Aromatic hydrocarbons, Chlorinated hydrocarbons (chloroform), Cyanide

ranging from natural to man-made, embody a delicate balance between natural dynamics and human intervention. Distributed across diverse regions of the country, each lake presents unique hydrological features and management challenges (Effendi et al., 2017). Their significance extends far beyond their aesthetic value; they represent essential nodes in Egypt's environmental, cultural, and socioeconomic landscape (Donia, 2016).

However, these lakes are not without their challenges. Issues such as water quality degradation, pollution, habitat loss, and invasive species threaten their ecological balance and long-term sustainability. Climate change poses additional uncertainties, affecting water availability and lake ecosystems. The choice of appropriate wastewater treatment techniques depends on various factors, including operating conditions, effluent types, and environmental conditions (Ahmed and El-Leithy, 2008)

The northern coast of Egypt, encompassing its lakes, holds significant socioeconomic and environmental importance. Along the Mediterranean shore, this area is made up of five major lakes: Burullus, Mariout, Manzala, Edku, and Lake Bardawil. Figure 1 shows that the deltaic lakes are brackish and shallow, with Mariout Lake being artificially enclosed. These lakes are connected by inlets that are essential for a variety of fish species and commercial fishing, and they are protected from the Mediterranean by coastal sandy barriers. (Donia and Ahmed, 2006)

In the south, one of the biggest artificial lakes in the world, Nasser Lake was created by the Aswan Dam on the Nile. Qarun Lake, an ancient lake in the Fayoum Oasis is believed to have been used for irrigation since ancient times. Timsah Lake, a small lake situated along the Suez Canal. Lake Wadi El Rayan, a freshwater lake in the Wadi El Rayan Protected Area was created by the Fayoum Oasis water system. Like many other countries, Egypt is continually exploring new water treatment techniques in its lakes to address water quality challenges.

Rehabilitation of Egyptian Lakes

Efforts to rehabilitate Egypt's lakes Centre on restoring their ecological integrity, improving water quality, and ensuring their long-term sustainability as vital natural resources. These projects are designed not only to preserve biodiversity but also to provide social and economic benefits, including opportunities for recreation, fisheries development, and enhanced community livelihoods. By integrating sustainable management practices with active community participation, the rehabilitation initiatives aim to safeguard the ecological and cultural value of these water bodies for future generations.

One of the most notable initiatives is the Burullus Lake Rehabilitation Project, which seeks to restore the ecological balance of the lake through a combination of protective and engineering measures. Key activities include shoreline protection to mitigate erosion, the removal of invasive aquatic vegetation, and dredging operations that deepen inlets and channels to improve water circulation and flushing capacity. These

Figure 1. Egyptian northern coastal lake.

interventions are expected to enhance both the hydrological performance and ecological resilience of the lake.

Similarly, the Manzala Lake Rehabilitation Project focuses on improving environmental quality while boosting fishery productivity, which is crucial for the surrounding communities. Government-led programs have incorporated the construction of wastewater treatment facilities to reduce pollutant loads entering the lake (Abd Ellah., 2021). In addition, advanced monitoring and modeling systems have been introduced, supported by satellite imagery, to provide critical data for effective management. These remote-sensing tools are particularly valuable for mapping islets and shorelines, creating sea-water channels, and estimating key hydrological processes such as water balance, sedimentation, and erosion. Collectively, these measures are directed toward ensuring the sustainable development and ecological health of the lake (Redwan & Elhaddad 2022).

Materials and Methods

This review employed a structured literature survey to ensure transparency and reproducibility. Peer-reviewed studies were identified through searches of major databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, using relevant keywords related to wastewater treatment technologies and Egyptian aquatic systems. The review primarily considered publications from the last 15 years, with key earlier studies included where necessary. Selected articles were evaluated based on their relevance to treatment efficiency, cost, scalability, environmental sustainability, and applicability to lake and surface water systems under arid and semi-arid conditions. Data on treatment methods, target pollutants, removal efficiencies, operational costs, energy requirements, and environmental impacts were extracted and comparatively analyzed to identify performance trends, limitations, and research gaps, ensuring a systematic and replicable review process.

Result and Discussion

Techniques of Wastewater Treatment

Wastewater treatment relies on a variety of approaches, each with its own advantages and limitations. Some techniques, while effective, are often constrained by high capital and operational costs, lengthy treatment times, limited throughput, or the generation of hazardous byproducts that pose secondary environmental risks (Yahya et al., 2018). These limitations highlight the importance of exploring alternative treatment strategies capable of achieving complete degradation or removal of contaminants in a safe and efficient manner (Wong et al., 2019).

Conventional treatment methods can be broadly categorized into physical, chemical, and biological processes, each playing a role in mitigating the harmful effects of pollutants.

Physical Methods

Physical treatment strategies are primarily based on mass transfer mechanisms (Samsami et al., 2020). These methods are widely favored due to their operational simplicity, adaptability, high efficiency, and the added advantage of pollutant recovery and reuse (Wong et al., 2019). A further benefit is the reduced reliance on chemical additives, making them comparatively safer and more environmentally friendly. Unlike biological treatments, physical approaches are not influenced by environmental fluctuations or the metabolic activity of microorganisms, which makes them highly reliable.

Examples of physical techniques include precipitation, coagulation, ion exchange, and membrane filtration. In precipitation, suitable anions are introduced to form insoluble metal salts, which can then be removed from the water. Among these methods, adsorption has gained significant attention in recent years due to its exceptional efficiency, cost-effectiveness, and ability to remove a wide spectrum of contaminants (Foroutan et al., 2019).

Adsorption

Adsorption is a well-known technology for eliminating pollutants from wastewater that is simple and less expensive than competing techniques. This method, where insoluble particles in wastewater, known as adsorbate, are separated by binding them to the surface of an adsorbent material. This adsorbent is typically a solid with an exceptionally great surface area (Abdelwahab et al., 2023). Clay colloids, activated carbon, resins, and activated alumina are a few examples of adsorbents. Before usage, the adsorbent must be activated to improve its adsorption capacity. Detergents and other hazardous organic substances can be effectively removed via adsorption (Samer, 2015)

Adsorption typically involves three consecutive steps: (1) the migration of the adsorbate toward the outer surface of the adsorbent, (2) the diffusion of the adsorbate into the material's pores, and (3) the adsorption and subsequent desorption of the solute (Pamukoglu & Kargi 200). The advancement of these stages is contingent upon the properties of the adsorbate, adsorbent, and substrate (Siswoyo et al., 2023). Adsorption isotherms are used by scientists to determine a material's maximal adsorption capacity. Adsorption isotherms plot the number of molecules adsorbed per unit area of an interface vs either gas pressure or the equilibrium amount in the aqueous solution. The Langmuir and the Freundlich isotherms are popular models for assessing the adsorption of contaminants (Wong et al., 2020).

An effective adsorbent must possess a high density of active binding sites that can efficiently capture and retain contaminants from aqueous systems (Prajapati and Mondal, 2019; Wadhawan et al., 2020). Among the wide range of materials explored, activated carbon (AC) has been extensively recognized for its superior adsorption performance in wastewater treatment (Azam et al., 2020; Liu et al., 2020). Its exceptional efficiency is attributed to its highly porous architecture and expansive surface area, which provide abundant sites for pollutant interaction. Moreover, AC is valued for being non-toxic, relatively inexpensive, and capable of delivering high adsorption capacities (Kamaraj et al., 2020; Prajapati et al., 2020).

When compared with other wastewater management strategies, adsorption emerges as one of the most practical and reliable techniques. It combines technological simplicity with cost-effectiveness, operational efficiency, and the added advantage of being a non-destructive process. This method has demonstrated remarkable effectiveness in eliminating a broad spectrum of contaminants, including heavy metal ions, inorganic minerals, and various organic pollutants from both water and wastewater (Crini et al., 2019) (Figure 2).

