

Review

Drinking Water Contaminants and Advanced Purification Technologies: A Review of Conventional and Emerging Treatment Approaches

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Abstract

Freshwater contamination has become a critical global challenge, driven by industrialization, urbanization, agriculture and climate change, threatening safe drinking water and sustainable development. This review synthesizes peer-reviewed literature identified through targeted searches of major bibliographic databases, including Scopus, Web of Science Core Collection and PubMed, with Google Scholar used as supplementary search tool, using contaminant- and technology-specific keywords. Conventional treatment processes, including coagulation–flocculation, sedimentation, filtration, adsorption, activated carbon, ion exchange and chemical disinfection, are critically evaluated alongside advanced technologies such as membrane filtration, reverse osmosis, nanofiltration, advanced oxidation processes (including photocatalysis), electrochemical treatment and nanotechnology-based systems, with emphasis on mechanisms, removal efficiency and operational limitations. Evidence indicates that adsorption-based technologies (GAC/PAC) achieve up to 97% removal of long-chain PFAS following advanced regeneration, coagulation–sedimentation removes up to 95% of microplastics, and precipitation-based processes achieve 70–99% removal of heavy metals, yet no single technology addresses the full contaminant spectrum across varying water quality conditions. Integrated multi-barrier systems combining conventional and advanced technologies therefore provide the most effective and sustainable approach for producing safe drinking water. The review also examines emerging trends, including smart water treatment systems, advanced functional materials, renewable energy integration, and circular water management and identifies key research gaps and priorities for cost-effective, energy-efficient and resilient purification technologies essential to global water security and supporting the achievement of Sustainable Development Goal 6 (Clean Water and Sanitation).

Keywords: water purification technologies; contaminant removal; advanced oxidation processes; emerging contaminants; sustainable water treatment



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1. Introduction

1.1. Global Access to Safe Drinking Water

Freshwater is a finite and invaluable resource, essential for sustaining life, economic development, and ecosystem stability. Despite decades of policy interventions and in-

frastructure investments, access to safe drinking water remains a pressing global public health challenge. Approximately 2.1 billion people lack safely managed drinking water services, including over 100 million relying directly on untreated surface water for daily consumption [1].

These gaps disproportionately affect rural populations, low-income countries, and vulnerable groups such as children, elderly, and marginalized communities. For instance, in Sub-Saharan Africa and South Asia, rural populations often walk long distances to collect water from unprotected sources, while urban slums face intermittent or unreliable municipal water supply. Even in high-income countries, pockets of populations experience water insecurity during infrastructure failures, natural disasters, or contamination events [2].

Global coverage of improved water sources has increased over the past decades, yet progress remains uneven. Rural areas improved from approximately 50% to 60% coverage between 2015 and 2024, while urban access has largely stagnated. Persistent disparities in access are driven by socio-economic inequalities, geographic isolation and infrastructural limitations. Achieving Sustainable Development Goal 6 (SDG6) by 2030 therefore requires accelerated investment and context-specific strategies to ensure reliable and equitable water services [3].

1.2. Health Impacts of Unsafe Drinking Water

Unsafe drinking water continues to be a major contributor to preventable illness and mortality worldwide as mentioned in Figure 1. Global estimates indicate that at least 2 billion people consume water that does not meet safe drinking standards, exposing populations to diseases such as diarrhea, typhoid, intestinal worms, and gastroenteritis [4]. Diarrheal diseases alone are estimated to cause approximately 505,000 deaths annually, with children under five disproportionately affected.

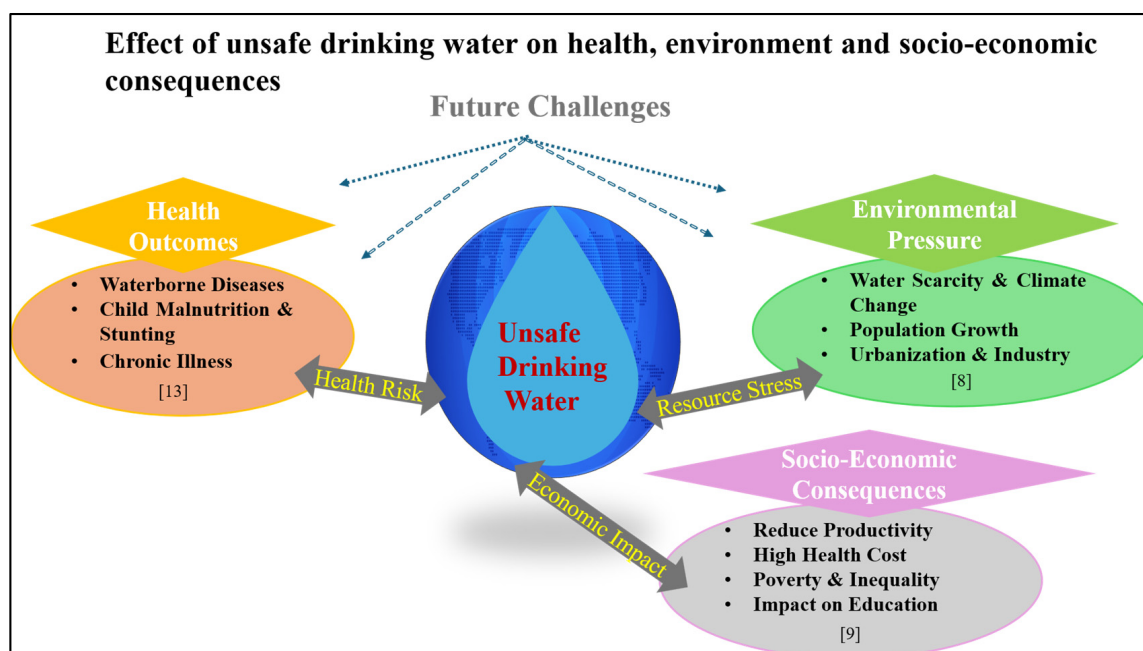


Figure 1. Schematic representation of unsafe drinking water effect on different factors (created with BioRender.com and power point).

Repeated exposure to unsafe water contributes to long-term health outcomes, including nutritional deficiencies, stunting, impaired cognitive development, and increased susceptibility to chronic diseases later in life. Repeated exposure to unsafe water contributes to long-term health outcomes, including nutritional deficiencies, stunting, impaired cognitive

development, and increased susceptibility to chronic diseases later in life. In developing countries, where groundwater is often the primary source of drinking water, contamination disproportionately drives this burden: the vast majority of the estimated 1.4 million annual deaths attributable to unsafe drinking water, sanitation, and hygiene occur in low- and middle-income countries [5]. Even mild or intermittent exposure to unsafe water can exacerbate malnutrition, particularly when coupled with food insecurity, undermining human development and life expectancy in affected regions.

1.3. Water Scarcity and Environmental Pressures

Water scarcity compounds the risks to safe drinking water access as mentioned in Figure 1. Over 2 billion people live in water-stressed countries, a burden projected to intensify due to climate change, population growth, and increased competition among agriculture, industry, and households. Climate variability has increased the frequency and severity of droughts and extreme weather events, reducing precipitation, lowering reservoir levels, and affecting river flows. Nearly 74% of natural disasters between 2001 and 2018 were water-related, highlighting the vulnerability of communities to hydrological shocks [6].

Rapid urbanization and industrial expansion further strain water availability. Groundwater overextraction, coupled with population growth, reduces sustainable water yields. Agriculture, which consumes up to 70% of global freshwater in many regions, competes with human consumption and industrial needs, especially in arid and semi-arid zones [7]. Consequently, ensuring reliable water access requires integrated management that considers hydrological cycles, seasonal variability, and equitable distribution across sectors and communities [8].

1.4. Socio-Economic Consequences of Unsafe Water

The socio-economic impacts of inadequate water access are profound as mentioned in Figure 1. Limited availability of safe water increases the burden of disease, resulting in higher healthcare costs, decreased workforce productivity, and slowed economic development [9]. In low-income regions, children exposed to unsafe water experience malnutrition, stunting, and impaired cognitive development, which can reduce future earning potential.

Women and girls bear a disproportionate burden in water collection, often traveling long distances daily, which limits access to education, employment opportunities, and social engagement, reinforcing cycles of poverty and gender inequality [10]. At the national level, water insecurity impairs economic growth, increases social inequities, and can exacerbate conflicts over resources. Globally, inadequate water supply and sanitation contribute to approximately 1.4 million deaths annually and are strongly linked to malnutrition and poverty.

1.5. Global Outlook and Policy Considerations

Looking forward, global water security is challenged by demographic trends, environmental pressures, and governance limitations [11]. Rising urban populations, industrialization, and increasing agricultural demands will further stress freshwater systems. Climate change is projected to reduce water availability in already water-scarce regions and increase competition for remaining resources.

If current trends continue, a substantial portion of the world's population will remain without safely managed water and sanitation services by 2030, undermining SDG targets for health, poverty reduction, and inequality. Effective governance, equitable water allocation, and sustainable management practices will be essential to prevent worsening health outcomes and socio-economic disparities.

