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A REVIEW ON INDUSTRIAL WASTEWATER TREATMENT TECHNIQUES

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Abstract: Due to rapid growth in population, urbanization, and industrialization, the world is facing immense challenges in the access to safe and clean water, and huge volumes of wastewater come out as a by-product. Poor-quality treated or untreated wastewater also carries serious risks to public health and aquatic ecosystems. The current paper reviews wastewater treatment processes, classified as physical, chemical, biological, and advanced or tertiary methods. The conventional methods of treatment, including screening, sedimentation, coagulation, and biological treatment, serve to reduce organic and suspended pollutants, while emerging contaminants are dealt with by advanced membrane filtration, adsorption, and electrochemical methods. Results: The large quantities of wastewater, therefore, call for a requirement of integrated and sustainable treatment approaches only, which can assure high-quality effluent, water reuses, and accomplish long-term environmental protection.

Keywords: Industrial wastewater; water treatment; pollution; environment.

1. Introduction

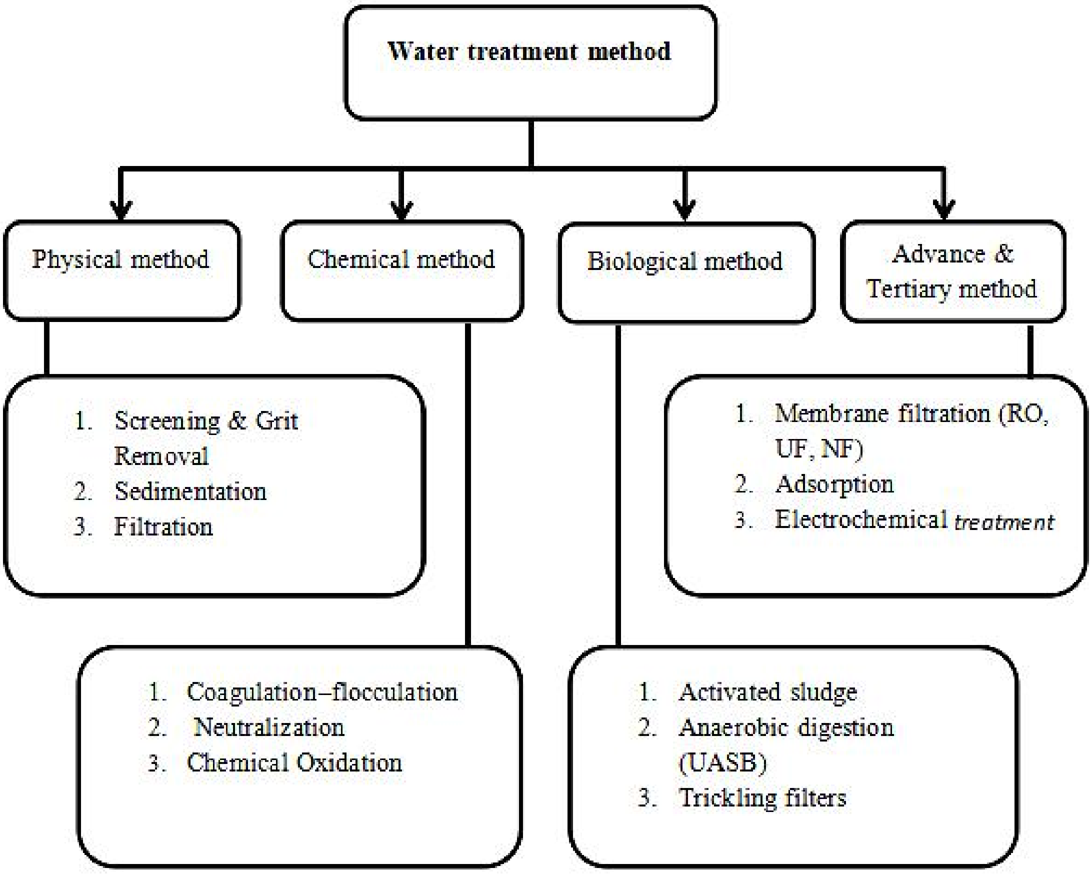
One of the most critical global challenges affecting human society is limited access to safe and clean drinking water. Approximately 1.2 billion people worldwide still lack access to potable water, while millions suffer from waterborne diseases caused by contaminated water sources. Safe water, free from toxic substances and pathogenic microorganisms, is essential to prevent adverse environmental and public health impacts. Various industrial activities generate highly polluted effluents that must be adequately treated before discharge into the environment to prevent contamination of natural water bodies. For example, textile industries release dye-containing wastewater, while pulp and paper industries discharge toxic contaminants such as adsorbable organic halides (AOX) into receiving waters, significantly degrading water quality (Zhang et al., 2022). A reliable supply of clean water is fundamental for the establishment and sustainability of diverse human activities. Water resources support food production through irrigation and aquatic ecosystems, which are vital for global food security. However, rapid industrialization and urban expansion have resulted in the discharge of large quantities of liquid and solid wastes into water bodies, leading to widespread pollution of surface and groundwater resources across the world (Dhote et al., 2012). The continuous increase in global population has intensified competition for natural resources, particularly water and energy. Human exploitation of these resources has resulted in severe environmental challenges, including water contamination and climate change. Although water is an abundant natural resource on Earth, its quality is increasingly compromised due to anthropogenic activities, making clean water availability a growing concern for human survival and sustainable development (Nishat et al., 2023). In this context, wastewater treatment has emerged as a globally significant challenge due to rapid population growth, urbanization, and industrial activities that continuously increase the volume of contaminated water discharged into freshwater bodies. Wastewater typically contains organic pollutants, nutrients, toxic chemicals, and pathogenic microorganisms, which can cause serious environmental degradation and health hazards if left untreated. Therefore, effective wastewater treatment techniques are essential for environmental protection, public health, and sustainable development. Historically, wastewater treatment processes have relied on a combination of physical, chemical, and biological methods to remove or neutralize contaminants prior to discharge. Conventional treatment techniques such as sedimentation, coagulation–flocculation, activated sludge processes, and trickling filters are widely used to reduce suspended solids, organic load, and microbial contamination in wastewater streams (Fahad et al., 2019).