Nonetheless, adsorption also presents certain limitations. In some cases, the process can inadvertently lead to an increase in total organic carbon (TOC), biological oxygen demand (BOD), and chemical oxygen demand (COD) within treated wastewater, which may pose secondary challenges (Chatterjee et al., 2020). Table 2 summarizes the adsorption capacities of different nano-adsorbents investigated for wastewater purification, highlighting the diversity of materials and their effectiveness in addressing specific contaminants (Aboukila et al.,2022).

Membrane Filtration

Membrane filtration is widely recognized as one of the most cost-effective and efficient techniques for separating and removing pollutants in wastewater treatment across industrial applications. Despite its advantages, designing membranes that simultaneously offer high efficiency and strong thermal stability remains a significant challenge. As highlighted by Yang et al. (2020), properties such as surface hydrophilicity and charge distribution play crucial roles in determining a membrane's permeability and its resistance to fouling. The general mechanism of the membrane filtration process is illustrated in Figure 3

(a) Nanofiltration

Nanofiltration (NF) has emerged as a promising approach for water purification and selective separation. However, its performance is often hindered by fouling and concentration polarization. Fouling occurs when organic compounds accumulate on the membrane surface, forming a barrier that blocks pores and reduces permeability. Additionally, high salinity exacerbates performance decline by increasing osmotic pressure, thereby lowering membrane flux due to salt rejection. To counter these issues, NF membranes with hydrophilic surface properties are particularly advantageous, as they allow higher throughput and improved resistance to fouling in water treatment processes (Zhu et al., 2020).

In industrial practice, commercially available NF membranes often exhibit tightly packed surface morphologies, enabling high rejection rates for salts and organic pollutants, such as dyes. Nevertheless, this high selectivity is frequently accompanied by reduced infiltration flow, which limits their overall efficiency (Ye et al., 2020).

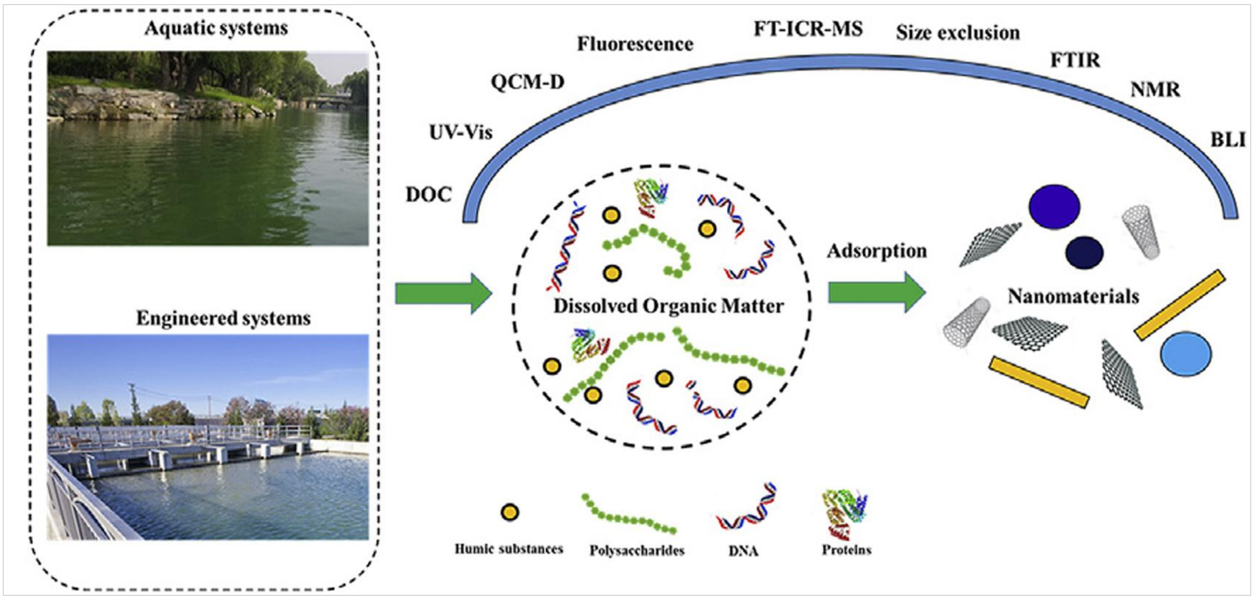

Figure 2. Nanomaterial adsorption in aquatic environments (Quang et al, 2021).

(b) Ultrafiltration

Ultrafiltration (UF) technology is increasingly applied in salt fractionation and wastewater treatment due to its ability to achieve high permeation flux while allowing greater salt passage compared to NF. Unlike NF, UF membranes operate under lower osmotic pressure, which contributes to their enhanced separation efficiency, high throughput, and stable performance. Comparative studies confirm that UF membranes are highly effective in processes requiring large volumes and moderate selectivity (Yang et al., 2020).

A variety of polymeric materials have been explored for the fabrication of UF membranes, including polysulfone (PSf), polyacrylonitrile (PAN), cellulose acetate (CA), poly(vinylidene fluoride) (PVDF), and polyethersulfone (PES). These polymers are favored due to their tunable chemical properties, structural stability, and adaptability for large-scale applications.

Coagulation/Flocculation

Coagulation represents one of the most established and widely applied techniques for wastewater treatment, primarily aimed at reducing the solubility and bioavailability of heavy metals and other contaminants in aqueous systems. This method relies on the addition of chemical agents referred to as coagulants or flocculants that aggregate suspended particles, making them easier to separate. Coagulants can generally be classified into three main categories based on their chemical composition and origin: inorganic coagulants, organic coagulants, and natural polymers (Al-Wasify et al., 2023). Each group exhibits distinct characteristics and application advantages. Figure 4 provides an overview of the commonly used coagulants in water treatment.

Coagulation-flocculation methods are effective for purifying wastewater containing dispersed contaminants, but their purifying efficiency is limited when it comes to reactive wastewater. These

Table 2. Adsorption capability of various nano-adsorbents for treatment of wastewater

No	Adsorbents	Pollutants	Adsorption capability (mg/g)	Maximum elimination efficacy	References
1	Activated carbon	Crystal violet dye	86.41	84–91%	Sarabadan et al., 2019
2	Natural zeolite	Phosphate	187.85	59%	Pan et al., 2020
3	Fe_3O_4 nanoparticles	PdCd	369.0–523.6	98%	Xin et al., 2012
4	SiO_2	Cu Cu	 6.35	–	Manyangadze et al., 2020
5	Anionic surfactant	Pb Cationic dyes	6.70 19	–	Pham et al., 2020
6	DS-Zn/Al LDHs	Organic pollutant	87–149.3	–	Grover et al., 2019
7	Fe_3O_4-silica	Pb Hg	–	97.34% 90%	Xu et al., 2012
8	Montmorillonite-supported MNPs	Cr	15.3	–	Xu et al., 2012
9	MWCNTs	Reactive dyes	95–352.1	–	Machado et al., 2011
10	Graphene	Cd Co	106.3 68.2	–	Zhao et al., 2011
11	TiO_2 nanotubes/CNT	Cu Pb	83–124 192–588	–	Sadegh et al., 2017

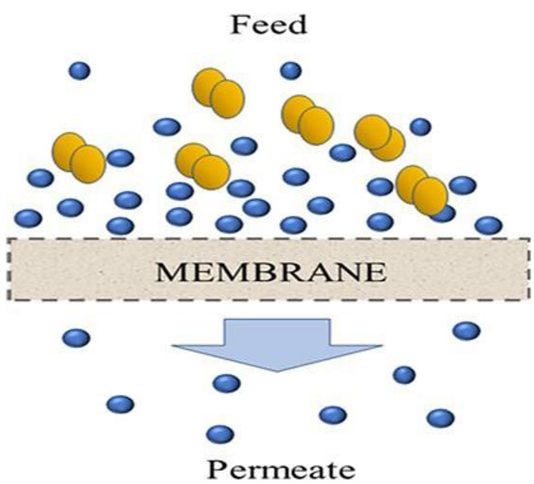

Figure 3. Mechanism of membrane filtration to eliminate contaminates (Ye et al., 2020.).

techniques are often restricted in their application owing to their subpar performance and the noteworthy production of sludge as a byproduct. Coagulation involves destabilizing pollutant solution systems to create flocs and agglomerates, while flocculation destabilizes suspended particles and combines aggregated flocs into larger agglomerates that settle under the influence of gravity, as illustrated in Figure 5 (Lee et al., 2011).

