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REVIEW

Water Pollutants and Approaches for Their Removal

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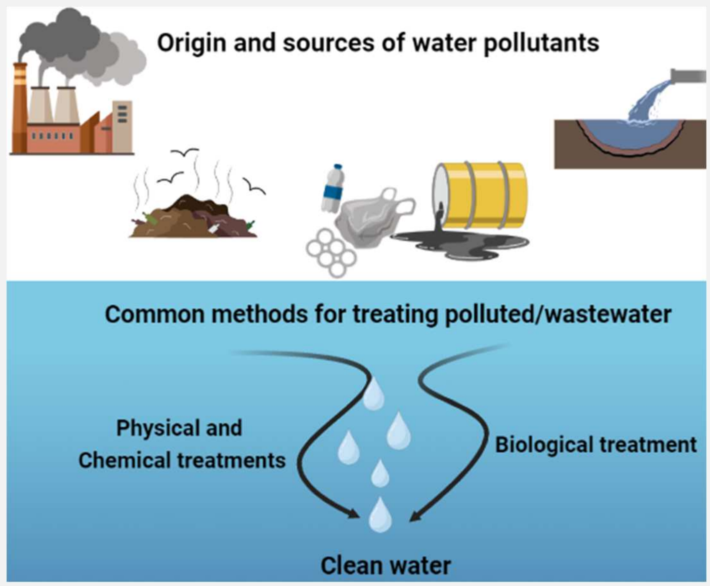
ABSTRACT

Pollution has emerged as a pressing global concern, as it negatively impacts various water bodies and poses severe threats to both human and aquatic life. Therefore, preventing and mitigating the adverse effects of pollutants on the environment and human health is of utmost importance. Comprehensive understanding of the sources, impacts, and treatment methods of different pollutants is essential. There are several methods available for removing pollutants from water, including physical, chemical, and biological approaches. Each technique possesses its unique advantages and limitations, and selecting the appropriate method largely depends on the nature and extent of contamination, cost, and efficiency. Thus, it is crucial to utilize a combination of different methods to detect and eliminate pollution more effectively. This review provides a detailed analysis of diverse pollutants found in water and the approaches adopted for their elimination, environmental regulations, and new pollutant detection techniques. It aims to compare and evaluate these methodologies for taking crucial steps in removing pollutants from water bodies. The significance of ongoing research in this field is also highlighted to improve and advance pollution prevention techniques in aquatic environments.



Keywords: Water pollutants, water treatment, removal, wastewater

1. Introduction

Water is one of the most vital components for living organisms, especially humans, as it makes up about 60% of the human body weight. Life is not possible without water [1,2]. It is predicted that by 2050, the demand for water and food will increase by 50% and 70%, respectively, compared to current levels. On the other hand, the problem of a shortage of safe drinking water is one of the serious issues in the modern world today. According to the World Health Organization report, only 5% of the water in the world is suitable for human consumption, while approximately 71% of the earth's surface is covered with water. In addition, World Health Organization has reported that 748 million people worldwide lack access to safe drinking water, 2.5 billion people lack access to sanitation, and 3,900 children die each day due to unhealthy drinking water and disease [1,3]. Due to the rapid increase in population and industrial growth, safe drinking water is at risk of pollution. Accordingly, access to safe water is considered one of the most fundamental goals of humanity and remains a major global challenge in the 21st century. Pollution happens when contaminants alter the physical properties, aesthetic qualities, or odor of water. Although some pollutants may not

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change the physical properties of water, water pollution can be caused by the toxicity of water pollutants, such as heavy metals, even in very low concentrations. These substances can create serious problems for humans, animals, and environment [4,5]. These pollutants include heavy metal ions, dyes, drugs, pesticides, organic compounds, and other dangerous compounds that can accumulate in the tissues of living organisms and lead to creation of dangerous diseases. Every year, waterborne illness epidemics claim the lives of millions of people, primarily in impoverished nations with insufficient access to clean water [6]. Therefore, the removal of these toxic substances from water is highly important and much attention has been paid to it [7–11].

To date, various technologies have been introduced for water purification. These technologies can be categorized into three physical, chemical, and biological classes. In this review, types of water pollutants and their toxic effects on humans and living organisms, and water treatment methods are presented to provide a basis for future research.

2. Origin and sources of water pollutants

The origin of pollutants can be attributed to their natural and artificial occurrence on the earth. For example, nitrogen, oxides, heavy metals, hydrocarbons, and radioactive substances are some of the natural pollutants. Many of the chemicals that cause pollution, such as various pesticide syntheses, surfactants, plastics, and petrochemicals, are entirely man-made [12–14].

The common sources of water pollution can vary from entirely natural to man-made sources, such as the discharge of household and industrial wastewater. The common sources of natural pollutants entering water reservoirs include rainwater, dust and storms, underground rocks and volcanoes, and vegetation cover [15–17].

In general, water pollution sources are divided into two major categories: direct and indirect pollution. Direct pollution occurs when liquids are directly released into water, such as when a factory discharges contaminated water or toxic solid materials mixed with water directly into the sea or river. Such toxicity can lead to the death of fish and other aquatic creatures. Nonetheless, animals also consume this water, which can cause disease or death. Indirect water pollution occurs when pollutants enter water indirectly. For example, fertilizers and chemical pesticides gradually wash through the soil and find their way into groundwater and then into various waterways. Additionally, air pollution causes acid rain to fall on the ground, which can be very harmful to the environment. Rainwater is an essential natural source of water pollution, which dissolves air pollutants and suspended particles and brings them down with it. For example, the occurrence of acid rain results from the dissolution of acidic gases such as oxides, sulfur, and nitrogen [15–17].