Wastewater quality is characterized by various physical and biochemical parameters, including pH, temperature, total dissolved solids (TDS), biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), turbidity, color and odor. Variations in these parameters can cause severe adverse effects on aquatic ecosystems and overall environmental health, making their monitoring and control essential in wastewater treatment processes (Ademiluyi et al., 2009). Despite the effectiveness of conventional treatment methods, they often fail to adequately remove emerging and complex contaminants such as pharmaceuticals, microplastics, and persistent organic compounds. These limitations have driven extensive research into the development of advanced and more efficient wastewater treatment technologies capable of meeting stringent regulatory standards and addressing modern environmental challenges. Advanced treatment technologies, including membrane filtration, advanced oxidation processes (AOPs), electrochemical methods, and adsorption using novel materials, have demonstrated superior performance in removing fine particulates, dissolved organic matter, and toxic pollutants that are difficult to eliminate using traditional techniques. These technologies play a crucial role in producing high-quality effluents suitable for reuse and protecting sensitive aquatic ecosystems. Membrane-based treatment methods such as ultrafiltration, nanofiltration, and reverse osmosis are increasingly adopted due to their ability to retain even microscopic contaminants while allowing purified water to pass through. Similarly, advanced oxidation processes utilize highly reactive radicals to degrade persistent organic pollutants, significantly enhancing overall treatment efficiency (Pandit & Sharma, 2024). Biological treatment processes remain a cornerstone of wastewater management due to their cost-effectiveness and environmental compatibility. Techniques such as activated sludge systems, biofilm reactors, and anaerobic digestion exploit microbial metabolism to degrade organic matter and nutrients, resulting in substantial reductions in BOD and COD levels (Fahad et al., 2019). To overcome the limitations of individual treatment methods, hybrid systems that integrate conventional and advanced treatment approaches have been developed. These integrated systems improve pollutant removal efficiency, optimize energy consumption, and allow treatment strategies to be tailored to specific wastewater characteristics. Furthermore, sustainable wastewater treatment increasingly emphasizes resource recovery, including biogas production through anaerobic digestion and nutrient recovery for agricultural reuse, thereby supporting circular economy principles and generating economic value from wastewater streams (Fernandes et al., 2024). The selection of an appropriate wastewater treatment technique depends on influent characteristics, target pollutant levels, regulatory requirements, economic feasibility, and site specific conditions. As no universally optimal treatment solution exists, wastewater treatment systems must be carefully designed to meet desired effluent quality and reuse objectives (Kato & Kansha, 2024). Continuous research and technological innovation continue to drive the evolution of wastewater treatment technologies, with recent studies focusing on improving efficiency, affordability, and environmental sustainability. These advancements aim to reduce ecological footprints while ensuring long-term protection of water resources (Fahad et al., 2019). In recent years, decentralized and modular wastewater treatment systems have gained attention as effective alternatives in rural, peri-urban, and low-resource settings where centralized infrastructure is often impractical. These systems offer greater flexibility, resilience, and improved access to wastewater treatment services in underserved regions (Sha et al., 2024). Produced water, a major byproduct of oil and gas production, is another significant wastewater stream that requires specialized treatment. It contains suspended solids, oil and grease, dissolved organic compounds, inorganic ions, and radioactive materials. Produced water treatment involves basic separation technologies such as flotation, media filtration, coagulation, flocculation, centrifugation and hydrocyclones, as well as advanced treatment processes. However, basic separation technologies alone are often insufficient to meet stringent standards for beneficial water reuse, necessitating advanced treatment solutions (Lin et al., 2020). Wastewater treatment technologies have evolved from conventional pollutant removal methods toward advanced, integrated, and sustainable systems. This transition reflects global efforts to improve water quality, protect ecosystems, achieve regulatory compliance, and promote efficient resource utilization through innovative and adaptable wastewater treatment approaches (Pandit & Sharma, 2024).