The coagulation-flocculation process works by neutralizing charges through the bridging or trapping of suspended particles, leading to the formation of gelatinous agglomerates large enough to be filtered or settled out. Due to its practicality from an economic standpoint, speed of detection, and ease of use, it is frequently used for wastewater treatment. With the use of coagulants like lime ($Ca(OH)_2$), ferric chloride ($FeCl_3.7H_2O$), ferric sulphate ($Fe_2(SO_4)_3.7H_2O$), and aluminium sulphate ($Al_2(SO_4)_3.18H_2O$), contaminants are removed by sorption and electrostatic forces. Sorption and bridging facilitate the coagulation-flocculation of pollutants in wastewater, due to the protonated amine groups and high-molecular-weight polymers, respectively. Overall, wastewater effluent is reduced by coagulation and flocculation of dissolved substances, colloidal particles, suspended matter and non-settable particles (Yogalakshmi et al., 2020).

Inorganic coagulants, when compared to organic coagulants, are cost-effective and highly efficient, particularly in treating low-turbidity aqueous solutions where organic coagulants may be less effective. Each

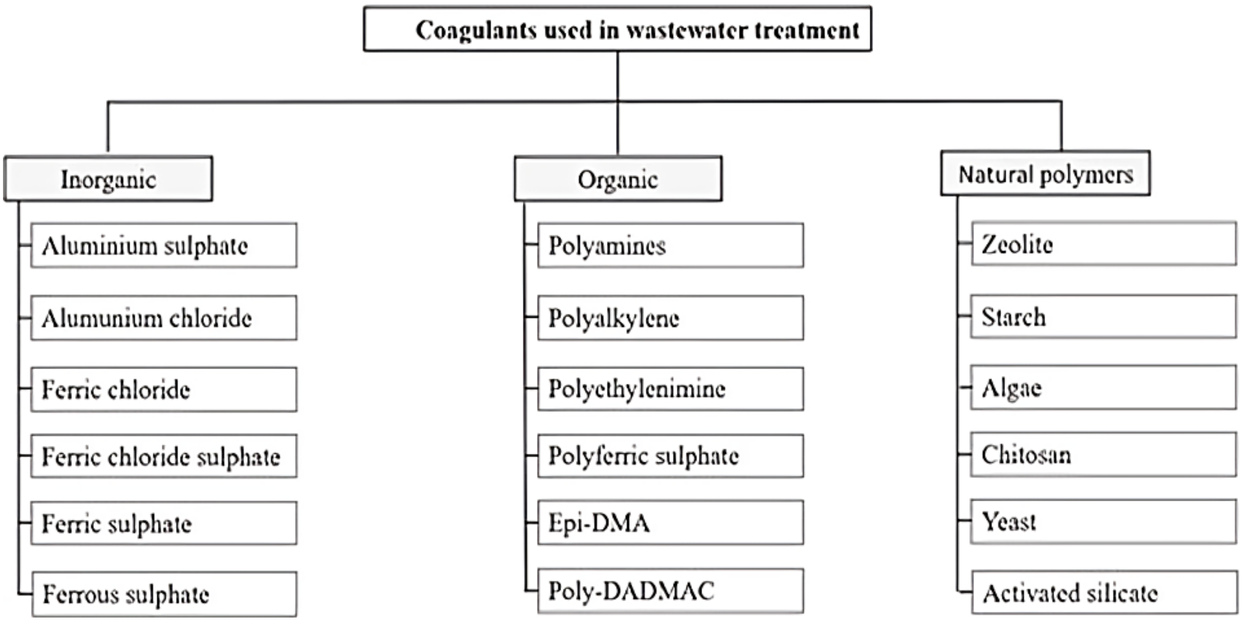

Figure 4. Coagulation agent classification for wastewater treatment (Lee et al., 2011.).

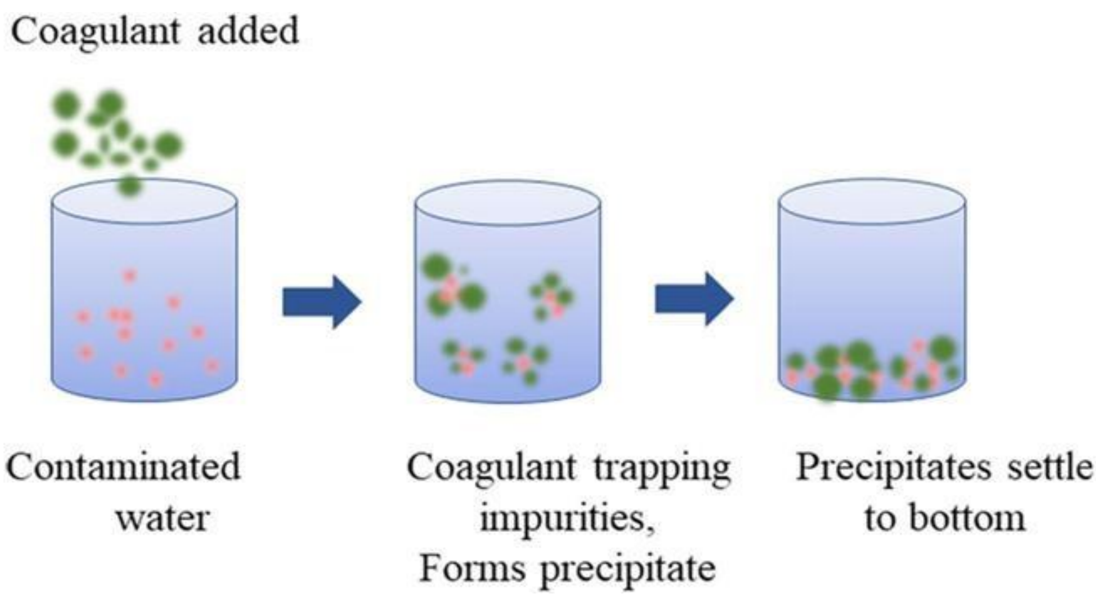

Figure 5. Mechanism of coagulation to eliminate pollutants (Yogalakshmi et al. 2020).

coagulant type has its unique advantages and disadvantages in practical applications (Table 3).

Coagulation and flocculation represent a physicochemical process but pose challenges in handling sludge volume generation, especially with the formation of large-sized flocs, which can increase the overall cost. However, it is a slow procedure, exhibits little biodegradability, and relies on maintaining optimal environmental conditions and proper microorganism maintenance (Kannaujiya et al., 2019).

Chemical Methods

Chemical Precipitation

Chemical precipitation is one of the most widely applied methods for eliminating dissolved toxic metals from wastewater. In this process, a suitable precipitating reagent is introduced into the aqueous solution, initiating a chemical reaction that converts dissolved metal ions into insoluble solid compounds. These solid particles can subsequently be separated from the liquid phase, often through filtration or sedimentation. The success of this technique largely depends on the type and concentration of metals present in the effluent, as well as the choice and dosage of the precipitating agent. Among the commonly used reagents, sodium hydroxide and calcium hydroxide are particularly effective, as they react with dissolved metal ions to form insoluble metal hydroxides, which can be readily removed (Wang et al., 2005).