3. Types of water pollutants and environmental hazards

Water pollution occurs when one or more added substances cause negative changes in its color, taste, or odor. While some pollutants may not alter the physical properties of water, they can still create toxicity in it. There are various types of pollutants that are categorized in the following paragraphs [18]:

3.1. Organic pollutants

Organic compounds are composed of carbon, hydrogen, oxygen, nitrogen, and sulfur. Sewage, canning industries, food processing units, slaughterhouses, paper and pulp mills, tanneries, and others contain significant amounts of organic compounds in suspended, colloidal, and dissolved forms. These pollutants cause anaerobic conditions in the ecosystem due to the complete consumption of oxygen in the water body. On the other hand, artificial organic pollutants are not biodegradable and persist in the water for a long time. Artificial organic pollutants include synthetic pesticides, detergents, food additives, drugs, insecticides, dyes, synthetic fibers, plastics, solvents, and volatile organic compounds.

3.1.1. Pesticides

The improper use of pesticides (mainly herbicides and insecticides) causes an increase in water pollution. The main problems of this type of pollutant in water are the incorrect use of effective amount and type of pesticides, incorrect combination of pesticides, and incorrect use of pest control poisons. Pesticide residues easily spread from agricultural lands to nearby rivers and are absorbed by plants and aquatic organisms, ultimately entering the human food chain. At the cellular level, the excessive production of reactive oxygen species by pesticides is considered as an important and effective factor in cellular damage [19,20].

3.1.2. Dyes

Dyes are one of the most widely used compounds in our industry and life, but the lack of natural dyes and advances in industrial dye technology have increasingly made people dependent on synthetic dyes. However, environmental pollution problems are also on the rise. The potential sources of this pollution include several industrial stages (such as sulfonation, nitration, diazotization, reduction, oxidation, and acidic deposition (salts)) and components of synthetic dyes (chromophore groups including aromatic structures, nicotine groups, nitrogen-containing groups, and anthraquinones, etc.). Dyes in water reduce light transmission and disrupt photosynthesis cycle of aquatic plants. Due to the presence of chemical groups (organic aromatic compounds with halogen, nitro, phenol, and amine groups), dye pollutants are often carcinogenic [21–23].

3.1.3. Polyfluoroalkyl

Polyfluoroalkyl substances (PFASs) are a group of water-soluble organic compounds that contain numerous fluorine atoms in an alkyl chain. PFAS compounds have been widely used in various industries, including food packaging, waterproof fabrics, waterproof sprays, Teflon, wax, dyes, and foams for the past 60 years. They can also be found in contaminated soil and water, typically associated with specific facilities, such as industrial plants where PFASs are produced or used to manufacture other products, oil refineries, airports, firefighting, or other locations where PFASs have been used. The most widely produced chemicals in this category are perfluorooctane sulfonate and perfluorooctanoic acid. These are fluorinated surfactants that are both hydrophobic and hydrophilic. PFOS and PFOA are persistent organic pollutants that do not degrade in the environment or in the human body and accumulate over time. There is evidence that exposure to PFASs can lead to thyroid disease (hypothyroidism), cancer (liver, testes, and pancreatic adenocarcinoma), high blood pressure during pregnancy, reduced antibody response to vaccines, asthma, decreased breast gland growth, low birth weight, decreased bone mineral density, and neurological developmental abnormalities [24–27].

3.2. Inorganic pollutants

Developing countries are concerned about the pollution of harmful chemicals such as nitrite, ammonium nitrate, and heavy metal ions in drinking water. High levels of nitrogen pollutants (nitrates, nitrites, ammonium) and mineral phosphates in river water caused by the discharge of water from agricultural farms and the release of urban/industrial wastewater can lead to many health problems. Nitrites are naturally carcinogenic and increase the risk of stomach, liver, and lung cancer and can lead to high levels of ammonium in the body [18,28].

3.2.1. Nitrate (NO_3)

Nitrogen in the forms of NO_3^-, NO_2^-, and NH_3^+ can be one of the most common pollutants in groundwater. In addition, nitrate is also found naturally in very low concentrations in groundwater. Nitrate has the ability to remain in groundwater and accumulate. Nitrogen is a vital element for plant growth, and farmers use many nitrogen fertilizers for better plant performance [29–31]. Excessive and incorrect use of fertilizers can cause an imbalance between plant uptake and the availability of nitrates, which ultimately wash away the excess fertilizer that is not used by plants and enter the water. On the other hand, human activities, waste disposal, sewage discharge, industrial effluent, contaminated sanitation services, landfill sites, and animal waste can cause nitrate-related pollution. An increase in nitrate concentration of more than 50 milligrams in water can cause health problems in humans and animals. The most oxidized chemical form of nitrogen in nature is NO_3-, which is found in natural systems and is an important component of living organisms such as DNA, RNA, hormones, proteins, vitamins, and enzymes. Therefore, the health consequences of exposure to high nitrates are a major concern. NO_3^- is not toxic, but it can be converted to nitrite in the human body, which can lead to health problems [29–31].

3.2.2. Heavy metal ions

Heavy metals are considered to be metals with an atomic number greater than 20 and an elemental density greater than 5 g per cubic centimeter, and are often assumed to be toxic even at very low concentrations (**Table 1**). Sources of heavy metal ions can be natural or anthropogenic. Natural water contains impurities of rare elements/heavy metals in solution. In addition, human activities such as the large-scale use of pesticides, fertilizers in agriculture, paints, and improper disposal of industrial and municipal waste add these metal ions to surface and groundwater. Although some of these metallic ions (such as zinc, copper, and iron) are essential for human health, an increase in their concentration can lead to water pollution and the creation of diseases such as cancer (testicular, uterine, breast, kidney, blood), high blood pressure, thyroid dysfunction, heart disease, mental retardation, and so on (**Figure 1**). Heavy metal pollutants include ion species Sb^{3-}, As^{3-}, Be^{2+}, Cd^{2+}, Cr^{3+}, Cu^{2+}, Pb^{2+}, Hg^{2+}, Ni^{2+}, Ag^{+}, and Zn^{2+}. **Table 1** shows the range of heavy metal ion levels in plants and regulatory standards for heavy metal ions in food and drinking water in different countries (Europe, India, Canada, and China) [4,32,33] .