In conclusion, wastewater treatment is essential for safeguarding public health, protecting aquatic ecosystems, and ensuring sustainable water resource management amid growing population and industrial pressures. The evolution from conventional treatment methods to advanced, integrated and resource efficient technologies highlights the need to address emerging contaminants and water scarcity challenges. Continued research, innovation, and the adoption of sustainable and decentralized treatment systems are crucial for achieving effective wastewater management and long-term environmental sustainability.

2. Classification of Wastewater Treatment Processes

The classification of wastewater treatment processes is based on the principles and objectives of treatment, as described in various research studies and standard literature. Wastewater treatment is mainly classified into physical, chemical, biological, and advanced or tertiary treatment processes. Physical treatment processes are used to remove suspended solids from wastewater. Chemical treatment processes are applied to eliminate color, heavy metals, and toxic substances. Biological treatment involves the removal of biodegradable organic pollutants with the help of microorganisms. In addition, tertiary and advanced treatment processes are employed to obtain high-quality treated water and to enable its reuse (Henze et al., 2008; Metcalf & Eddy et al., 2014).



2.1 Physical Treatment Methods

Physical treatment methods are the initial steps in wastewater treatment, aimed at removing large solids and suspended particles. Screening and grit removal involve the use of bar screens to eliminate large floating debris such as plastics, rags, and other waste, while grit chambers remove heavy inorganic particles like sand and gravel. This prevents damage and clogging of downstream equipment. Sedimentation is a process where wastewater is held in a tank, allowing heavier suspended solids to settle at the bottom under gravity. The settled sludge is collected, and the clarified water moves on for further treatment, effectively reducing turbidity. Filtration then passes the water through porous materials like sand, gravel, or fabric filters to remove remaining fine particles, improving water clarity and preparing it for chemical or biological treatment (AJ Englande et al., 2015).