Ion Exchange

Ion exchange is another well-established treatment method, frequently employed to reduce water hardness, which is primarily caused by calcium and magnesium ions. Excessive hardness can result in undesirable scaling, residues, or discoloration of surfaces. The mechanism is conceptually similar to reverse osmosis, though it relies on ionic substitution rather than membrane separation. In ion exchange, a resin saturated with sodium ions interacts with hard water, releasing sodium ions into the water while simultaneously capturing calcium and magnesium ions. This exchange process softens the water, replacing hardness-causing ions with sodium, and thereby improving its quality for domestic and industrial use (Clifford, 1991; Samer, 2015).

Advanced Oxidation Processes (AOPs)

Advanced oxidation processes (AOPs) represent a class of highly effective chemical oxidation methods designed for the degradation of a wide range of persistent pollutants in wastewater. These processes are distinguished by their ability to generate highly reactive oxidizing species, particularly hydroxyl radicals (•OH), which possess exceptionally strong and non-selective oxidative potential. Hydroxyl radicals can rapidly attack and decompose complex organic molecules, leading to their mineralization into less harmful byproducts such as carbon dioxide and water (Pamukoglu et al. 2024). AOPs encompass a variety of techniques, including photocatalysis, ozonation, Fenton and photo-Fenton reactions, and catalytic oxidation, all of which are gaining increasing recognition as key strategies in modern wastewater treatment (Shafiq et al., 2020, 2021; Sicardi, 2020).

Advanced Oxidation Processes (AOPs) primarily aim to generate highly reactive species in the treatment of challenging organic compounds, contaminants, aquatic pathogens, pesticides, toxicants and disinfection by-products (Figure 6). A significant advantage of employing AOPs lies in their ability to avoid the production of sludge and toxic end products, eliminating the need for additional handling or secondary treatment. AOPs offer several benefits over alternative techniques, including cost-effectiveness, complete contaminant degradation, minimal or no waste disposal concerns, and reduced reliance on specific temperature and pressure conditions (Elhaddad et al., 2023, Lim et al. 2018).

AOPs operate through a free radical originated by the interaction of photons with chemical species or catalysts in the solution. Key factors influencing AOPs include the initial pollutant concentration, the amounts of catalysts and oxidizing agents, light intensity, time of irradiation, and solution characteristics like pH, solids presence, and other ions (Seow et al., 2016). The most used AOP technologies can be divided into the following groups (Poyatos et al. 2010) as irradiation based and non-irradiation based as shown in Figure 7.

These techniques can also be categorized into two main groups, as outlined by Poyatos et al. (2010):

Table 3. Compensations and drawbacks of normally used inorganic coagulants (Zhou et al., 2019)

Coagulant/Flocculant	Advantages	Disadvantages
Aluminum sulfate (alum)	Easily available Most commonly used Low sludge volume index Effective within pH 5.5–7.5	Add dissolved salt water Effective in limited pH range
Ferric sulfate	Effective within pH 4–6 and 8.8–9.2	Add dissolved salt to water
Sodium aluminate	Effective in hard water Low dosage of coagulant	Ineffective in soft water High cost
Lime	Commonly used Do not add dissolved salt	pH sensitive More sludge generation

a) Homogeneous AOP: UV radiation is frequently used in these processes, which use energy in the form of light. For photodegradation processes, substances that absorb UV at certain wavelengths are useful.

b) Heterogeneous AOP: In heterogeneous processes, catalysts are employed to enhance contaminant degradation. These processes involve two phases, with the catalyst typically in the solid phase and pollutants in the aqueous phase. Semiconductor catalysts like TiO_2, ZnO, ZnS, CdS, and etc., are used in conjunction with a light source (e.g., UV/solar radiation). This setup accelerates chemical reactions by generating electron-hole pairs. The resulting electrons and holes facilitate redox reactions for contaminant degradation (Kim and Ihm, 2011).

Classification of various advanced oxidation processes can be summarized as follow (Figure 8).

Photocatalysis

Distinct as the acceleration of a photoreaction through catalysis plays a crucial role in maintaining ecological balance (Fujishima et al., 2007). It is a rather simple process: a photon of light produces two charge carriers when its energy is equal to or higher than the band gap. This energy exchange leads to the formation of holes and electrons, resulting in the production of hydroxide and other radicals. These radicals are instrumental in degrading organic pollutants (Elhaddad & Al-fawwaz, 2023, Litter, 1999). The effectiveness of photocatalysis hinges on the catalyst's ability to generate electron-hole pairs.

Semiconductor-based photocatalysis has received a lot of attention in the literature. This process involves activating the photocatalyst through exposure to UV radiation, creating a redox environment in the reaction. It accelerates chemical reactions in the presence of a semiconductor catalyst, which remains unaltered (Khan et al., 2020; Nosaka et al., 2014). The main factor in this process is the generation of hydroxyl radicals, which can convert various toxic or non-biodegradable pollutants into environmentally friendly compounds like CO_2, H_2O, and others (Wang et al., 2014). The effectiveness of photocatalysis depends on the energy levels of the valence band (VB) and conduction band. The complete processes of semiconductor-mediated photocatalysis during the light illumination are shown in Figure 9.

Fenton-Based AOP

The Fenton Reaction, like other Advanced Oxidation Processes (AOPs), relies on hydroxyl radicals for breaking down organic compounds through oxidation reactions (Muruganandham et al., 2014a, b). However, the Fenton process is stringent and demands precise pH control to stop iron precipitation. Proper reactor design is essential to ensure optimal mixing of H_2O_2 and Fe (II), which promotes hydroxyl species

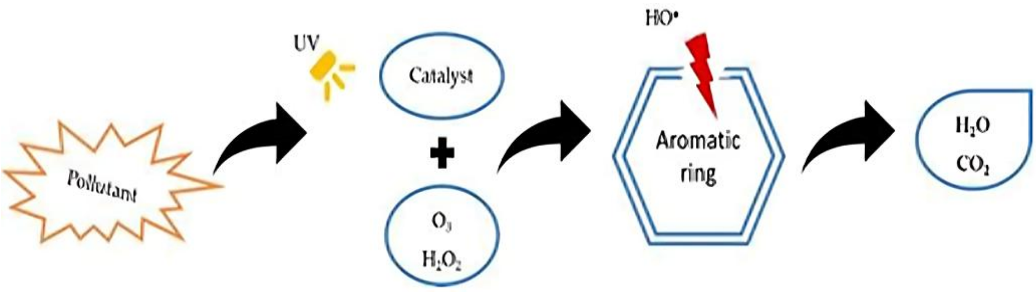

Figure 6. Diagrammatic representation of the production of hydroxyl radicals for the breakdown of organic contaminants. (Lim et al. 2018).