Figure 1. Effects of heavy metal ions in water and their effect on the human body, as well as their permissible values according to the standard of the World Health Organization.

Table 1. Ranges of heavy metal ions content in plants and regulatory standards for heavy metals in food and drinking water in different countries (Europe, India, Canada & China) [32].

Metal ions	Amount measured in different plants (µg/g)	Indian standards		Canada (mg/kg)	World Health Organization (mg/kg)	China (mg/kg)
		Food (mg/kg)	Water (mg/L)			
As^{3-}	0.02-7	1.1	0.05	5	Nil	2
Cd^{2+}	0.1-2.4	1.5	0.01	0.3	0.3	1
Hg^{2+}	0.005-0.02	Nil	Nil	0.2	Nil	0.5
Pb^{2+}	1-13	2.5	0.1	10	10	10
Co^{2+},Co^{3+}	0.05-0.5	Nil	Nil	Nil	Nil	Nil
Cr^{3+},Cr^{6+}	0.2-1	20	0.05	2	Nil	Nil
Cu^{2+}	4.15	30	0.05	Nil	Nil	Nil
Fe^{2+},Fe^{3+}	140	Nil	0.03	Nil	Nil	Nil
Mn^{2+}	15-100	Nil	0.1	Nil	Nil	Nil
Ni^{2+}	1	1.5	Nil	Nil	Nil	Nil
Zn^{2+}	8-100	50	5.0	Nil	Nil	Nil

3.2.3. Halogens

Halides are usually the natural salts found in water, including chloride, fluoride, bromide, and iodide. These ions are highly soluble and exist in all natural water sources such as lakes, rivers, and underground water. The sources of halides include hard rocks, air pollution, industrial wastewater, pesticides, and fertilizers, among others. Chloride and bromide have a natural conservative behavior and their ratio is used as a source of salinity in coastal areas and underground water sources[34–37]. The conservative nature of these elements reduces their biological uptake and sedimentation. The maximum fluoride limit in drinking water should not exceed 1.5 mg/L according to the World Health Organization guidelines. Both low (<0.6 mg/L) and high (1.5 mg/L) concentrations of fluoride in groundwater have health effects. A very low concentration (<0.6) of fluoride in drinking water leads to dental caries, while consumption at higher concentrations (>1.5 mg/L) causes fluorosis with higher concentrations (>3 mg/L) leading to skeletal fluorosis [34–37].

3.3. New emerging water pollutants

The investigation of the adverse effects of new emerging water pollutants on ecosystems compared to traditional pollutants has received attention in recent years. Traditional water pollutants include F^-, NO_3^-, and heavy metal ions (Be^{2+}, Cd^{2+}, Cr^{3+}, Cu^{2+}, Pb^{2+}, Hg^{2+}, Ni^{2+}, Ag^+ and Zn^{2+}, etc.), while new emerging water pollutants include steroids and hormones, pharmaceuticals and personal care products, artificial sweeteners, surfactants, etc. These emerging pollutants are added to our environment daily, and their primary source is the by-products of our modern lifestyle. We use chemical products every day, and these chemicals remain in wastewater due to the lack of appropriate sewage treatment [18,38,39].

3.3.1. Medicines and personal care products

Recently, due to the continuous presence of pharmaceuticals and personal care products (PPCPs) in aquatic environments, they have been recognized as emerging pollutants. PPCPs are released into the environment through various sources, including household sewage, wastewater treatment plants, and hospitals. Among them, hospital wastewater often shows a high frequency and concentration of drugs. It is possible that pollutants released from a source to the aquatic environment may maintain their initial concentration and structure, or their structure may change and convert to active or inactive forms throughout their lifetime. In addition, significant amounts of pharmaceutical products, including anti-inflammatory drugs and antibiotics, do not even pass through wastewater treatment but directly enter the water surface. PPCPs have been classified into several categories based on their characteristics and applications. Drug classes include antibiotics, painkillers, steroid hormones, anti-inflammatory drugs, statin regulators, and more. While types of personal care products (PCPs) include perfumes, antibacterials/disinfectants, insect repellents, preservatives, and sunscreens[40–42].

3.3.2. Artificial sweeteners

As the newest group of emerging pollutants, artificial sweeteners are widely used as low-calorie sugar substitutes in many foods and beverages. Examples of these compounds include saccharin, aspartame, sucralose, and cyclamates. Some of them, such as aspartame, are heat-stable and are used in soft drinks with long expiration dates due to their high durability in liquids. In addition, a particular group of sweeteners that are created by the human body cannot be broken down, and their accumulation in surface waters is highly dangerous [43,44].

3.3.3. Surfactants

Surfactants (surface active agents) are another diverse group of chemicals that have a polar head soluble in water and a non-polar hydrocarbon tail insoluble in water. Surfactants have high solubility and cleaning abilities, which have given them a higher ranking among cleaning agents and other detergents. Surfactants are used in various industries and daily household products, which leads to their increased dispersion in soil, water, sediment, and so on[45,46]. Surfactants are classified into cationic, anionic, nonionic, and amphoteric, based on the charge on their head. The most common and oldest type of surfactants is anionic surfactants, which are usually found in regular detergents or soaps. Quaternary ammonium compounds are the most commonly used cationic surfactants. They are mainly used in hair conditioners, fabric softeners, and detergents. According to studies, the best surfactants are amphoteric aminoxide surfactants. AO is also used in the textile industry, rubber industry, and deodorant sticks, respectively, as antistatic agents, floor fixatives, polymerization catalysts, and antibacterial agents. Non-ionic surfactants are mostly used in various biotechnological processes and in facilitating drug carrier dissolution and increasing stability[45,46].