1.6. Aim of the Review

This review primarily focuses on assessing the challenges to drinking water safety by examining the occurrence of various contaminants in freshwater sources. It aims to provide a comprehensive analysis of the different types of biological, chemical, and physical contaminants that threaten human health, as well as the technological and methodological approaches developed to mitigate these risks. By exploring the effectiveness, advantages, and limitations of diverse water treatment and purification strategies, the review highlights how these solutions can enhance access to safe drinking water. Ultimately, this work contextualizes the critical importance of addressing water contamination for public health, socio-economic development, and the achievement of sustainable development goals.

While several reviews have separately addressed drinking-water contaminant sources or purification technologies, most treat these as parallel, loosely connected discussions and do not explicitly link contaminant class to the treatment best suited to remove it. This review addresses that gap by organizing purification technologies according to their position in the treatment train; primary/secondary, tertiary/polishing, disinfection, and advanced/emerging treatment; rather than by arbitrary categories of technological sophistication, and by discussing, for each contaminant class, which treatment stage(s) offer the highest removal efficiency and why. This framework is intended to serve both as a critical synthesis of current evidence and as a practical reference for technology selection in real-world treatment-train design.

1.7. Literature Search and Critical Synthesis Approach

This review was conducted as a non-systematic synthesis of scientific literature addressing drinking-water contaminants and conventional, advanced and emerging purification technologies. The literature search was designed to identify relevant and representative scientific evidence rather than to undertake an exhaustive systematic review or quantitative meta-analysis. Search was conducted using major bibliographic databases, including Scopus, Web of Science Core Collection and PubMed, while Google Scholar was used as a supplementary search tool to identify additional relevant publications and potentially overlooked studies. Reference lists of key publications were also examined to identify relevant foundational studies and complementary evidence.

The search strategy combined contaminant-specific terms, including heavy metals, arsenic, lead, nitrate, fluoride, PFAS, microplastics, pharmaceuticals, pesticides, pathogens, and disinfection by-products, with technology-specific terms, including coagulation, sedimentation, adsorption, activated carbon, membrane filtration, reverse osmosis, nanofiltration, advanced oxidation processes, ozonation, photocatalysis, electrochemical treatment and nanotechnology. These terms were combined with the terms “drinking water treatment” and “drinking water purification” using appropriate Boolean operators. The search focused primarily on recent scientific literature while retaining earlier publications when they provided foundational evidence, established treatment mechanisms, or information that remained directly relevant to current drinking-water treatment practices.

Because this study is a non-systematic review, a formal PRISMA-style numerical screening and selection process was not undertaken and no predetermined number of studies was targeted for inclusion. Accordingly, the numbers of studies identified, screened and excluded were not formally recorded. Instead, the body of literature considered in this review was determined iteratively according to scientific relevance, evidential value, methodological clarity and contribution to the objectives of the review. Studies were considered particularly relevant when they addressed drinking-water applications and provided quantitative information on contaminant removal, treatment mechanisms, operational conditions, comparative performance, limitations, scalability, or environmen-

tal implications. Literature focused exclusively on unrelated wastewater or industrial process-water applications was generally excluded from the discussion unless the findings were directly applicable to drinking-water contamination, treatment mechanisms, or technology development.

A qualitative assessment of study quality and strength of evidence was applied during the critical synthesis. The selected literature was evaluated with respect to the quality and strength of the available evidence. Attention was given to the adequacy of contaminant characterization, clarity of experimental or operational conditions, appropriateness of analytical methods, reporting of treatment performance, reproducibility of the reported findings, consideration of water-matrix effects and discussion of operational, environmental and practical limitations. Greater interpretive weight was given to studies providing well-characterized experimental conditions, quantitative removal data, mechanistic evidence, comparative assessments, pilot- or full-scale validation, or information relevant to practical drinking-water treatment. Where substantially different removal efficiencies were reported among studies, the results were interpreted in relation to differences in contaminant concentration, water matrix, pH, treatment dose, contact time, operating conditions, analytical methods and treatment scale rather than being treated as directly comparable performance values.

The review primarily emphasizes publications from 2017 to 2026 to capture recent developments in drinking-water purification technologies. However, the publication year was not applied as an absolute exclusion criterion. Earlier studies were retained where their findings represented foundational knowledge, established treatment mechanisms, or scientifically important evidence necessary for understanding current technologies. Accordingly, the reference base includes selected publications predating 2017 where their continued scientific relevance was necessary for establishing foundational knowledge, treatment mechanisms, or other evidence directly supporting the critical assessment presented in this review.

2. Types of Contaminants

There are different types of contaminants that affect drinking water are also mentioned in Figure 2.

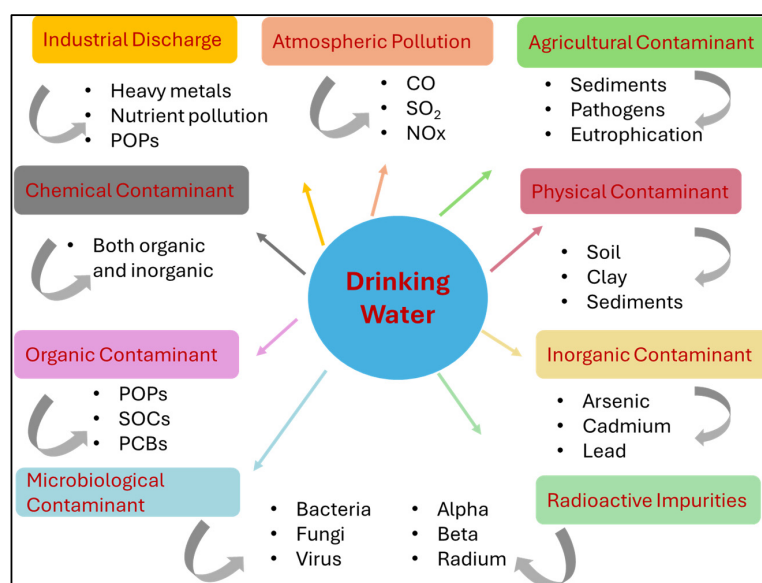


Figure 2. Illustration of different sources and categories of drinking water contaminants (created with BioRender.com and power point).

2.1. Contaminant Classes

2.1.1. Physical Contaminants

Physical contaminants are primarily responsible for altering the visual and aesthetic characteristics of drinking water, including turbidity, color, taste, odor, and temperature as mentioned in Table 1 [12]. Although they are often not directly toxic, their presence can significantly influence water quality and safety by facilitating the transport of harmful microorganisms and chemical pollutants.

Table 1. Overview of physical contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
Turbidity	Reduce water clarity, interferes with UV penetration and disinfection efficiency.	Silt, clay, organic matter, plankton and microorganisms.	Increase the risk of waterborne disease by protecting the pathogenic microorganisms from disinfections process. It also leads to higher exposure to gastrointestinal infections and other microbial illnesses.	[13]
Color	Alters the aesthetic quality of water.	Natural organic matter, decaying vegetation and industrial effluents.	Indicates the presence of hazardous organic compounds, heavy metals, or industrial pollutants that cause chronic health effect including toxicity, and carcinogenic risk.	[14]
Odor	Produce unpleasant smell and taste.	Organic matter decomposition, microbial activity and industrial discharge.	Indicate the presence of contaminants from microbial metabolites, anthropogenic chemicals and industrial effluents. They create risk of public health including acute gastrointestinal disorders and systemic toxicity.	[15]
Temperature	Influence chemical reactions and dissolve oxygen levels.	Environmental conditions, climate variations and industrial discharge.	Elevated temperatures can enhance microbial proliferation, increase pathogen survival and accelerate chemical reactions that generate harmful by-product and increase public health risks.	[16]
Suspended Solids	Increase turbidity and affect water clarity.	Soil runoff, wastewater and organic debris.	Increase human exposure to infectious diseases and chemical contamination through drinking water.	[17]

Turbidity is one of the most critical physical parameters and is caused by suspended particles such as silt, clay, organic matter, plankton, and microscopic organisms [18]. Elevated turbidity levels can shield pathogens from disinfection processes by reducing the penetration of ultraviolet (UV) light or decreasing the effectiveness of chemical disinfectants such as chlorine. As a result, even treated water may still harbor viable pathogens, increasing the risk of waterborne diseases.

Color and odor in water often arise from natural organic matter (NOM), decaying vegetation, or industrial effluents [14]. These characteristics, while not always harmful, can indicate the presence of underlying chemical or biological contamination. Temperature is another important factor, as it influences chemical reaction rates and microbial growth. Warmer temperatures tend to promote microbial proliferation and decrease the dissolved oxygen levels, thereby affecting aquatic ecosystems and water quality.

Furthermore, suspended solids can absorb heavy metals, pesticides, and other toxic substances, acting as carriers that facilitate their transport through water systems. Therefore, monitoring physical contaminants is essential not only for aesthetic reasons but also as an early warning indicator of potential contamination risks [19].

2.1.2. Chemical Contaminants

Chemical contaminants represent one of the most significant categories of drinking water pollutants due to their toxicity, persistence, and potential for bioaccumulation as mentioned in Table 2. These contaminants can originate from both natural processes, such as mineral dissolution, and anthropogenic activities, including industrial discharge, agricultural practices, and urban runoff [20].