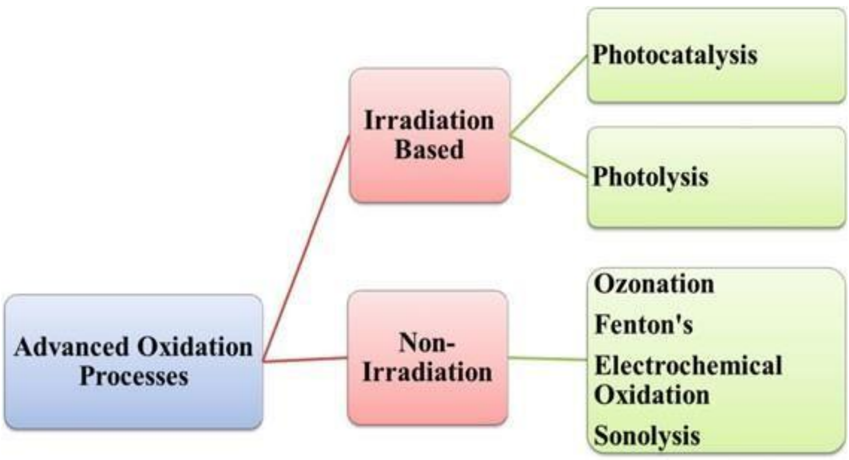

Figure 7. Advanced oxidation processes categorization (Wang et al., 2019).

creation for effective contaminant degradation (Kornweitz et al., 2015). The benefit of the Fenton process is its simplicity; it generates HO without the need for special equipment or chemicals, operating at standard pressure and temperature conditions (Schrank et al., 2005).

Fenton and Photo-Fenton Reactions:

The Fenton reaction combines ferrous ions (Fe^{2+}) with hydrogen peroxide (H_2O_2) to create $^{\bullet}OH$ radicals. In photo-Fenton processes, this reaction is enhanced under UV or sunlight. Both methods are effective for the oxidation of organic contaminants and the removal of water color (Kornweitz et al., 2015) (Figure 10).

Sonolysis

Sonolysis, a green chemistry-based, environmentally friendly Advanced Oxidation Process (AOP), utilizes ultrasound to induce fast bubble creation and collapse in water. This phenomenon, known as acoustic cavitation, involves compression and rarefaction, causing bubbles to explosively collapse

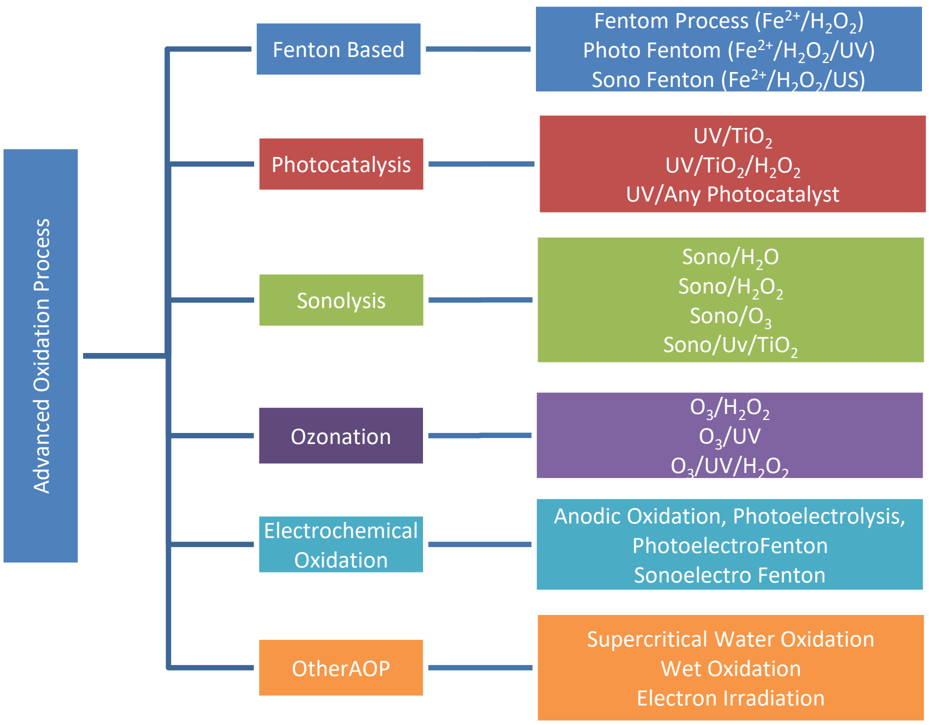

Figure 8. Classification of various advanced oxidation processes (Mais et al. 2020).

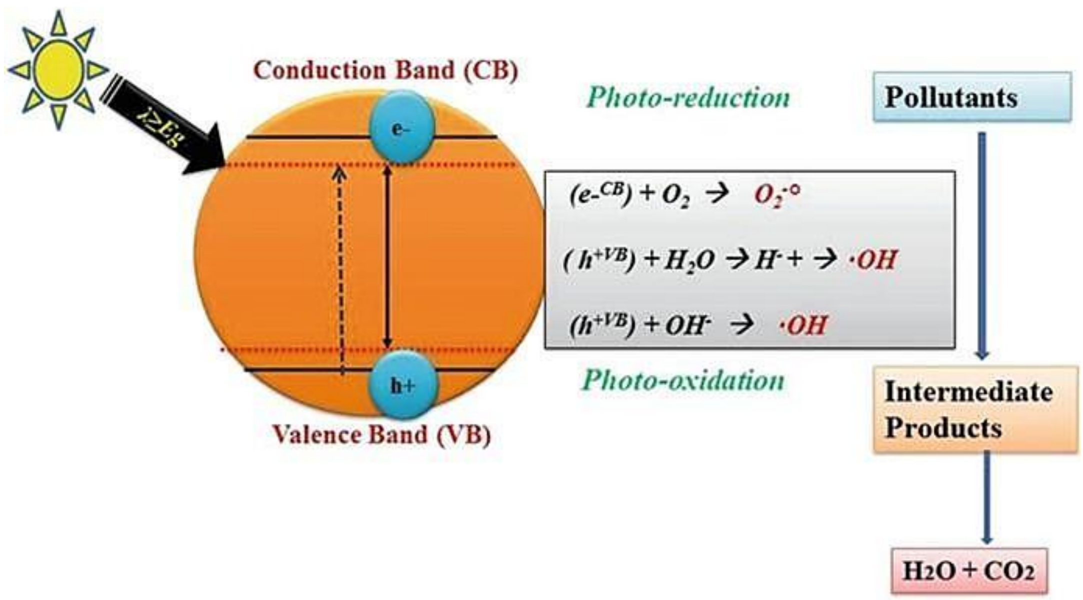

Figure 9. The process of photocatalytic degradation's mechanism (Wang et al., 2014).

upon reaching a critical resonance size. This process generates extremely high pressures, high temperatures and highly reactive oxidative species (Stock et al., 2000; Ince and Tezcanlı, 2001).

Ozonation

Ozone (O_3) is a potent oxidant used widely for treating wastewater from various industries. It's effective for managing wastewater from sources like marine tanks, textiles, refineries, and more (Wu et al., 2007) (Figure 11). Nowadays, ozone-based methods, including ozone/UV, ozone/ultrasound, ozone/ hydrogen peroxide and ozone/titanium dioxide photocatalysis, are commonly used for wastewater treatmentWhen ozone is introduced to water, it causes a sequence of events that result in the creation of radicals such as hydroxyl (HO) and superoxide (Ried et al., 2007). These radicals have the power to quickly oxidise a variety of pollutants, including pathogens and organic substances. According to Liu et al. (2019), the effectiveness of this process is influenced by variables including pH, alkalinity, contact duration, and ozone dosage.

In ozonation, two reactions are particularly significant and are influenced by the pH level:

Direct Pathway (pH < 4): In this process, dissolved substances in water interact with molecular ozone.

Indirect Pathway (pH > 10): This reaction entails the interaction between hydroxyl radicals generated from the breakdown of ozone and dissolved compounds. (Sicardi, 2020).