3.4. Radioactive pollutants

Radioactive materials naturally come from the Earth's crust and settle on the ground surface, and dissolve in drinking water. Generally, radioactive materials from the remnants of uranium extraction, nuclear fusion derivatives, nuclear weapons tests, medical research, and accidental leaks and explosions in nuclear reactors and industrial effluents are the source of radioactive pollution in water[47,48]. Radioactive materials present in drinking water can cause various health hazards such as cancer, radiation sickness, and genetic mutations. Radioactive pollution in water can be controlled by using advanced water treatment processes such as reverse osmosis, ion exchange, and adsorption. Additionally, regular monitoring and testing of water sources are necessary to prevent and control radioactive pollution[47,48].

3.5. Pathogens

Pathogens, including bacteria, viruses, fungi, and some parasites, are small microorganisms that cause disease. Generally, the viruses present in sewage are mainly viral hepatitis, and the pathogenic fungi *Candida* are among their common pathogens [49–51]. Disease-causing agents enter water through various sources such as sewage discharge. Viruses and bacteria found in industrial wastewater, such as *Cryptosporidium*, *Campylobacter*, *Salmonella*, and *Shigella*, can lead to waterborne diseases. Waterborne diseases such as cholera, typhoid, dysentery, polio, and hepatitis are among the common diseases caused by microbial pollutants in humans. Microbial contamination with heterotrophic bacteria is more common in lake water. Some studies have shown that contamination with *Escherichia coli* and *coliform* bacteria in untreated stagnant sewage exceeds the permissible limit, creating a high level of pathogenic factors in the aquatic ecosystem. Some common examples of pathogens found in water include coliforms, *E. coli*, fecal coliforms, and fecal streptococci, which are caused by fecal contamination. It is interesting to note that sewage pathogens can lead to serious gastrointestinal diseases [49–51]. Types of sources of water pollutants shows in the **Figure 2**.

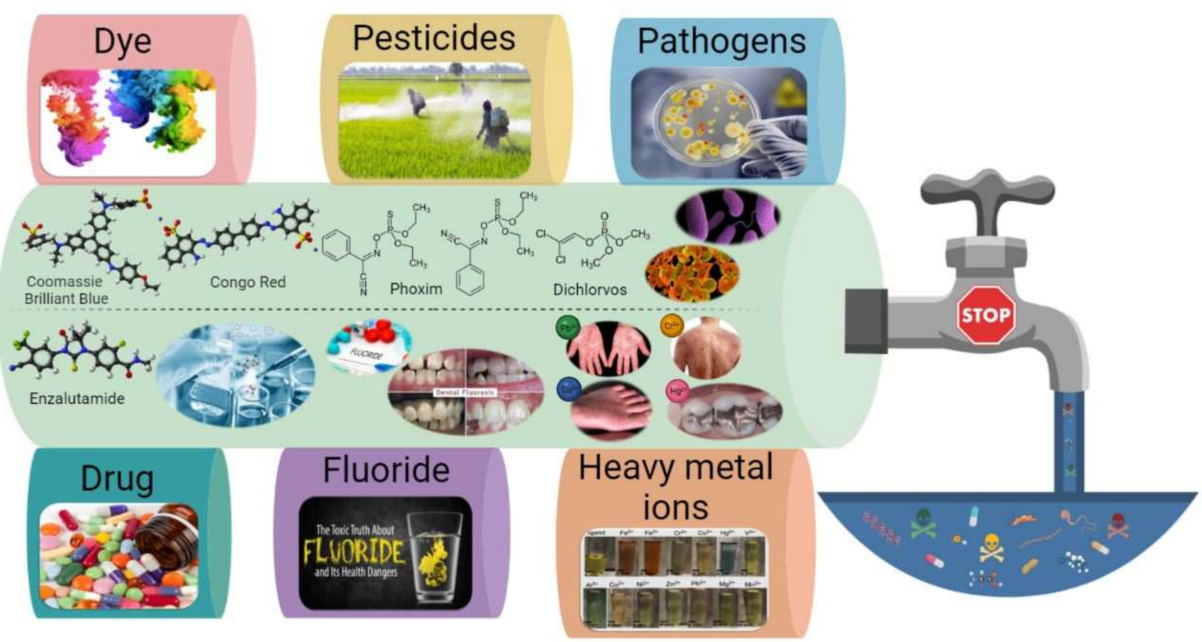

Figure 2. Some Common Water Pollutant Sources

4. Common methods for treating polluted/wastewater

Today, pollution control is a general concern and challenge for the years to come. Therefore, focusing on water treatment towards implementing an efficient and cost-effective method that enables resource recovery is of considerable importance. In recent decades, various technologies have been developed to remove water pollutants, such as physical, chemical, and biological processes, to increase the potential of water resources, reduce challenges, and concerns related to water pollution.

4.1. Chemical methods

Chemical treatment refers to a set of processes in which chemical substances and reactions are used for water treatment. One of the main wastewater treatment methods is injecting chemicals into the wastewater and separating pollutants from it. These include solvent extraction, ion exchange, neutralization, adsorption, chemical precipitation, electrochemical oxidation, and photocatalytic degradation.

4.1.1. Solvent extraction

Solvent extraction or liquid-liquid extraction is used to separate aromatic compounds (e.g., in the petrochemical industry) and metal ions from aqueous solutions (**Figure 3a**). Separation is based on the relative solubility of the pollutant in two different immiscible or partially miscible solvents, generally a polar (water) and non-polar (an organic solvent) solvent. In this method, salts are transferred from one polar solvent to another non-polar solvent or vice versa. The solvent extraction process is widely used in chemical and mining industries and also in the treatment of fermentation products, such as antibiotics, amino acids, and steroids. Solvent extraction is often used on a large scale for wastewater treatment. Despite its effectiveness, this method has limitations such as the release of fugitive organic compounds, the use of toxic solvents, the fire hazard of flammable solvents, the need for high investment in equipment, and the fact that they are not cost-effective for pollutants with concentrations less than 0.5 g/L [52].