Table 2. Classification of chemical contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
Heavy metals	Includes metals like lead, arsenic, cadmium and mercury.	Industrial waste, mining and natural geological sources.	Associated with toxic effects in human such as neurological impairment, renal dysfunction and increase the risk of chronic disease following prolonged exposure.	[19]
Nutrients	Excessive nitrates and phosphates.	Agricultural fertilizers and wastewater discharge.	High nitrate level is linked to methemoglobinemia in infant, while nutrient enrichment in water bodies may indirectly affect human health through degradation of drinking water quality.	[21]
Organic Compounds	Contain pesticides, hydrocarbon and industrial solvents.	Agricultural runoff and industrial activities.	Some compounds are associated with toxic, endocrine-disruption or potentially carcinogenic effects but it depends on exposure level and duration.	[22]
Synthetic Chemicals	Man-made substances and industrial additives.	Industrial processes and consumer products.	May exhibit persistent toxicity and are associated with potential endocrine, immune and hormonal disruption under chronic exposure conditions.	[23]
Emerging Contaminants	Pharmaceuticals, personal care products and microplastics.	Wastewater effluents, urban runoff and improper disposal.	Potential long-term ecological and human health risks, including endocrine disruption and unknown chronic effects due to limited toxicological data.	[24]
Mixture Effects (Synergistic)	Combined exposure to multiple contaminants.	Real-world environmental exposure scenarios.	Combined exposure may result in additive or synergistic toxicity, increasing overall health risk and complicating risk assessment and regulatory evaluation.	

Chemical pollutants encompass a wide range of substances, including heavy metals, nutrients, organic compounds, and synthetic chemicals. Their presence in drinking water is often associated with long-term exposure risks, as many of these compounds are not easily degraded and can accumulate in human tissues over time. Chronic exposure to chemical contaminants has been linked to various health issues, including cancer, endocrine disruption, reproductive disorders, and neurological damage.

One of the major concerns associated with chemical contamination is the combined or synergistic effects of multiple pollutants. In real-world scenarios, individuals are exposed to mixtures of contaminants rather than isolated compounds, making risk assessment more complex. Additionally, emerging contaminants such as pharmaceuticals, personal care products, and microplastics are increasingly being detected in water sources, raising concerns about their long-term impacts on human health and ecosystems [25].

2.1.3. Inorganic Contaminants

Inorganic contaminants include metals, metalloids, and mineral ions that occur naturally in the environment or are introduced through human activities as mentioned in Table 3. These contaminants are particularly prevalent in groundwater due to the dissolution of minerals from geological formations [26].

Table 3. Profiling of inorganic contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
Arsenic	Highly toxic metalloids are commonly found in groundwater.	Natural geochemical processes, groundwater extraction.	Chronic exposure is associated with increased risk of dermatological disorders, cardiovascular effects and various adverse health outcomes including certain cancer.	[27]
Lead	Toxic heavy metal is often associated with plumbing systems.	Corroded pipes and industrial emission.	Associated with neurodevelopmental impairment cognitive deficits and other adverse health effects, particularly among infants and children.	[28]
Nitrates	Water-soluble nitrogen compounds.	Agricultural fertilizers, animal waste and wastewater.	Elevated nitrate concentrations are linked to methemoglobinemia particularly in infants and may compromise oxygen transport in the blood stream	[29]
Fluoride	Naturally, occurring mineral with dose-dependent effects.	Natural deposits, groundwater and industrial discharge.	Adequate concentrations support dental health, whereas excessive exposure is associated with dental and skeletal fluorosis and related health concerns.	[30]

Arsenic is one of the most widespread and hazardous inorganic contaminants, especially in regions relying heavily on groundwater [27]. Chronic exposure to arsenic is associated with skin lesions, cardiovascular diseases, and various cancers. Similarly, lead contamination often originating from corroded plumbing systems, can cause severe neurological damage, particularly in children.

Nitrate contamination is primarily linked to agricultural activities, including the excessive use of nitrogen-based fertilizers and improper management of animal waste [31]. High nitrate levels in drinking water can lead to methemoglobinemia, a condition that reduces the blood's ability to carry oxygen, particularly in infants. Fluoride, another common inorganic contaminant, has both beneficial and harmful effects; while low concentrations help to prevent the dental caries, excessive exposure can result in dental and skeletal fluorosis [30]. The persistence and non-biodegradable nature of inorganic contaminants make them particularly challenging to remove from water, necessitating advanced treatment technologies and continuous monitoring.

2.1.4. Microbiological Contaminants

Microbiological contaminants are among the most immediate and acute threats to human health as mentioned in Table 4 [32]. These contaminations typically occur due to inadequate sanitation, sewage leakage, and agricultural runoff. In many developing regions, the lack of proper wastewater treatment infrastructure exacerbates these problems, leading to widespread outbreaks of waterborne diseases such as diarrhea, cholera, dysentery, and typhoid fever [20]. These contaminants also include bacteria, viruses, protozoa, and helminths, which primarily originate from fecal contamination of water sources.

Table 4. Assessment of microbiological contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
Bacterial contaminants	Includes common waterborne bacterial pathogens.	Fecal contamination, untreated wastewater.	Correlated with waterborne disease and gastrointestinal illnesses particularly in areas with inadequate sanitation and water treatment.	[20]
Major bacterial pathogens	<i>Escherichia coli</i> , <i>Salmonella</i> , and <i>Vibrio cholerae</i> .	Human and animal waste contamination.	May contact gastrointestinal infections, severe dehydration and outbreaks of enteric diseases but depend upon pathogen and virulence and exposure level.	[33]
Viral contaminants	Infectious viral agents present in contaminated water.	Fecal contamination, sewage discharge.	Linked with acute gastrointestinal illness and other enteric infections particularly in vulnerable populations.	[34]
Major viral pathogens	Norovirus and Rotavirus.	Contaminated drinking water and food.	May cause acute gastroenteritis characterized by diarrhea, vomiting and dehydration specially among the children and immunocompromised individuals.	[34]
Protozoan contaminants	Microscopic parasites resistant to conventional treatment.	Contaminated surface water, fecal matter.	In conjunction with persistent gastrointestinal infections and prolonged diarrheal illness due to their resistance against to some treatment methods.	[35]
Major protozoan pathogens	<i>Giardia lamblia</i> , <i>Cryptosporidium</i> .	Waterborne transmission via cysts/oocysts.	May caused prolonged gastrointestinal symptoms including diarrhea, abdominal discomfort and malabsorption.	
Parasitic helminths	Parasitic worms transmitted through contaminated water.	Poor sanitation, agricultural runoff.	Influenced by intestinal infections, nutritional deficiencies and other health effects resulting from chronic parasitic infestation.	[36]

Common bacterial pathogens include *Escherichia coli*, *Salmonella*, and *Vibrio cholerae*, while viruses such as norovirus and rotavirus are also frequently detected in contaminated water. Protozoan parasites like *Giardia lamblia* and *Cryptosporidium* are particularly resistant to conventional disinfection methods and can survive for extended periods in the environment.

The health impacts of microbiological contaminants are often immediate, causing gastrointestinal illness, dehydration, and, in severe cases, death. Vulnerable populations,

including children, the elderly, and immuno-compromised individuals, are at greater risk [37].

2.1.5. Organic Contaminants

Organic contaminants are carbon-based compounds that include a diverse group of pollutants such as pesticides, herbicides, industrial chemicals, pharmaceuticals, and hydrocarbons as mentioned in Table 5 [38]. These contaminants are primarily introduced into water systems through agricultural runoff, industrial discharge, and domestic wastewater.

Table 5. Characterization of organic contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
Persistent Organic Pollutants (POPs)	Long-lasting organic chemicals resistant to environmental degradation.	Certain pesticides, PCBs and industrial chemicals.	May persist in the environment and bioaccumulate through food webs, potentially increase long-term exposure risks and adverse health outcomes following chronic exposure.	[39]
Volatile Organic Compounds (VOCs)	Organic compounds characterized by high vapor pressure and mobility.	Industrial activities and petroleum products.	Prolonged exposure has been associated with adverse effects on the nervous system, liver and kidney also some compounds recognized as potential carcinogens.	[40]
Emerging Organic Contaminants	Pharmaceuticals, endocrine-disrupting compounds (EDCs) and personal care products.	Wastewater effluents, urban runoff and improper disposal.	May interfere with endocrine functions and are linked with potential reproductive, developmental and ecological effects, although many long-term impacts remain under investigation.	[41]
Bioaccumulative Contaminants	Organic compounds that persist in the environment and accumulate in organisms.	POPs, selected pesticides and industrial organic chemicals.	Long-term accumulation may increase the likelihood of chronic exposure and associated with health risks, particularly in populations relying on contaminated water and food sources.	[39]
Industrial Organic Contaminants	Includes solvents, hydrocarbons, and industrial by-products.	Industrial discharges, manufacturing factories and petrochemical operations.	Exposure may be associated with toxic effects on multiple organ systems including neurological and hepatic functions but depend upon contaminants and their concentrations.	[40]

Persistent organic pollutants (POPs), such as polychlorinated biphenyls (PCBs) and certain pesticides, are of particular concern due to their long-term environmental persistence and ability to bioaccumulate in the food chain. Volatile organic compounds (VOCs), including benzene and toluene, are commonly associated with industrial activities and can pose significant health risks, including cancer and liver damage [40].