Advanced Oxidation Processes (AOPs) exhibit high effectiveness in removing recalcitrant organic pollutants, pharmaceuticals, dyes, and pathogens, with typical removal efficiencies ranging from 80–99%, depending on the process type and operating conditions. Ozonation, UV-based systems, and Fenton reactions commonly achieve >90% pollutant degradation, particularly for dyes and aromatic compounds. However, AOPs are associated with relatively high operational costs (0.3–1.5 USD m^{-3}) and energy requirements (0.5–5.0 kWh m^{-3}), driven mainly by chemical and energy inputs. Despite these limitations, AOPs generate minimal sludge and can achieve near-complete mineralization of persistent contaminants. Under Egyptian environmental conditions, their most effective application is as pre-treatment or polishing steps, particularly when integrated with biological processes, which enhances biodegradability and improves overall cost-effectiveness and sustainability.

Biological Methods

Using either anaerobic or aerobic routes, microorganisms are vital for the breakdown and degradation of organic colourants during biological treatment (Saxena and Bharagava, 2017). These microorganisms harness organic compounds as an energy source through degradation processes.

Bioremediation

This method makes use of biological elements in a procedure called bioremediation. In bioremediation, dangerous environmental contaminants are broken down, detoxified, transformed, immobilised, or stabilised into less toxic chemicals using living systems, including bacteria, fungi, algae, and certain plants (Karić et al., 2022). The term "bioremediation" refers to a variety of processes, such as phytoremediation (using particular plants), biomineralization (turning organic materials into inorganic components), bioaugmentation (stimulating native microorganisms with additional nutrients), and the use of genetically modified microorganisms. (Prajapati & Mondal, 2019; Nahar et al., 2022)

Microorganisms naturally present in the lake water can be stimulated or augmented with specific microbial

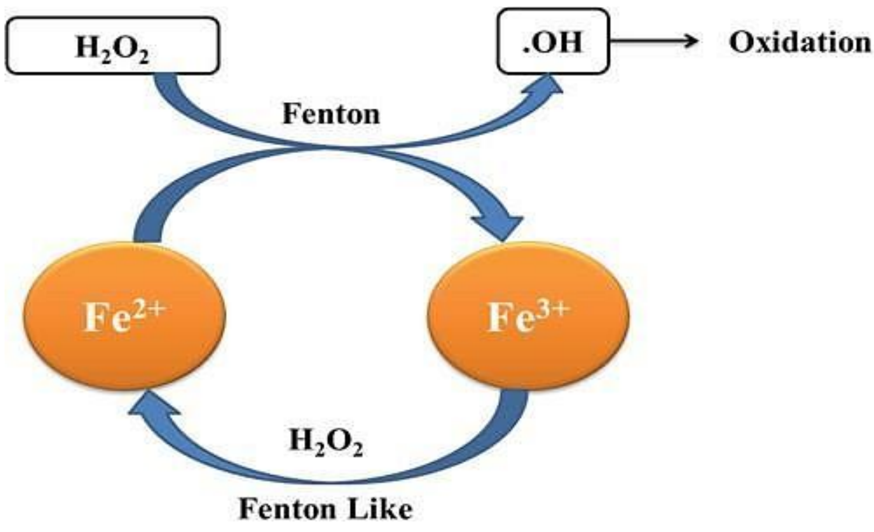

Figure 10. The Fenton process (Kornweitz et al., 2015).

cultures to enhance the breakdown of organic contaminants like pesticides and industrial chemicals. This biodegradation process reduces the concentration of harmful compounds. (Ibrahim et al., 2010)

In Lakes, the use of various pollutants is associated with harm to aerobic organisms, resulting in issues such as sludge formation, flocculation, and sludge bulking. Consequently, the biological treatment approach predominantly reliant on aerobic pathways, has been found inadequate (Ibrahim et al., 2010). This method not only demands more considerable space but also requires an extended hydraulic retention time. Aeration is essential in this context, facilitating the production of unknown oxidation compounds that may intensify the color of the effluent.

In comparison to physical or oxidation-based methods, biological methods for achieving complete wastewater degradation have a number of benefits, including (a) environmental friendliness, (b) cost effectiveness, (c) reduced sludge production, (d) the generation of safe metabolites or complete mineralization, and (e) decreased water consumption. The adaptability of certain microorganisms and the activity of enzymes are key factors in the effectiveness of biological degradation processes. As a result, great effort has been put into isolating and testing different microbes and enzymes to see how well they can break down a variety of contaminants. (Prajapati & Mondal, 2019).

This method is considered a useful for addressing various water quality challenges in Egyptian lakes, including the reduction of pollutants, improvement of water clarity, and restoration of ecosystem health. Microbial and enzymatic treatments are used to biologically degrade organic contaminants and nutrients in lake water.

Although bioremediation offers notable benefits compared to conventional remediation methods (Silva et al., 2020), it is not without drawbacks. Some of its key limitations include the potential for incomplete contaminant degradation, its applicability being restricted to biodegradable substances, and the necessity of carefully selecting microbial strains with specific traits. In certain cases, this requirement reduces the reliance on genetically engineered microorganisms. Microorganisms play an essential role in environmental detoxification processes, particularly by facilitating the dissolution of metals and driving the redox transformations of transition metals (Ansari et al., 2020). However, exposure to certain organic solvents can compromise the integrity of microbial cell membranes. To counteract this stress, many microorganisms develop adaptive resistance strategies, such as producing hydrophobic barriers or activating solvent efflux pumps, thereby preserving membrane stability (Saxena and Bharagava, 2017).

One of the advanced approaches in this field is bioaugmentation, an in-situ bioremediation strategy that enhances microbial metabolic activity through genetic engineering. For example, Yogalakshmi (2020) demonstrated the successful genetic modification of Escherichia coli by overexpressing the ArsR gene, which significantly increased the bacterium’s ability to accumulate and bind arsenic. Such modifications, coupled with selective ligand application, have shown promise in improving the efficiency of arsenic removal from contaminated environments. Bioaugmentation generally involves introducing tailored microorganisms into natural systems, such as lakes, to enhance their intrinsic capacity for self-purification.

Biosorption

Biosorption is another environmentally sustainable and cost-effective bioremediation method that relies on a wide range of biological materials, including bacteria, fungi, and algae. These organisms possess surface functional groups capable of binding pollutants, making the process highly effective for in-situ ecological remediation. Compared to untreated or native biomass, immobilized biomass has been found to offer superior performance and greater stability, particularly when scaled up for industrial or large-scale wastewater treatment applications (Crini et al., 2019).

Figure 11. Schematic drawing of catalytic ozonation (Lina 2016).

Biosorbents improve the microbial selectivity and accumulation features of microorganisms employed in the bioremediation process. This approach primarily relies on genetic engineering to develop the remediation capabilities of microorganisms. Genetically modified microbes have been shown in studies to have excellent adsorption abilities and selectivity for removing harmful ions of metal.

In comparison to other physicochemical cleanup techniques, this strategy has a lot of benefits. Acidithiobacillus ferrooxidans, a chemolithotrophic bacterium, was isolated from mines and exploited as a natural biosorbent for the biological elimination of harmful inorganic as well as organic arsenic substances in aqueous solutions, for example, in a work by Putri et al. 2020. Five distinct fungal strains were discovered, and their capacity to clean contaminated locations with hazardous arsenic pollutants was assessed. In Table 4, different treatment techniques, basic purpose, and consequent pollutant(s) removal.

Additionally, further research is needed to assess its effectiveness, cost-efficiency, and ease of implementation thoroughly and characterize biosorbents in terms of functional groups, surface, morphology and particle size, crucial factors in biosorption tests (Tatarchuk et al., 2020).

These techniques and strategies reflect Egypt's commitment to improving water quality in its lakes, which are essential resources for agriculture, industry, and recreation. The specific methods chosen depend on each lake's unique challenges and conditions and its surrounding environment.