4.1.2. Ion exchange

Ion exchange is a reversible exchange method between an insoluble solid phase and a liquid phase (**Figure 3b**). The solid phase in the ion exchange method can be a crystalline network or gel. If the exchanged ions are positive, it is called a cation exchange; if the ionic species have a negative charge, it is called an anion exchange. Using a cation exchange resin, cations such as Ca^{2+}, Mg^{2+}, Ba^{2+}, Sr^{2+}, and Ra^{2+} can be separated from an aqueous solution. Similarly, using an anion exchange resin, anions such as F^{-}, AsO_3^{2-}, NO_3^{2-}, SeO_3^{2-}, CrO_4^{2-}, and humic and fulvic acids can be removed. This approach is used in various fields, including water treatment, medical research, food processing, mining, agriculture, etc[53].

4.1.3. Neutralization

Neutralization is a common method used in water and wastewater treatment and is employed in many processes. Chemical neutralization is used to balance the acidic and basic properties of excess substances in water and wastewater. Generally, chemical neutralization is used as a pre-treatment before a wide range of biological, chemical, and physical treatment processes, as many chemical treatments (such as coagulation, flocculation, and adsorption) are pH-dependent processes. There are two suitable methods for neutralizing overly acidic or alkaline water, which include adding CaO, $Ca(OH)_2$, $NaOH$, and Na_2CO_3 to acidic water, and adding H_2SO_4 and H_2CO_3 to alkaline water[7].

4.1.4. Adsorption

Adsorption is one of the most effective methods for removing toxic organic and mineral compounds from polluted waters. The advantages of this method over others include simplicity in design, low cost, ease of use, and insensitivity to toxic pollutants. Adsorption is a common phenomenon in which the mechanism for removing pollutants occurs on the surface of the absorbent [4,11,54]. When an aqueous solution containing pollutants comes into contact with the surface of a porous absorbent, intermolecular forces between the liquid and solid lead to the adsorption and/or precipitation of some pollutant molecules on the surface of the absorbent. In adsorption processes, the falling of pollutant molecules on the solid surface is called adsorption, while the substances that absorb pollutants are known as adsorbents. The exact nature of adsorption depends on the type of forces between the adsorbent and the adsorbate. In general, adsorption is classified into two categories: chemical and physical adsorption, with chemical adsorption involving the forces of multi-capacity forces and physical adsorption involving intermolecular forces (such as van der Waals forces). The influential parameters for adsorption of pollutants include the pH of the aqueous solution, the amount of adsorbent, contact time, initial pollutant concentration, and temperature [55–58]. Optimizing these parameters can have a significant effect on improving the removal of pollutants [4,54,59].

4.1.5. Chemical precipitation

Chemical precipitation is the removal of dissolved and suspended substances from water using chemicals (**Figure 3c**). This process involves two stages: coagulation and flocculation, which require a sedimentation stage to complete. In the first stage, coagulation, the neutralization of charge occurs through a chemical reaction between coagulant chemicals and colloidal particles, resulting in closer proximity of particles to each other and the formation of larger jelly-like particles[60–62]. Typically, metal compounds such as aluminum or iron are used to remove colloidal materials from water and wastewater. Metal salts that enter the water as coagulants hydrolyze into ionic or charged hydroxides. Examples of coagulants include aluminum sulfate, sodium aluminate, ferric sulfate, ferric chloride, and polyaluminum chloride. Additionally, coagulant aids can be used to help in the coagulation stage. Coagulant aids create bridges between tiny flocs formed by coagulants, causing them to come together as larger, heavier flocs, accelerating the sedimentation process. They also expand the optimal pH range and decrease the amount of coagulant used. The second stage, flocculation, involves gentle mixing of the suspension to increase contact between particles, resulting in the aggregation of colloidal particles and their conversion into larger flocs with better settling ability. The coagulation/flocculation process can be used as a primary or intermediate stage between other treatment processes such as filtration and sedimentation to enhance particle removal and process efficiency. It offers several advantages, including simplicity and low cost, and can separate or remove various types of particles, improving filtration processes and using inexpensive chemical reagents. However, it may also produce large amounts of sludge, requiring proper disposal or treatment[60–62].

4.1.6. Electrochemical oxidation

Electrochemical oxidation is currently a good alternative to conventional methods for treating wastewater containing toxic compounds (**Figure 3d**). In the electrochemical process, an electric field between anode and cathode electrodes is used to remove various pollutants. The efficiency of electrochemical methods is generally related to the nature of the selected anode and electrode material. Electrochemical oxidation is one of the most commonly used electrochemical methods, which has been successfully used for mineralization of stable organic compounds and biorefractory compounds present in water[63,64]. In chemical oxidation approaches, pollutants are oxidized on the surface of the anode through both direct and indirect oxidation mechanisms. Direct oxidation of pollutants on the anode requires suitable electrodes to reach strong oxidation conditions, which generally exhibit additional potentials. Indirect electro-oxidation is carried out by producing OH radicals from water on the anode surface. Electrochemical oxidation has been used to remove oxygen demand and color from wastewater. This method has advantages such as high operational efficiency, small equipment size requirements, minimal sludge production, and rapid start-up[63,64].

4.1.7. Photodegradation

Photodegradation is one of the potentially important methods for removing pesticides, colors, pharmaceuticals, and organic compounds from water and wastewater (**Figure 3e**) [65]. This process mainly occurs by photolysis or photocatalytic oxidation. Photolysis is a process in which pollutants dissolved in water absorb ultraviolet (UV) or visible light. In photolysis, radiation causes photochemical transformations, while photocatalytic oxidation (or photocatalysis) leads to the degradation of pollutants through interaction with hydroxyl radicals (OH) or similar oxidants. The efficiency of the photocatalytic process depends on operational factors such as the initial concentration of pollutants, the type and amount of photocatalyst used, and the intensity of light. This process has several advantages such as no chemical addition, complete mineralization of pollutants, and easy operation[65].