Emerging organic contaminants such as pharmaceuticals and endocrine-disrupting compounds (EDCs) are increasingly being detected in drinking water sources. These substances can interfere with hormonal systems even at low concentrations, raising concerns about their long-term effects on human health and aquatic organisms [42].

2.1.6. Radioactive (Radiological) Contaminants

Radiological contaminants in drinking water originate from both natural and anthropogenic sources as mentioned in Table 6. Naturally occurring radionuclides, such as uranium, radium, and radon, are commonly found in groundwater due to the weathering of rocks and soils [43].

Table 6. Classification of radioactive contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
Radiological Contaminants	Radioactive substances that persist in the environment and may accumulate in biological systems.	Natural sources (uranium, radium, radon), anthropogenic sources (nuclear power, mining and radioactive waste).	Long-term exposure may increase radiation-related health risk including cellular damage and an elevated likelihood of adverse health outcomes depending on dose and exposure duration.	[44]
Naturally Occurring Radionuclides	Uranium, radium and radon commonly detected in groundwater.	Weathering of rocks and soils, geogenic processes and groundwater-rock interactions.	Prolonged exposure may contribute to internal radiation doses and associated with increased risks of chronic health effects including certain cancers.	[43]
Anthropogenic Radioactive contaminants	Radioactive substances introduced through human activities.	Nuclear power plants, mining, improper disposal of radioactive waste and	May contribute to chronic radiation exposure and accumulation in specific tissues potentially increase long-term health risks.	[45]
Exposure Pathways	Routes by which radionuclides enter the human body.	Ingestion of contaminated water.	Continuous intake may result in internal exposure to radionuclides and increased cumulative radiation dose overtime.	[46]

Anthropogenic sources include nuclear power plants, mining activities, and improper disposal of radioactive waste. Exposure to radioactive contaminants can occur through ingestion of contaminated water, leading to the accumulation of radioactive substances in the body over time [47].

The health effects of radiological contamination are primarily associated with an increased risk of cancer, particularly bone, liver, and kidney cancer. Long-term exposure may also result in genetic mutations and developmental abnormalities [48]. Due to their invisible and persistent nature, radiological contaminants require specialized detection and treatment methods.

2.2. Contaminant Sources and Transport Pathways

2.2.1. Industrial and Sewage Contaminants

Industrial and sewage discharges are major sources of chemical and inorganic contaminants, including heavy metals and organic solvents, as discussed in the corresponding contaminant class sections. Industrialization and urbanization have significantly increased the discharge of pollutants into water bodies as mentioned in Table 7. Industrial effluents often contain heavy metals, toxic chemicals, solvents, and petroleum products, which can severely degrade water quality [49].

Table 7. Overview of industrial and sewage contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
General Industrial and Sewage Contaminants	Pollutants discharged from industrial and municipal sources affecting water quality.	Industrial effluents, municipal wastewater and inadequately treated sewage.	May introduced a wide range of chemical and biological contaminants into drinking water sources, increase the potential risks of infectious diseases and chronic toxic exposure.	[49]
Industrial Effluents	Contains heavy metals, toxic chemicals, solvents, and petroleum products.	Factories, refineries and chemical industries.	Exposure may be associated with toxic effects on multiple organ systems, depending on contaminant composition and duration of exposure, including potential long-term health risks.	[49]
Sewage/Municipal Wastewater	Organic matter, nutrients, pathogens, and emerging contaminants.	Domestic wastewater and urban runoff.	Associated with increased risk of waterborne diseases and gastrointestinal infections due to pathogen presence, as well as potential chemical exposure risks.	[50]
Oxygen Depletion/ Anaerobic Conditions	Accumulation of organic matter leads to reduced dissolved oxygen levels.	Untreated sewage and industrial organic discharge.	Anaerobic conditions may promote the formation of harmful gases and indicate severe water quality deterioration, indirectly increasing exposure to unsafe drinking water conditions.	[51]
Nutrient Enrichment/ Eutrophication	Excess nitrogen and phosphorus promote algal blooms.	Sewage and agricultural runoff.	Indirectly affects human health by contributing to harmful algal blooms and degradation of drinking water sources, potentially leading to toxin exposure and water quality risks.	[52]
Infrastructure-Related Issues	Lack of proper wastewater treatment and management system.	Poorly managed municipal treatment infrastructure.	Increases likelihood of untreated contaminants entering water supplies, elevating risks of microbial infection and chemical exposure through contaminated drinking water.	[53]

Sewage and municipal wastewater are major sources of contamination introducing organic matter, nutrients, pathogens, and emerging contaminants into water systems. Inadequate or poorly managed wastewater treatment facilities can lead to the release of untreated or partially treated sewage into rivers, lakes, and groundwater [53].

The accumulation of organic matter in water bodies can result in oxygen depletion, promoting anaerobic conditions and the production of harmful gases such as methane and hydrogen sulfide [51]. Additionally, nutrient enrichment from sewage can lead to eutrophication, causing algal blooms and further deterioration of water quality [52].

2.2.2. Agricultural Contaminants

Agricultural runoff is a major source of inorganic contaminants such as nitrates and phosphates, and organic contaminants such as pesticides and herbicides, discussed above under Inorganic and Organic Contaminants. Agricultural activities are a major source of water pollution, contributing to the contamination of both surface water and groundwater as mentioned in Table 8. The use of fertilizers, pesticides, herbicides, and animal manure introduces a wide range of pollutants into water systems [54].

Table 8. Description of agricultural contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
General Agricultural Contaminants	Pollutants introduced water systems through agricultural practices.	Fertilizers, pesticides, herbicides and animal manure.	May contribute to degradation of drinking water quality and increase exposure to chemical and microbial contaminants, posing potential risks to human health through contaminated water consumption.	[55]
Nutrients (Nitrogen & Phosphorus)	Essential plant nutrients that cause pollution at elevated concentrations.	Fertilizer runoff and manure leaching.	Excessive nutrient levels may indirectly affect human health by promoting harmful algal blooms and deteriorating drinking water quality, potentially leading to toxin exposure and oxygen-related water quality issues.	[52]
Pesticides & Herbicides	Synthetic chemicals used for pests and weeds control in agriculture.	Crop protection applications in agricultural fields.	Exposure has been associated with potential toxic effects, including endocrine, neurological, and metabolic disturbances, depending on concentration and duration of exposure.	[56]
Chronic Exposure Effects	Long-term effects of agricultural chemical residues in water.	Consumption of contaminated drinking water and occupational exposure.	Chronic exposure may increase the risk of long-term health effects, including endocrine disruption, neurological impairment, and other systemic toxicological outcomes.	[57]
Eutrophication-Related Impacts	Excess nutrients leading to algal growth and oxygen depletion in water bodies.	Agricultural runoff containing nitrogen and phosphorus.	Indirectly affects human health through deterioration of drinking water quality and potential exposure to algal toxins, along with reduced suitability of water for consumption.	[58]

Nutrient runoff, particularly nitrogen and phosphorus, is a leading cause of eutrophication, resulting in excessive algal growth and oxygen depletion. This process not only affects aquatic ecosystems but also compromises drinking water quality by producing toxins and unpleasant tastes and odors [58].

Pesticides and herbicides can persist in the environment and accumulate in water sources, posing risks to human health [56]. Effective management practices, such as precision agriculture and buffer zones, are essential to minimize agricultural pollution.

2.2.3. Atmospheric Contaminants

Atmospheric deposition contributes both inorganic contaminants (e.g., heavy metals, sulfates) and organic contaminants (e.g., persistent organic pollutants) to surface and groundwater sources, as described under the corresponding contaminant classes. Atmospheric deposition is an often-overlooked pathway of water contamination as mentioned in Table 9. Pollutants released into the atmosphere from industrial emissions, vehicle exhaust, and biomass burning can be transported over long distances and deposited into water bodies through precipitation [59].

Table 9. Classification of atmospheric contaminants in drinking water and effects of human health.

Category	Description	Source	Potential Human Health Impact	Ref.
General Atmospheric Contaminants	Pollutants deposited from the atmosphere into water bodies via precipitation or dry deposition.	Industrial emissions, vehicle exhaust and biomass burning.	Increase the exposure to contaminated drinking water, respiratory and cardiovascular disorders that associated with airborne pollutants and long-term toxic effects through the food chain.	[60]
Heavy Metals	Mercury and other metals transported from the atmosphere.	Industrial emissions, coal combustion and mining activities.	Neurotoxicity, kidney damage, developmental disorders and bioaccumulation leading to chronic dietary exposure.	[61]
Acidic Compounds	Sulfur dioxide (SO ₂) and nitrogen oxides (NO _x).	Fossil fuel combustion and biomass burning.	Respiratory irritation, aggravation of asthma and cardiovascular diseases and indirect health risk through acidification, induced mobilization of toxic metals in drinking water.	[62]
Organic Pollutants	Polycyclic aromatic hydrocarbons (PAHs) and other organic compounds.	Vehicle emissions, industrial activities and biomass burning.	Carcinogenicity, mutagenicity, endocrine disruption and chronic toxicity following inhalation or dietary exposure.	[61]

Common atmospheric contaminants include mercury, sulfur dioxide, nitrogen oxides, and polycyclic aromatic hydrocarbons [61]. Acid rain, resulting from the deposition of sulfur and nitrogen compounds, can lower the pH of water bodies, affect aquatic life and mobilize heavy metals from sediments.