Case studies

a) Case study 1

Gaballah et al (2021) used the water hyacinth (Eichhornia crassipes) in Lake Marriott for remediation (Figure 12). This floating aquatic macrophyte possesses well-known phytoremediation potential. Through duplicate pilot floating treatment wetlands (FTWs) with E. crassipe.

Over a 7-day cycle, Notably, NH4-N removal reached 97.4% in unit in 3 days, BOD removal was 75% in 3 days, TN removal was 82% in in 4 days, and TP removal was 84.2% in 4 days. . Moreover, heavy metals were effectively removed, primarily accumulating in plant roots, with a sequence of Fe > Pb > Cu > Ni (62.5%, 88.9%, 81.7%, and 80.4%). There were significant differences in the biochemical composition between plant shoots and roots. The study concluded that the most effective design for remediating Marriott Lake in Egypt involved FTWs with 70% E. crassipes coverage.

b) Case study 2

In a study conducted at Marriott Lake (Gaballah et al., 2020), three distinct configurations of constructed wetlands were evaluated: (i) a system planted with Typha angustifolia and equipped with an enhanced atmospheric aeration system, (ii) a system planted with Typha angustifolia without aeration, and (iii) a control system consisting of an unplanted wetland without perforated pipes (Figure 13).

Table 4. Treatment techniques, basic purpose, and consequent pollutant(s) removal (Ferrera and Sanchez 2016)

Technique	Basic purpose	Pollutant(s) removed
1. Chemical techniques		
pH regulation	pH adjustment, Neutralization	H^+/OH concentration modification, heavy metal particle precipitate
Precipitation	Removal of dissolved inorganic substances	Some inorganic cations and anions
Oxidation and reduction	Specific dissolved substances elimination	Some resistant organic compounds and certain harmful chemicals
2. Physical technique		
Gravity separation	Free oil, Heavy particlesand grease removal	Finer suspended particles, oil, grease and biological oxygen demand (BOD)
Dissolved air flotation	Both heavy and light particles, free oil and grease removal	Finer suspended particles, oil, grease and (BOD)
Filtration	Both heavy and light particles	Suspended solid particles and BOD
Adsorption	Volatile organic compounds (VOCs) dissolved/suspended non-biodegradable organic substances	Recalcitrant organic substances, recoverable organic compounds, color and odor
Membrane-based processes	Dissolved inorganic and organic substances removal	Dissolved inorganic and organic substances and BOD
Coagulation and flocculation	Colloidal particles removal	Turbidity (due to suspended fine solid particles) and BOD
3. Biological techniques		
Aerobic treatment	Biodegradable dissolved and suspendedorganic substances	Biodegradable organic, BOD, some nitrogenous and phosphorous compounds
Anaerobic treatment	Biodegradable dissolved and suspendedorganic substances	Biodegradable organic, BOD, some nitrogenous

The experimental setup employed polymethyl methacrylate (PMMA) tanks to establish horizontal subsurface flow constructed wetlands (HSFCWs). Each tank was filled with commercial gravel of varying sizes, where medium-sized gravel was placed at the base, while the upper layers contained smaller aggregates. The beds were fully saturated with water to mimic natural wetland conditions.

Among the three HSFCWs, one was maintained as a control (C), lacking vegetation and aeration. The two planted systems differed in their configurations: the first was vegetated with T. angustifolia but without supplemental aeration (CWR), while the second (CWA) incorporated an innovative aeration design consisting of perforated T-shaped polypropylene pipe networks embedded beneath the beds.

The aerated system (CWA) demonstrated superior performance across all measured parameters. It achieved removal efficiencies of 98.4% for turbidity, 83.3% for biochemical oxygen demand (BOD), 95.8% for chemical oxygen demand (COD), 99.9% for ammonia-nitrogen (NH_3-N), 94.7% for total nitrogen (TN), and 99.7% for total phosphorus (TP). Furthermore, CWA accomplished complete (100%) elimination of Vibrio species and Escherichia coli, alongside a 97.5% reduction in anaerobic bacteria.

The modified constructed wetland planted with T. angustifolia and enhanced by aeration exhibited remarkable potential for the remediation of polluted lake water. The introduction of aerobic conditions significantly improved the removal of organic matter, nutrients, and turbidity. Moreover, the system effectively eradicated microbial pathogens including Vibrio spp., E. coli, total bacterial counts, and anaerobic bacteria achieving complete removal in most cases.

The integrated perforated pipe network enhanced the removal process by improving oxygen circulation, making it a cost-effective alternative to artificial aeration methods, particularly suitable for application in developing countries.

Comparative Summary of Wastewater Treatment Techniques for Egypt

The comparative assessment of wastewater treatment techniques indicates that their efficiency,

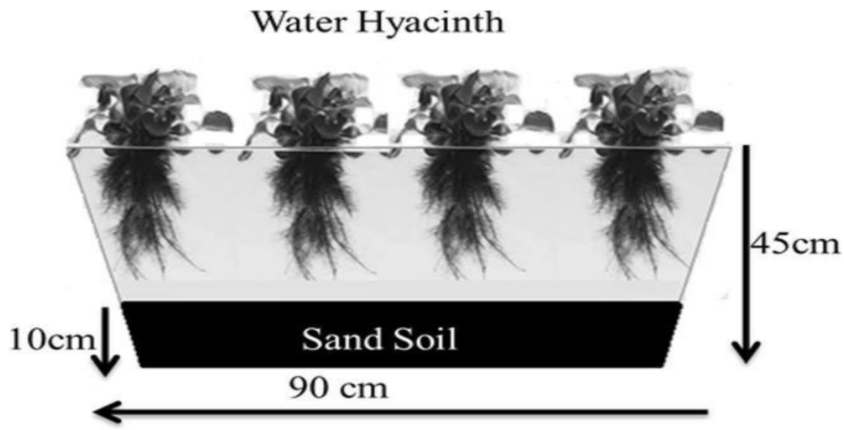

Figure 12. Schematic representation of the pilot floating treatment wetland design tested in this study (Gaballah et al., 2021).

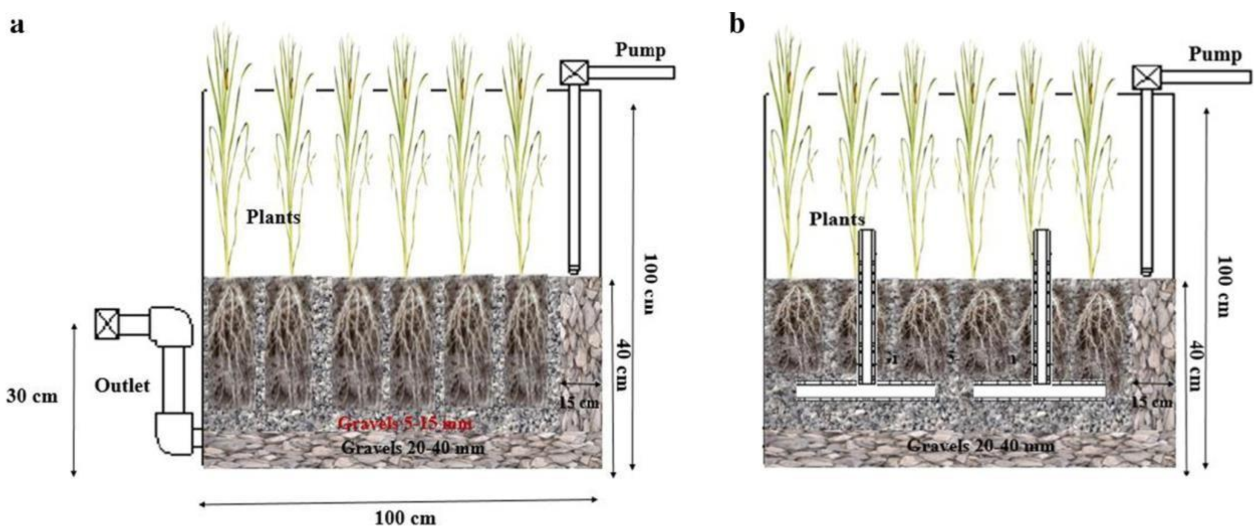

Figure 13. Constructed wetlands units of two different models. a CWR. b CWA (Gaballah et. al., 2020).

cost, scalability, and environmental suitability vary significantly depending on pollutant characteristics and local conditions (Table 5). Physical methods, such as adsorption and membrane filtration, exhibit high removal efficiencies for heavy metals and organic pollutants; however, their large-scale application is often constrained by operational and maintenance costs, particularly due to membrane fouling and energy requirements. Chemical methods, including coagulation–flocculation and chemical precipitation, are economically favorable and readily scalable, yet they generate substantial sludge volumes that require proper environmental management.