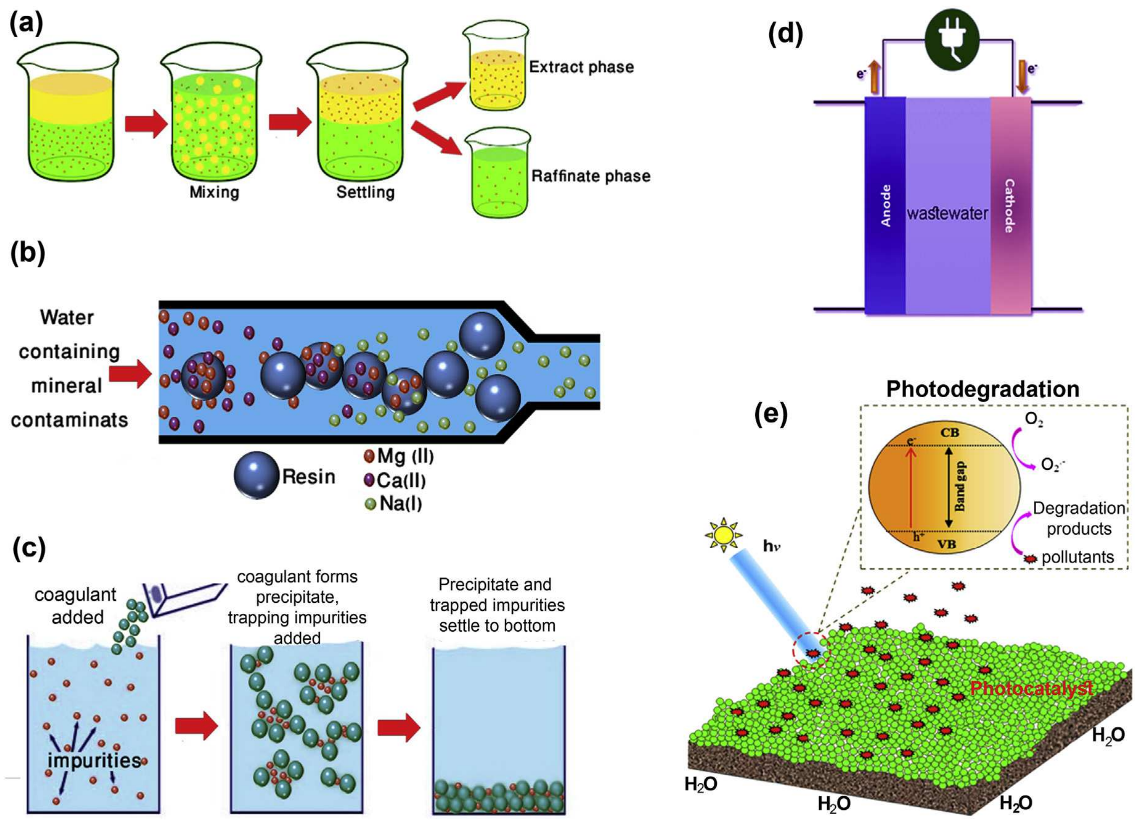

Figure 3. Types of chemical water treatment methods: solvent extraction (**a**), ion exchange (**b**), chemical precipitation (**c**), electrochemical oxidation (**d**), and photodegradation (**e**). Reprinted with permission from ref [7].

4.2. Physical water treatment

Physical water treatment refers to a set of methods that are used to purify water using physical properties and physical forces. Some of these methods include distillation, sedimentation, membrane filtration, microfiltration (ultrafiltration, nanofiltration, reverse osmosis). It should be noted that in this method, only large-sized solid particles in industrial wastewater can be removed, and it has no effect on organic and inorganic materials, bacteria, and microorganisms.

4.2.1. Distillation

Distillation may be the oldest and simplest method for water treatment, which can remove various types of pollutants, bacteria, mineral and organic compounds, except for volatile substances (some organic compounds such as ethanol and acetone) from water (**Figure 4a**). It uses a source of heat to evaporate and separate water from unwanted substances. In this method, contaminated water is heated to boiling point and then water vapor is directed to a condenser to be cooled, collected, and finally stored. This method can successfully remove many impurities, such as mineral compounds like sodium, magnesium, and lead, nitrates, and other annoying particles like iron and some rare metals, microbial pollutants such as microorganisms like gram-negative and positive bacteria and fungi. Most pollutants such as mineral compounds and non-volatile large organic molecules remain in the primary container. This method is very slow and has some drawbacks such as being unusable for removing organic compounds with boiling point below 100 degrees Celsius and high energy consumption for heating[66,67].

4.2.2. Sedimentation

Sedimentation (or clarification) is one of the oldest physical methods used as the initial stage of water treatment processes (**Figure 4b**). It uses gravity force to separate suspended particles such as clay in water. The efficiency of the sedimentation process depends on factors such as particle size, particle shape, particle density, and water temperature. The bottom of the container in which water is stored will collect the precipitated particles. This method is not effective in removing dissolved substances, such as organic and inorganic compounds, and microorganisms. It is often used in conjunction with other methods such as filtration to improve the overall efficiency of water treatment[68].

4.2.3. Membrane filtration

Membrane filtration involves the use of a thin semipermeable membrane to separate contaminants from water based on particle size or charge. There are different types of membrane filtration methods such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis, which are classified based on the size of particles they can remove. This method is effective in removing various types of impurities, including organic and inorganic compounds, bacteria, and microorganisms. However, it requires high energy consumption and maintenance costs. It is often used in conjunction with other methods such as sedimentation and coagulation to improve the efficiency of water treatment. Membrane filtration is a process that uses artificial membranes to separate pollutants from contaminated sources (**Figure 4c**). In fact, membranes are selective barriers for removing two different phases using an external barrier. Driving forces such as pressure, electrical and chemical potential, and temperature are used. This approach is a physical separation method without any change in the phase or addition of chemicals to the feed stream, so it has the potential to be a suitable replacement for common processes such as ion exchange, biological treatment, distillation, and precipitation. This method has advantages such as reduced processing stages, low energy consumption, good separation efficiency, and high quality of the final water. Various membranes with significant performance improvements have been developed and distributed worldwide, with some of the most common polymer materials used in membrane preparation technology mentioned in **Table 2**. Four types of commercialized membrane filters for water treatment include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis. In fact, due to the difference in membrane pore size in these systems, they can be used for various applications [69].