3. Purification Technologies

Different techniques to remove contaminants from drinking water are as follows.

3.1. Primary and Secondary Treatment

3.1.1. Coagulation and Precipitation

Coagulation and precipitation are fundamental physicochemical processes widely applied in drinking water treatment to remove suspended, colloidal, and dissolved contaminants. This technique plays a crucial role in mitigating water contamination arising from natural organic matter (NOM), heavy metals, pathogens, and emerging pollutants. Coagulation involves the destabilization of colloidal particles through charge neutralization, followed by aggregation into larger flocs (flocculation), which can then be removed via sedimentation and filtration. Precipitation, on the other hand, relies on chemical reactions that convert dissolved contaminants into insoluble forms, enabling their separation from water [63].

The effectiveness of coagulation is strongly governed by factors such as pH, coagulant type (aluminum or iron salts), and water chemistry [64]. These conditions influence hydrolysis reactions, charge neutralization, and sweep flocculation mechanisms that facilitate the removal of contaminants. Studies have shown that coagulation can effectively remove turbidity, NOM, algae, and even microplastics and pathogens, making it indispensable in conventional drinking water treatment plants. One of Recent study indicates that coagulation sedimentation can remove up to 30 to 90% of NOM and pesticides, and up to 95% of microplastics, although efficiency for pharmaceuticals and polyfluoroalkyl substances (PFAS) remains limited [65]. It should be noted that these removal efficiencies vary considerably across studies and are strongly influenced by influent contaminant concen-

tration, water matrix composition, pH, coagulant dose, contact time, and treatment scale, as well as the analytical method used for quantification; the ranges reported here should therefore be interpreted as indicative rather than directly comparable across studies.

It has also been reported that optimized coagulation using iron- or aluminum-based coagulants can achieve turbidity and suspended solids removal efficiencies above 95 to 99%, confirming its effectiveness as a primary treatment barrier in drinking water systems. Furthermore, coagulation processes are highly efficient in removing algal cells and cyanobacteria (>90%), thereby reducing toxin risks and improving downstream disinfection performance. In addition, coagulation–precipitation systems can remove heavy metals such as arsenic, lead, and chromium with efficiencies ranging from 70 to 99%, mainly through adsorption and co-precipitation with metal hydroxides.

Precipitation processes have been widely reported as highly effective for the removal of inorganic contaminants from water systems, particularly under controlled pH conditions and in the presence of chemical precipitants such as lime, iron, and aluminum salts [66]. For instance, optimized lime softening and metal hydroxide precipitation can achieve arsenic removal efficiencies ranging from 80 to 99%, primarily through co-precipitation with ferric hydroxides and adsorption onto freshly formed metal precipitates. Similarly, fluoride removal via calcium-based precipitation (forming CaF_2) has been reported to reach efficiencies of 70 to 95% depending on initial concentration and solution chemistry [67]. Furthermore, phosphorus removal through chemical precipitation using iron and aluminum salts is highly efficient, with reported removal rates between 75 to 98%, due to the formation of insoluble FePO_4 and AlPO_4 complexes under optimal pH conditions [68]. In addition, precipitation-based processes are widely applied for heavy metal removal, including lead, cadmium, chromium, and mercury, achieving efficiencies of 70 to 99% through hydroxide, carbonate, and sulfide precipitation mechanisms. As with coagulation, these precipitation-based removal efficiencies are influenced by pH, precipitant dose, contact time, water matrix, and analytical method, and should be compared with caution across studies employing different conditions. Mechanisms of coagulation and precipitation is illustrated in Figure 3, that showing the (i) coagulation in which chemical agents are added to destabilize colloidal particles by neutralizing their surface charges. (ii) flocculation in which gentle agitation and the addition of flocculants promote the aggregation of these particles into larger, settleable “flocs” and (iii) sedimentation in which gravity facilitates the separation of these dense flocs as sludge, leaving behind clarified water for subsequent treatment stages such as filtration and disinfection.

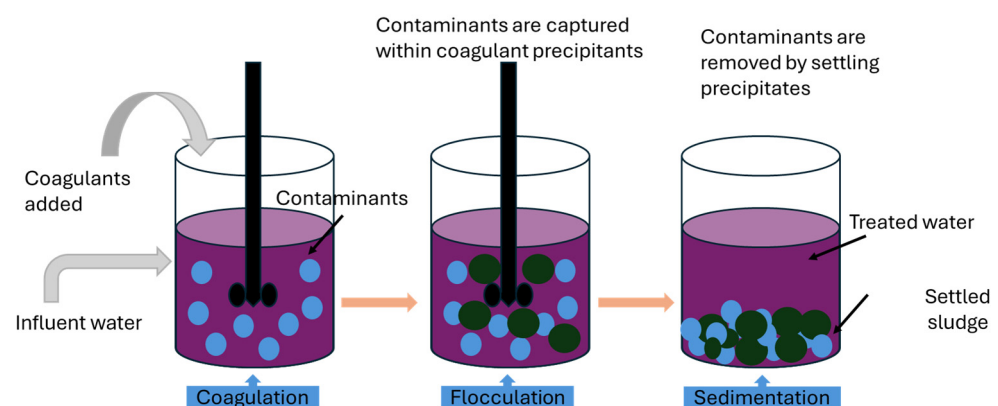


Figure 3. Schematic representation of coagulation and precipitation mechanisms in drinking water contaminations (created with BioRender.com and power point).

3.1.2. Magnetic Separation

Magnetic separation is an emerging and highly efficient physicochemical technology used for the removal of contaminants from drinking water, particularly in cases involving suspended solids, heavy metals, dyes, microorganisms, and certain organic pollutants that can be associated with magnetic materials or modified to respond to magnetic fields. With increasing global concerns over water pollution caused by industrial discharge, agricultural runoff, and urban wastewater [69], magnetic separation has gained considerable attention as a rapid, reusable, and energy-efficient method that can complement or even replace conventional water treatment technologies. Compared with traditional separation processes such as sedimentation, filtration, and chemical coagulation, magnetic separation offers faster operation, reduced chemical consumption, and easier recovery of treatment materials, making it an attractive option for sustainable water purification systems.

The basic principle of magnetic separation relies on the application of an external magnetic field to isolate magnetic or magnetically responsive particles from water [70] as mentioned in Figure 4. In its simplest form, naturally magnetic contaminants, such as iron oxides, can be directly separated from aqueous systems. However, most contaminants found in drinking water are non-magnetic and therefore require modification prior to separation. This is commonly achieved by attaching pollutants to magnetic materials, particularly iron oxide nanoparticles such as magnetite (Fe_3O_4) and maghemite ($\gamma\text{-Fe}_2\text{O}_3$) [71]. Once contaminants become associated with these magnetic particles, an external magnetic field can rapidly extract them from the water matrix. This approach enables high selectivity, rapid treatment rates, and efficient pollutant removal while minimizing the need for additional chemical reagents.

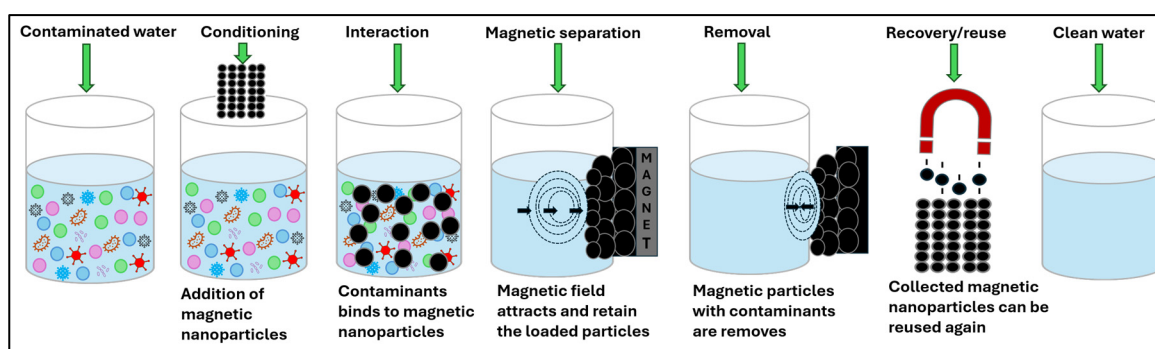


Figure 4. Representation of the mechanisms of magnetic separation technology in drinking water contamination (created with BioRender.com and power point).