Biological treatment methods, including bioremediation and constructed or floating wetlands, offer high sustainability and strong compatibility with Egyptian environmental conditions. These systems benefit from low energy consumption and favorable climatic conditions, although their treatment rates may be slower compared to physicochemical methods. Advanced oxidation processes (AOPs) demonstrate very high efficiency in degrading recalcitrant organic pollutants, but their high energy and chemical demands limit their use as standalone large-scale solutions. Overall, integrated and hybrid systems provide the most balanced approach by combining high removal efficiency with economic and environmental sustainability, making them particularly suitable for the diverse pollution loads encountered in Egyptian lakes.

Conclusion

This study addresses wastewater treatment as a critical component of sustainable water quality management in Egyptian lakes. The challenges associated with wastewater treatment in Egypt are not unique but reflect global concerns related to water scarcity, pollution, and increasing demand for clean water resources. Rapid population growth and limited freshwater availability are expected to widen the gap between water supply and demand, underscoring the need for effective and sustainable treatment strategies.

Advanced wastewater treatment technologies play a key role in enhancing water security by enabling the reliable production of high-quality treated water suitable for reuse and environmental discharge. Investment in research and development of these technologies is essential to support long-term water sustainability and economic development. However, the successful implementation of advanced treatment systems depends on coordinated efforts among researchers, policymakers, and industry stakeholders to translate scientific findings into scalable and practical solutions.

Given Egypt's unique environmental and climatic conditions, including high temperatures, variable humidity, and distinct water chemistry, treatment systems must be specifically adapted to local contexts. Integrated and hybrid treatment approaches represent a promising strategy, as they combine the strengths of individual methods to optimize contaminant removal while minimizing operational limitations. In particular, coupling advanced oxidation processes with biological treatment or membrane filtration has demonstrated strong potential for addressing complex pollution loads in aquatic environments.

Future wastewater treatment strategies should also prioritize minimizing environmental impacts by reducing energy consumption, sludge generation, and secondary pollution. In addition, implementing mechanical filtration at drainage outlets can serve as an effective preventive measure by intercepting pollutants at their source, thereby reducing contaminant loads entering lake systems. Collectively, these approaches support sustainable, eco-friendly water management and the long-term restoration of Egyptian lakes.

Perspectives for Future Research and Technology Development

The selection of treatment technologies for the removal of toxic heavy metals from wastewater and polluted lake water is governed by multiple interdependent factors, including solution pH, initial

Table 5. Comprehensive evaluation of treatment techniques under egyptian environmental conditions

Technique	Efficiency	Cost	Scalability	Suitability under Egyptian Conditions	Key Remarks
Adsorption	High	Low–Moderate	Moderate	Suitable for polishing stages and localized contamination	Effective for metals; regeneration required
Membrane Filtration	Very High	High	Moderate	Limited by energy demand and fouling under high salinity	Best for tertiary treatment
Coagulation–Flocculation	Moderate–High	Low	High	Highly suitable for large inflows to lakes	Sludge management is critical
Chemical Precipitation	High (metals)	Low–Moderate	High	Effective where metal pollution dominates	Restricted to inorganic contaminants
AOPs	Very High	High	Moderate	Suitable for pollution hotspots and pre-treatment	Requires skilled operation
Bioremediation	Moderate–High	Low	High	Highly suitable due to warm climate and natural conditions	Slower kinetics
Constructed / Floating Wetlands	High	Low	Very High	Excellent suitability for Egyptian lakes	Land/water area required
Hybrid Systems	Very High	Moderate	High	Most suitable for mixed pollution loads	Requires integrated design and monitoring

metal concentration, achievable removal efficiency, capital and operational costs, energy requirements, sludge production, and overall environmental footprint. A critical analysis of current literature indicates that no single technique is universally optimal; rather, integrated and hybrid approaches consistently outperform standalone processes in terms of robustness, cost-effectiveness, and long-term sustainability, particularly under the challenging conditions of Egyptian lakes (high salinity, elevated temperature, and mixed pollutant loads).

Promising directions for future research and full-scale implementation include the following hybrid configurations:

a) Biological Activated Carbon (BAC) Systems In BAC filtration, adsorption onto activated carbon and microbial biodegradation occur simultaneously. Organic substrates are initially captured within the macropores of the carbon bed, where they remain sufficiently long to be degraded by the established biofilm. This synergy significantly prolongs the service life of activated carbon (often 2–5 times longer than granular activated carbon alone) and substantially reduces backwashing frequency and regenerant consumption. BAC systems are particularly suitable as tertiary treatment for Egyptian lake rehabilitation projects, where moderate-to-low concentrations of recalcitrant organics and nutrients persist after primary/secondary treatment.

b) Sequential AOP–Biological Treatment Advanced oxidation processes are highly effective at degrading recalcitrant and non-biodegradable compounds, but complete mineralization is energy-intensive and costly. In contrast, conventional biological treatment is economical but ineffective against compounds of low biodegradability ($BOD_5/COD < 0.2$). Integrating AOP as a pre-treatment stage partially oxidizes refractory molecules into more biodegradable intermediates, which are subsequently mineralized in a downstream biological unit (activated sludge, MBBR, or constructed wetland). This sequential approach has been demonstrated to reduce total treatment costs by 30–60% while achieving >95% removal of persistent organics and >90% overall COD reduction in pilot studies.

c) Hybrid AOP Configurations Combining multiple AOPs (e.g., O_3/H_2O_2, $UV/H_2O_2 + TiO_2$, ozonation + Fenton, or Fenton + photocatalysis) produces synergistic increases in •OH radical yield and reaction kinetics. Such systems exhibit enhanced removal rates for mixed pollutant matrices (pharmaceuticals, pesticides, dyes, and heavy metal–organic complexes) commonly found in drains discharging into Lakes Manzala, Mariout, and Burullus. Successful implementation, however, requires continuous monitoring of degradation by-products (e.g., bromate, aldehydes, carboxylic acids) and adjustment of oxidant/catalyst doses to match seasonal variations in lake water chemistry.

d) Sonophotocatalysis The coupling of ultrasonic cavitation with photocatalytic oxidation (typically TiO_2 under UV or solar irradiation) generates extreme localized conditions (>5000 K, >1000 atm) that accelerate •OH production and mass transfer. Recent laboratory and pilot studies report 20–50% higher degradation rates for recalcitrant pollutants compared with photocatalysis alone, with simultaneous pathogen inactivation. Given Egypt's abundant solar resource and the frequent presence of complex pollutant mixtures in northern lakes, solar-driven sonophotocatalysis represents a highly promising area for future scale-up and field validation.

Ethical Statement

Not applicable.

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Author Contribution

E.E.: Writing -review and editing; A.T.A.: review

Conflict of Interest

The authors declare that they have no known competing financial or non-financial, professional, or personal conflicts that could have appeared to influence the work reported in this paper.

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