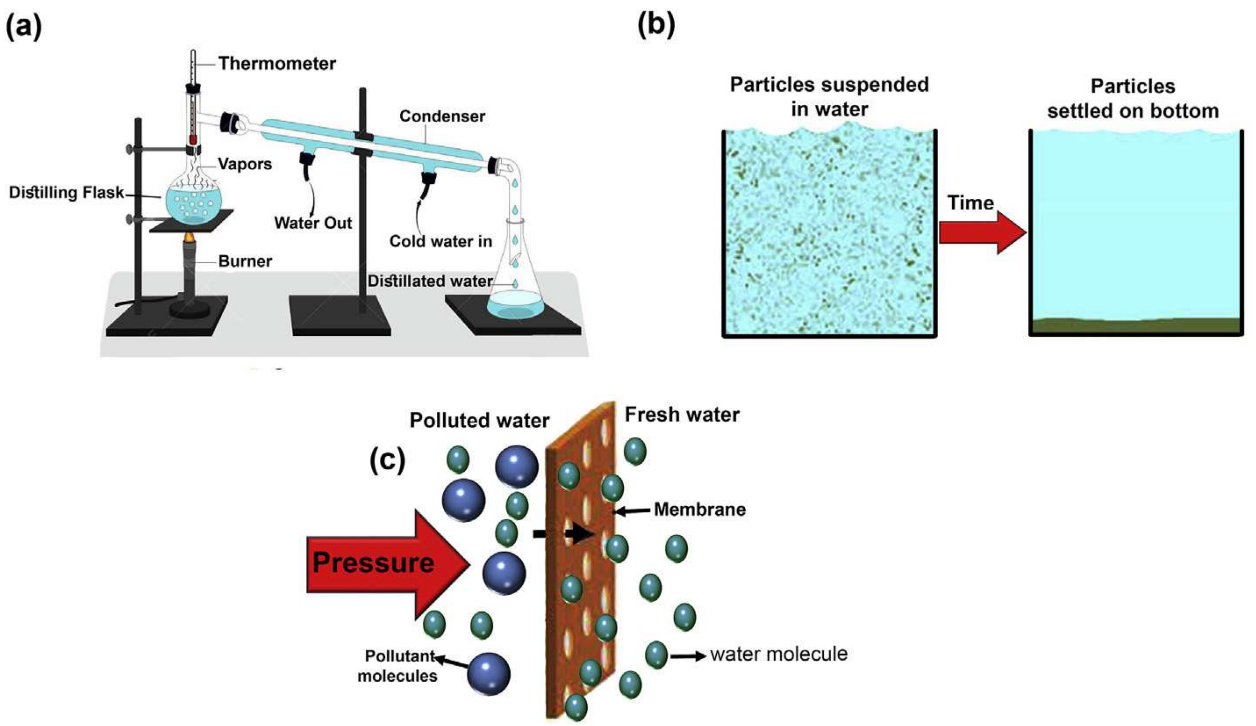

Figure 4. Types of physical methods for water treatment: distillation (**a**), sedimentation (**b**), and membrane filtration (**c**). Reprinted with permission from [7].

4.3. Biological treatment

Biological methods are one of the most important methods for treating water/wastewater (**Figure 5**). The biological process can be classified into aerobic and anaerobic. This method removes bacteria and microorganisms present in chemical wastewater without adding chemicals. However, these processes are not sufficient for water and wastewater treatment, and other treatment methods such as chemical and physical treatment are required. Anaerobic conditions (in the absence of oxygen) and aerobic conditions (in the presence of oxygen) are related to the type of bacteria or other microorganisms (such as algae and fungi) that play a role in the degradation of pollutants in wastewater [70,71]. In biological treatment methods, the removal of pollutants takes place through biological activities. The biological treatment method is based on the growth of microorganisms in wastewater. Organic and nitrogen compounds present in wastewater are used as nutrients for rapid microbial growth in aerobic, anaerobic, or facultative conditions. These three types of conditions differ in their use of oxygen. Aerobic microorganisms require oxygen for their metabolism, while anaerobic microorganisms grow in the absence of oxygen, and facultative microorganisms reproduce in the presence or absence of oxygen. Although these two processes have different metabolic processes, the major microorganisms present in wastewater treatment systems use the materials present in wastewater as a source of energy and growth. Therefore, they are known as heterotrophic microorganisms. The active population in a biological wastewater treatment system is a complex mixture of microorganisms that depend on each other for growth and nutrition [70,71].