One of the most important mechanisms involved in magnetic separation is adsorption-assisted magnetic capture. In this process, magnetic nanoparticles are functionalized with specific chemical groups, including carboxyl, amine, thiol, or polymer coatings, to enhance their affinity toward target contaminants [72]. These functionalized surfaces interact with pollutants through electrostatic attraction, coordination bonding, hydrophobic interactions, hydrogen bonding, and ion-exchange mechanisms. As a result, contaminants can be effectively concentrated onto the magnetic adsorbent surface and subsequently removed using an external magnetic field. For example, toxic heavy metals such as lead, cadmium, arsenic, and chromium exhibit strong binding affinities toward functionalized magnetite-based adsorbents, allowing their efficient extraction even at relatively low concentrations.

Another key mechanism is co-precipitation and in situ magnetic particle formation. In this approach, contaminants are incorporated into magnetic precipitates generated directly within the water system. Iron salts containing Fe^{2+} and Fe^{3+} ions are introduced under controlled alkaline conditions, resulting in the formation of magnetite particles that

can capture dissolved pollutants and suspended particulates simultaneously. During the precipitation process, contaminants become entrapped within or adsorbed onto the growing magnetic particles, facilitating their subsequent magnetic recovery. This technique is particularly useful for treating industrial effluents containing complex mixtures of inorganic and organic pollutants [73].

To target suspended solids, colloidal particles, and natural organic matter, magnetic flocculation employs magnetic particles that function as bridging agents, accelerating the aggregation of impurities into larger and denser flocs. The incorporation of magnetic materials enhances floc formation and improves separation efficiency under an applied magnetic field. This process significantly reduces settling time, increases pollutant removal efficiency, and decreases sludge production compared with conventional coagulation-flocculation methods used in drinking water treatment [74]. Additionally, the magnetic flocs can be easily recovered and separated, improving overall operational efficiency.

Furthermore, advances in surface functionalization have enabled magnetic nanoparticles to be modified with highly selective ligands, biomolecules, and molecularly imprinted polymers. These engineered materials exhibit enhanced specificity toward target contaminants, allowing the selective removal of trace-level emerging pollutants, including antibiotics, pesticides, dyes, pharmaceutical residues, and endocrine-disrupting compounds [75]. Such selectivity is particularly important in modern water treatment applications where contaminants often occur at very low concentrations but pose significant environmental and public health risks.

3.2. Tertiary/Polishing Treatment

3.2.1. Adsorption

Adsorption has emerged as one of the most efficient, versatile, and widely applied physicochemical techniques for the removal of contaminants from drinking water. It is particularly effective for eliminating a broad range of pollutants including heavy metals like Pb^{2+} , Cd^{2+} , Hg^{2+} , As^{3+} / As^{5+} [76], organic micropollutants, i.e., pesticides, pharmaceuticals, dyes, and emerging contaminants due to its simplicity, cost-effectiveness, and high removal efficiency over a wide range of operating conditions.

In drinking water purification, adsorption plays a central role in tertiary treatment stages, where trace-level contaminants must be removed to meet strict drinking water standards. According to different studies and the World Health Organization (WHO) sets extremely low permissible limits for toxic metals in drinking water (Pb: 0.01 mg/L, Cd: 0.003 mg/L) which often cannot be achieved by primary and secondary treatment processes alone. Adsorption therefore acts as a polishing step to ensure water safety. A wide range of adsorbents has been explored, including activated carbon, biochar, clay minerals, agricultural waste-based biosorbents, and engineered nanomaterials, all of which offer different surface chemistries and porosities that enhance pollutant uptake. The adsorption procedure illustrated in Figure 5 begins with contaminated water containing various pollutants. An adsorbent material, such as activated carbon, biochar, or functional resins, is then introduced into the solution. Continuous mixing or agitation is applied to enhance contact between pollutants and the adsorbent surface, promoting interactions such as electrostatic attraction and bonding. After sufficient contact time, the mixture is left to settle, allowing the pollutant-loaded adsorbent particles to separate from the liquid phase due to gravity. Finally, the treated water is obtained as a purified effluent after removal of the spent adsorbent through filtration or decantation [77].

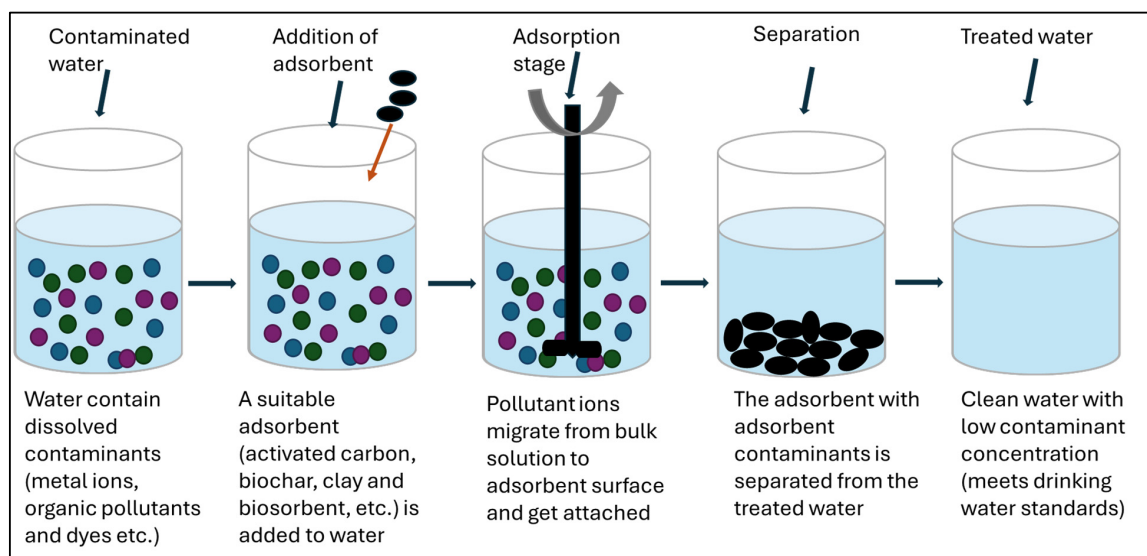


Figure 5. Representation of whole procedure of the adsorption technique for contaminating drinking water (created with [BioRender.com](https://www.biorender.com) and power point).

The subsequent removal of these pollutants is driven by complex physical and chemical interactions at the solid–liquid interface, which are influenced by the contaminant characteristics and adsorbent properties (Figure 6). The main mechanisms include:

- (a) **Electrostatic attraction:** Electrostatic attraction in adsorption is a primary mechanism where charged adsorbent surfaces attract oppositely to charged contaminants. This interaction is heavily influenced by the solution's pH and the point of zero charge of the adsorbent, mentioned in Figure 6a.
- (b) **Ion Exchange:** Ion exchange in adsorption involves in the replacement of naturally bound ions (Ca^{2+} , Na^+ , K^+) on the adsorbent surface with target metal ions from solution. This process is common in materials with abundant exchangeable functional groups and is influenced by ion affinity, concentration, and solution chemistry. It is an important and reversible adsorption mechanism that contributes significantly to metal removal efficiency [78], mention in Figure 6b.
- (c) **Surface Complexation (Chelation):** Surface complexation (chelation) occurs when functional groups such as OH, COOH, and NH_2 bind metal ions through coordination bonds, and form a stable surface complex. This mechanism is highly important for strong and selective metal adsorption and is often more stable than physical adsorption processes [79] mention in Figure 6c.
- (d) **Physical adsorption (van der Waals forces):** Physical adsorption occurs through weak van der Waals forces between the adsorbent surface and pollutant molecules, enabling their initial attachment. It is generally non-specific, reversible, and often serves as the first step before stronger interactions such as chemisorption take place [80], mention in Figure 6d.
- (e) **Precipitation at surface sites:** Surface precipitation involves the formation of insoluble compounds on the adsorbent surface when specific chemical conditions, especially pH, promote metal ion precipitation. This mechanism effectively immobilizes contaminants by converting them into stable solid phases [63], mention in Figure 6e.

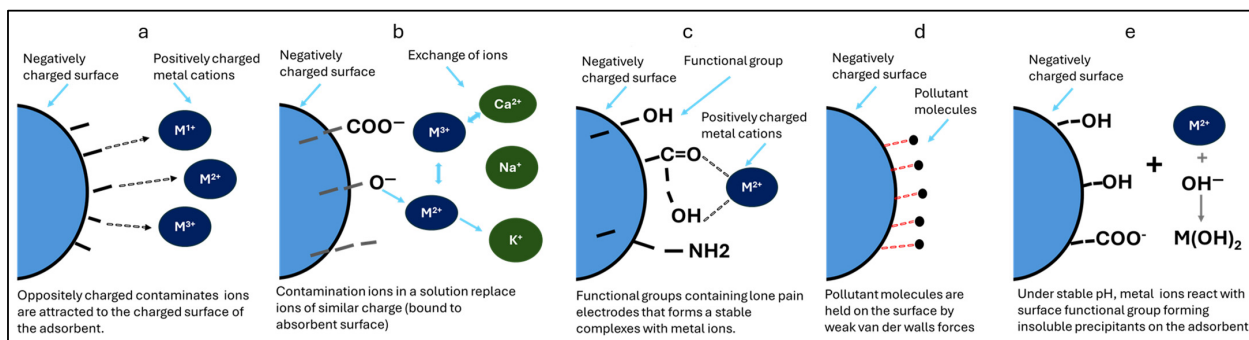


Figure 6. Illustrates the different mechanisms of the adsorption in which (a) (electrostatic attraction), (b) (ion exchange), (c) (surface complexation (chelation)), (d) (physical adsorption (van der Waals forces)) and (e) (Precipitation at surface sites) are showing different mechanisms properties (created with BioRender.com and power point).