2.2 Chemical Treatment Methods

Chemical treatment focuses on modifying the chemical characteristics of wastewater to remove pollutants. Coagulation–flocculation involves adding coagulants such as alum or ferric salts to destabilize colloidal particles. These particles aggregate into larger flocs, which can be easily separated through sedimentation or filtration, enhancing water clarity. Neutralization adjusts the pH of wastewater by adding acids or bases to bring it to a neutral range, ensuring safe discharge and creating favorable conditions for subsequent biological processes. Chemical oxidation uses strong oxidizing agents like ozone, hydrogen peroxide, or Fenton's reagent to break down toxic and non-biodegradable compounds, transforming harmful pollutants into simpler, less toxic substances and improving overall wastewater quality (Kumar Gupta et al., 2012).

2.3 Biological Treatment Methods

Biological treatment relies on microorganisms to degrade organic pollutants in wastewater. The activated sludge process is an aerobic method where wastewater is mixed with microorganisms in the presence of oxygen. These microbes consume organic matter, reducing biochemical oxygen demand (BOD) and chemical oxygen demand (COD), and convert it into stable biomass and treated effluent. Anaerobic digestion, carried out in systems like UASB reactors, occurs in the absence of oxygen. Microorganisms break down organic matter to produce biogas rich in methane, which can be harnessed as an energy source, while simultaneously reducing the organic load. Trickling filters are fixed-film systems where wastewater flows over a media bed coated with microbial biofilm.

The biofilm metabolizes organic pollutants as water passes through, providing a stable and efficient method for municipal wastewater treatment (Kato & Kansha, 2024).

2.4 Advanced and Tertiary Treatment Methods

Advanced and tertiary treatments are employed to further polish wastewater, removing dissolved salts, micropollutants, and pathogens. Membrane filtration techniques, including reverse osmosis (RO), ultrafiltration (UF), and nanofiltration (NF), use semi-permeable membranes to remove dissolved salts, pathogens, and heavy metals, producing high-quality water suitable for industrial or domestic reuse. Adsorption using activated carbon removes color, odor, taste, and organic micropollutants, as contaminants adhere to the large surface area of the carbon, making it an effective polishing step. Electrochemical treatment applies an electric current to oxidize, reduce, or separate pollutants. This method is particularly effective for industrial effluents containing toxic compounds, heavy metals, and refractory substances, and achieves treatment with minimal chemical usage (Chalaris et al., 2023).

Table 1 Removal of large solids by separations methods (Metcalf & Eddy et al., 2014)

Phase	Activity	Description
1. Preliminary Treatment	1. Screening	Removal of large floating and suspended solids such as plastics, rags, and debris to protect downstream equipment
	2. Grit removal	Elimination of heavy inorganic particles like sand and grit to prevent abrasion and clogging
2. Primary Treatment	3. Sedimentation	Settling of suspended solids by gravity in primary clarifiers to reduce total suspended solids (TSS)
	4. Skimming	Removal of oil, grease, and floating materials from the wastewater surface
3. Secondary (Biological) Treatment	5. Activated sludge process	Aerobic microbial degradation of organic matter to reduce biochemical oxygen demand (BOD)
	6. Aeration	Supply of oxygen to support microbial metabolism and enhance organic matter breakdown
	7. Secondary clarification	Separation of biological sludge from treated effluent
4. Tertiary / Advanced Treatment	8. Filtration	Removal of remaining fine particles and turbidity using sand or membrane filters
	9. Nutrient removal	Reduction of nitrogen and phosphorus to prevent eutrophication
	10. Disinfection	Inactivation of pathogenic microorganisms using chlorine, UV, or ozone
5. Sludge Treatment & Disposal	11. Anaerobic digestion	Stabilization of sludge and production of biogas under anaerobic conditions
	12. Dewatering and disposal	Reduction of sludge volume followed by safe disposal or reuse

Conclusion

Wastewater treatment plays a vital role in protecting public health, preserving aquatic ecosystems, and ensuring sustainable water resource management. Conventional physical, chemical, and biological treatment methods are effective in removing suspended solids and biodegradable organic pollutants, but they are often insufficient for emerging and complex contaminants. Advanced and tertiary treatment technologies, including membrane filtration, adsorption, and electrochemical processes, provide improved removal efficiency and enable water reuse. The integration of conventional and advanced methods, along with resource recovery and sustainable system design, is essential to meet stringent environmental regulations and address growing water scarcity challenges.

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