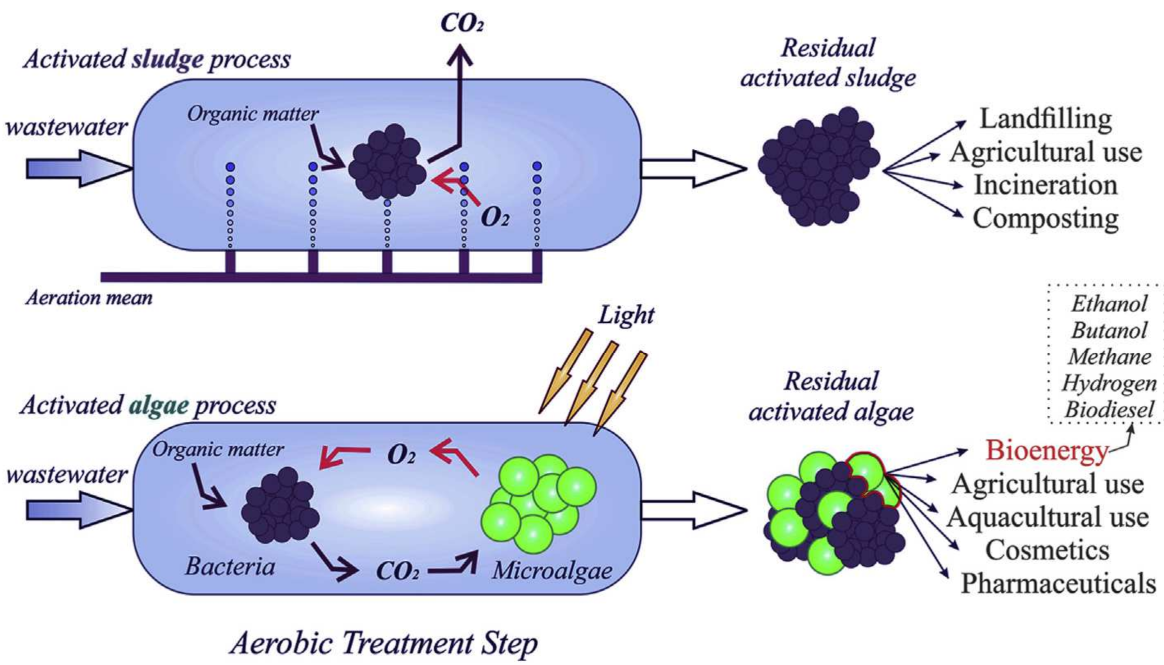

Figure 5. Schematic of biological wastewater treatment. Aerobic processes can occur in the active algal system without mechanical aeration because oxygen is produced through photosynthetic processes, the carbon dioxide released during wastewater treatment is used in photosynthesis by microalgae, and residual microalgae Biomass can be used in a wide range of applications. Reprinted with permision from [7].

Table 3. Some advantages and disadvantages of techniques used for wastewater treatment. Reprinted with permission from [72].

Water treatment methods	Advantages	Disadvantages
Oxidation	Fast process for removal of toxic pollutants without the need for pre- or post-treatment processes	High energy costs and production of byproducts
Ion Exchange	Effective removal of a wide range of heavy metals and colors with minimal energy requirements	High operational and chemical costs, sensitivity to fouling
Membrane Filtration	Technologies Effective removal of heavy metals and colors	Production of thick, expensive sludge, requires periodic cleaning
Coagulation/Flocculation	Economically viable	High sludge production and formation of large particles
Electrochemical Treatment	Fast and effective process for removal of specific metal ions	High energy costs and production of byproducts
Photochemical Treatment	No sludge production	Formation of byproducts
Biological Treatment	Possible for removal of some metals	Technology has not yet been developed and commercialized
Adsorption	Ease of use, low cost, can treat nearly 100% of water	Adsorbents require regeneration

5. Environmental regulations

A synopsis of the legislation enacted from 1974 and 1986 in an effort to safeguard water and the environment. The Waste Management Act took into account both the generation of waste and the accessibility of useful supplies. Standards for pollutants were used to establish regulations. There are regulations in place governing the maximum allowable waste produced by various entities. The possibility of taking minimal precautions during waste disposal is also taken into account. Parliament approved the water law (Prevention and Control of Pollution) in 1974 as a preventative step against the risks of liquid pollution from industry. Since water was a state that necessitated the adoption of the same legislation in all nations, this Act was not enacted by all provinces until 1990. Each state will have its own Water Pollution Prevention and Control Board to carry out the Act's provisions and enforce pollution regulations. The nation's minimum requirements have been established. The LSS serve as the foundation for the integrated standards.

The Air (Prevention and Control of Pollution) Act was approved by parliament in 1981 to address air pollution. Several boards were necessary to ensure this. In a same vein, "Boards" became "Pollution Control Boards" (PCB). The former Central Board is now known as the Central Pollution Control Board. The Environment Protection Act (EPA) was approved by parliament in 1986. The Department of Environment and Forestry's primary action authorizes national governments to undertake this action. The EPA sets pollution and fluid limits for certain industrial sectors. Some parameters differ from MINA. PCBs usually survive in companies that follow these two requirements.

6.New pollutant detection techniques

Previous studies showed that growing chemical or microbiological contaminants were likely released to the environment for quite some time, but might not have been recognized until new detection tools were created. Metal analysis, as well as other spectroscopic and chromatographic procedures, can be used in the detection processes. Chromatographic techniques are the gold standard for compound detection and identification in almost any sample type. Liquid chromatography (LC) is used in the investigation of nonvolatile, polar, and thermolabile contaminants, whereas gas chromatography (GC) is utilized in the investigation of nonpolar, thermostable, and volatile ones, including flame retardants, filters, and some insecticides.

7. Conclusion and perspective

Water pollution is a major environmental problem that needs to be addressed urgently. The presence of various pollutants, both organic and inorganic, poses a significant threat to the health and wellbeing of humans and aquatic life. However, with the development of advanced treatment technologies, it is now possible to remove these pollutants effectively from water resources. Treating polluted or wastewater through chemical, physical, and biological methods is essential to ensure the safety and health of individuals and the environment. Each method has distinct advantages and limitations, and it largely depends on the type of pollutants present in the water.

The chemical method involves the use of chemicals to precipitate the contaminants, which is fast but can cause secondary pollution. Physical methods include filtration, sedimentation, and adsorption, which are highly effective but may require significant amounts of time and resources to complete the process. Biological methods, on the other hand, utilize microorganisms to degrade pollutants and are environmentally friendly but may be time-consuming.

In perspective, the future of wastewater treatment will involve a combination of these methods, taking into account the type and quantity of pollutants present, the efficiency of the process, and the environmental impact. Technological advances will enable the implementation of innovative and eco-friendly methods to treat wastewater. Additionally, there will be a greater emphasis on resource recovery from waste water, such as the extraction of energy, nutrients and the reuse of water.

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Declaration of competing interest

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