3.2.2. Activated Carbon

Activated carbon is also referred to as activated charcoal. It is one of the most widely applied adsorbent materials in drinking water treatment due to its exceptionally high surface area, porous structure [81] and strong affinity for a wide range of organic and inorganic contaminants. It is typically produced from carbon-rich precursors such as coal, coconut shells, wood, and peat through physical or chemical activation processes at high temperatures, which generate extensive micro, meso and macropores that significantly increased adsorption capacity [82].

The primary mechanism by which activated carbon removes contaminants is adsorption, a process in which pollutants accumulate on the extensive internal surface of carbon particles [83]. This occurs through multiple interactions, including van der Waals forces, hydrophobic interactions, π - π electron donor-acceptor interactions, and electrostatic attraction depending on the nature of the contaminant and surface chemistry of the carbon [84]. In addition, catalytic surface reactions may occur, especially in the presence of oxidants or dissolved oxygen, contributing to the degradation of certain organic compounds, as mentioned in Figure 6a. Activated carbon is particularly effective in removing the, i.e., natural organic matter, pesticides, herbicides, and industrial dyes, volatile organic compounds [81], disinfection by-products, e.g., trihalomethanes and taste and odor-causing compounds [85]. Furthermore, it can partially reduce chlorine and chloramine residues through adsorption and catalytic reduction reactions, improving water palatability and reducing formation of harmful by-products during disinfection as mentioned in Figure 7a.

In drinking water treatment systems, activated carbon is commonly used in two forms: granular activated carbon (GAC) and powdered activated carbon (PAC) [86]. GAC is widely used for Per- and polyfluoroalkyl substances (PFAS) removal from contaminated water, because of its high surface area and porous structure, enabling adsorption through hydrophobic and electrostatic interactions [87]. Its removal efficiency depends on PFAS properties, GAC characteristics, and operating conditions, with better performance generally observed for long-chain PFAS [88]. Small-scale column studies are useful for predicting PFAS breakthrough and optimizing system performance [89]. Surface modifications, such as Cu^{2+} ion or goethite coatings, can further improve adsorption by enhancing ligand interactions. However, GAC adsorption capacity declines with saturation, and PFAS desorption may occur under certain conditions, requiring regeneration or replacement. Advanced regeneration methods, such as modified supercritical CO_2 extraction, have shown high efficiency (>97% for perfluorooctanoic acid) while preserving GAC properties [90]. Despite its effectiveness, improving short-chain PFAS removal and developing cost-effective regeneration strategies remain key challenges.

Powdered Activated Carbon (PAC) is a cost-effective and flexible option for PFAS removal due to its rapid adsorption kinetics and shorter diffusion path compared to GAC showed in Figure 6b. Its efficiency depends on PFAS characteristics, with higher removal of long-chain compounds, while short-chain PFAS remain more difficult to adsorb [91]. To overcome the limitations of conventional PAC, modified materials such as ionic-liquid-impregnated activated carbon and goethite-coated PAC have been developed, showing improved adsorption capacity through enhanced hydrophobic and electrostatic interactions.

Combining PAC with biochar or membrane technologies has further improved PFAS removal efficiency [92]. Modified biochar from agricultural wastes and activated-carbon-based nanocomposite membranes provide sustainable alternatives with high adsorption performance, especially for long-chain PFAS. Advanced porous materials such as metal–organic frameworks and covalent organic frameworks are also emerging as promising adsorbents due to their higher capacity and faster equilibration [93]. Despite these advances, PAC remains less effective for short-chain PFAS and may require higher dosages and frequent replacement, especially under conditions such as elevated temperature or high dissolved organic matter, which can reduce adsorption efficiency and promote desorption. These systems act as a polishing step after conventional treatment or as a barrier for emerging contaminants as mentioned in Figure 7b.

Activated carbon (AC) plays an important role in drinking water treatment by reducing exposure to toxic organic micropollutants linked to carcinogenic, endocrine-disruption and neurotoxic effects, thereby lowering long-term health risks from contaminated water. Beyond physical adsorption, AC can also support microbial colonization on its surface, enabling biodegradation of adsorbed organic matter through biofiltration, which improves long-term removal efficiency. Despite its high efficiency, AC has some limitations. It is less effective for removing inorganic contaminants such as nitrates, fluoride, and dissolved salts, and its performance is influenced by factors such as pH, temperature, contact time, and dissolved organic matter, which can reduce adsorption capacity [94].

3.2.3. Activated Alumina

Activated alumina (AA) is widely recognized as one of the most effective adsorption-based technologies for removing inorganic contaminants from drinking water, particularly fluoride and arsenic, which remain major global public health concerns [95]. In many regions where groundwater is the primary drinking source, geogenic contamination of fluoride and arsenic exceeds safe limits, leading to severe health effects such as dental and skeletal fluorosis, skin lesions, and long-term carcinogenic risks. Among various treatment approaches, activated alumina has gained significant attention due to its relatively low cost, operational simplicity, renderability, and high selectivity for oxyanions, making it especially suitable for decentralized and rural water treatment systems [96].

The importance of activated alumina technology lies primarily in its effectiveness in meeting drinking water quality standards under field conditions. It is widely used in community-scale treatment plants and household filtration units, especially in regions affected by fluoride contamination such as India, China, and parts of Africa. Its ability to reduce fluoride concentrations below the World Health Organization guideline value of 1.5 mg/L makes it a critical intervention for preventing fluorosis-related health problems [97]. Similarly, AA is also used for arsenic removal in groundwater treatment systems, where it can achieve high removal efficiencies under optimized conditions. Studies have shown that activated alumina systems can provide reliable performance across varying water chemistries, making them suitable for diverse environmental conditions [98].

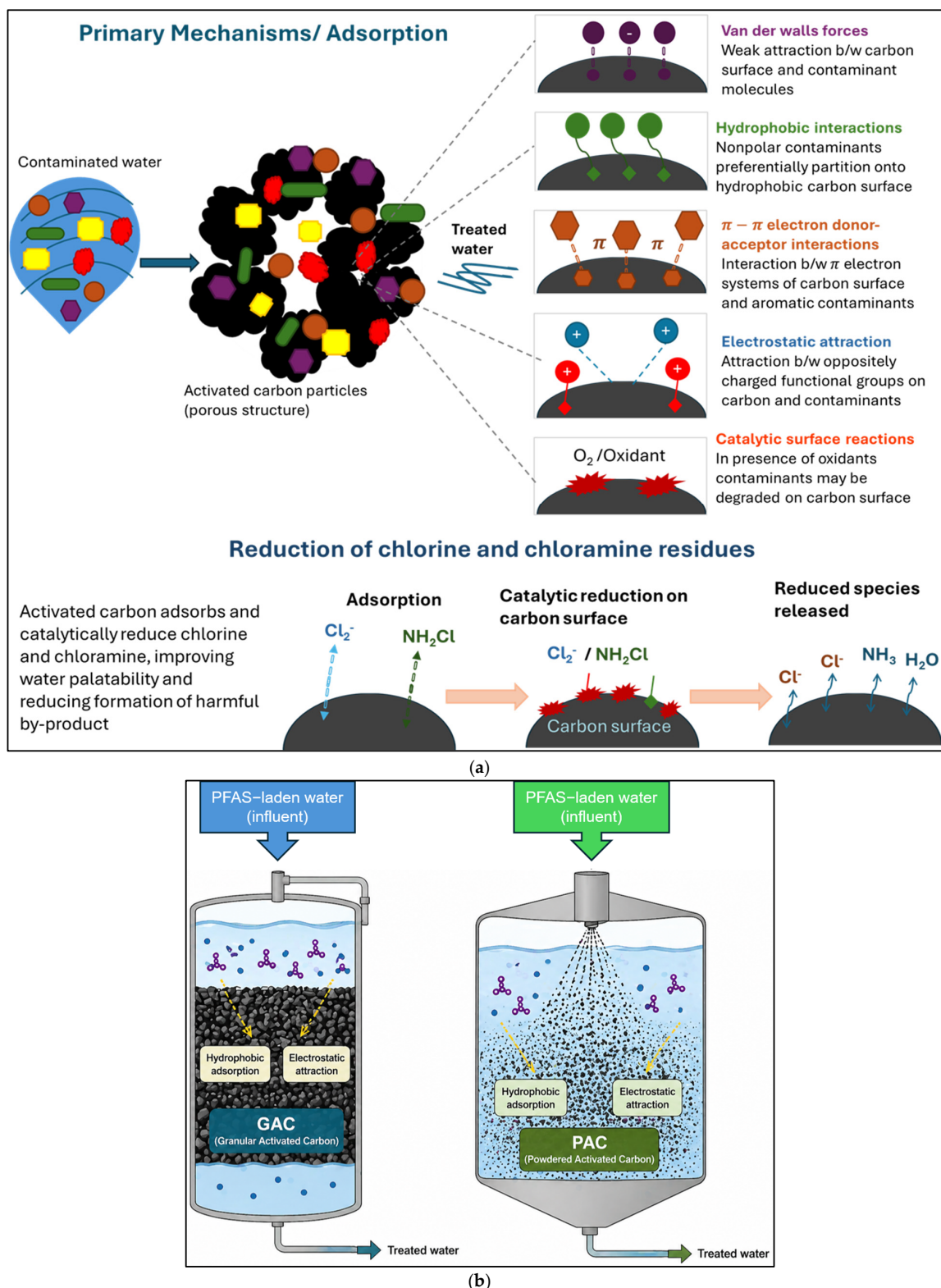


Figure 7. (a) Illustrates the mechanisms of activated carbon technology (created with BioRender.com and power point). (b) Illustrates the GAC and PAC mechanisms for removal of drinking water contamination (created with BioRender.com and power point).

Activated alumina is a porous form of aluminum oxide (Al_2O_3) with a high specific surface area and abundant surface hydroxyl groups ($-\text{OH}$), which are responsible for its adsorption properties. Its effectiveness in water treatment is strongly linked to these surface functional groups, which can interact with contaminants through ligand exchange,

ion exchange, and electrostatic attraction. The material is typically produced by thermal dehydration of aluminum hydroxide, resulting in a stable, highly porous structure with surface areas often over 200 m²/g or higher depending on activation conditions [99]. This structural feature provides many active sites for adsorption, making AA particularly efficient for trace-level contaminant removal.

The primary mechanism governing contaminant removal by activated alumina is ligand exchange between surface hydroxyl groups and target anions present in water. In the case of fluoride removal, the process involves the substitution of surface hydroxyl groups with fluoride ions, forming strong aluminum–fluoride complexes on the adsorbent surface. A similar mechanism, operates for arsenate and other oxyanions, where inner-sphere complexes are formed with the alumina surface. This chemisorption process is generally considered irreversible under normal operating conditions, although regeneration is possible using alkaline solutions.

Another important aspect of the mechanism is the strong dependence of adsorption efficiency on pH. The surface charge of activated alumina varies with pH and is characterized by its point of zero charge (PZC), typically around pH 8 to 9 [100]. Below this range, the surface becomes positively charged (Al–OH₂⁺), which enhances electrostatic attraction toward negatively charged species such as fluoride (F[−]) and arsenate (AsO₄^{3−}). As a result, adsorption is most efficient under mildly acidic conditions, generally in the pH range of 5.0 to 6.5. At higher pH values, hydroxide ions (OH[−]) compete strongly with target anions for active sites, significantly reducing adsorption efficiency. Recent studies have confirmed that fluoride removal is highly pH-sensitive, whereas arsenic adsorption shows relatively broader pH tolerance depending on its oxidation state and water chemistry conditions [101].

3.2.4. Distillation

Distillation is one of the oldest and most reliable techniques used for water purification and desalination. It is a thermal separation process that removes contaminants from water by utilizing the natural processes of evaporation and condensation [102]. Due to its ability to eliminate a wide range of impurities, distillation has gained significant importance in the production of safe drinking water, especially in regions facing severe water contamination and freshwater scarcity. The technique is widely applied in domestic water purification systems, industrial water treatment plants, laboratories, pharmaceutical industries, and seawater desalination facilities [103]. Distillation is also a physical water purification process in which contaminated water is heated until it changes into vapor. The vapor is then cooled and condensed back into liquid form in a separate container. During this process, most contaminants remain behind because they do not evaporate at the same temperature as water [104]. As a result, the condensed water obtained after distillation is significantly purer and safer for human consumption. The distillation process generally involves four major steps: heating, evaporation, separation and condensation.

3.3. Disinfection

3.3.1. Ozone

Ozone technology has become one of the most effective and widely applied advanced treatment methods for removing contaminants from drinking water. In modern water purification systems, ozone is primarily used because of its strong oxidizing ability, rapid disinfection capacity and environmentally friendly nature [105]. Unlike conventional disinfectants such as chlorine, ozone does not remain in water for long periods and decomposes naturally into oxygen, making it an attractive alternative for improving drinking water quality. Over the last few decades, the use of ozonation in drinking water treatment has

increased significantly due to growing concerns about microbial contamination, organic pollutants, taste and odor problems, pharmaceutical residues, pesticides, and emerging contaminants [106].

Ozone (O_3) is an unstable triatomic molecule composed of three oxygen atoms. It possesses a very high oxidation potential, greater than chlorine and many other oxidants used in water treatment processes. Because of this high oxidative strength, ozone reacts rapidly with organic and inorganic contaminants present in water. During ozonation, ozone molecules attack pollutants either directly or indirectly through the generation of hydroxyl radicals, which are among the strongest oxidizing species known in water chemistry. These reactions destroy microorganisms, degrade toxic organic compounds, remove unpleasant odors, and improve water clarity [107].

The importance of ozone in drinking water treatment is mainly associated with its excellent disinfection efficiency. Ozone can effectively inactivate bacteria, viruses, fungi, protozoa, and other pathogenic microorganisms [108]. It is particularly efficient against chlorine-resistant microorganisms such as *Cryptosporidium* and *Giardia*, which are major concerns in drinking water safety. Ozone destroys microbial cells by oxidizing cellular membranes, proteins, and nucleic acids, resulting in rapid cell death. Besides microbial disinfection, ozone play an important role in the removal of organic contaminants from drinking water. Industrial discharge, agricultural runoff, and pharmaceutical waste introduce numerous organic compounds into water sources. Many of these pollutants are difficult to remove using conventional filtration methods. Ozone reacts with double bonds, aromatic rings, phenolic groups, and other reactive structures present in organic molecules, converting them into simpler and less toxic compounds [109].

The mechanism of ozone treatment depends on several chemical and operational factors that control its oxidation behavior in water. Ozone can react through two main pathways: direct oxidation and indirect oxidation. In the direct oxidation, molecular ozone selectively reacts with contaminants, particularly those containing electron-rich functional groups such as double bonds, phenols, and aromatic compounds. This pathway is generally more selective and effective for the degradation of specific organic pollutants and for disinfection purposes. In the indirect oxidation, ozone decomposes in water and generates hydroxyl radicals, which are extremely reactive and non-selective oxidants capable of rapidly degrading a broad range of organic and inorganic contaminants [110]. The balance between these two mechanisms depends largely on water chemistry, especially pH, temperature, and the presence of natural organic matter or inorganic ions.

Despite its high disinfection and oxidation efficiency, ozonation can generate potentially harmful oxidation byproducts. The most significant concern is bromate formation, which occurs when source water containing bromide ions is ozonated; bromate is classified as a probable human carcinogen and is subject to regulatory limits in drinking water [111]. Ozonation can also produce aldehydes, ketones, and carboxylic acids as byproducts of the partial oxidation of natural organic matter, and, in the presence of nitrogen-containing precursors, can contribute to the formation of N-nitrosodimethylamine (NDMA) [112]. Byproduct formation is influenced by ozone dose, bromide concentration, pH, and contact time, and is typically minimized through dose optimization, ammonia addition to suppress bromate formation, or combination with biological filtration to remove residual byproducts [113].

3.3.2. Chlorine

Chlorination is one of the most widely used and effective techniques for disinfecting drinking water. It involves the addition of chlorine or chlorine-containing compounds to water in order to destroy harmful microorganisms such as bacteria, viruses, and parasites.

Since its introduction in the early 20th century, chlorination has played a major role in reducing waterborne diseases and improving public health worldwide. It is considered a simple, economical, and reliable method for ensuring safe drinking water [114].

The main purpose of chlorination is to disinfect contaminated water by killing pathogenic microorganisms. Chlorine is usually added to water in the form of chlorine gas (Cl_2), sodium hypochlorite (NaOCl), or calcium hypochlorite (Ca(OCl)_2) [115]. When chlorine is added to water, it reacts chemically with water molecules and forms hypochlorous acid (HOCl) and hydrochloric acid (HCl). Hypochlorous acid is the most important disinfecting agent produced during chlorination, and it further dissociates into hydrogen ions (H^+) and hypochlorite ions (OCl^-). Among these compounds, hypochlorous acid is highly effective in killing microorganisms because it can easily penetrate the cell walls of bacteria and viruses. Once inside the microbial cell, it oxidizes essential enzymes and proteins, disrupts metabolic activities, damages nucleic acids, and ultimately causes cell death. This oxidation process prevents microorganisms from reproducing and spreading diseases [116].

The efficiency of chlorination depends on several factors, including water pH, temperature, contact time, and chlorine concentration. At lower pH levels, more hypochlorous acid is present, making chlorination more effective. Adequate contact time is also necessary to ensure complete disinfection [117]. Contaminated drinking water may contain harmful pathogens originating from sewage, industrial waste, agricultural runoff, or natural sources. Chlorination helps clean this water by destroying disease-causing microorganisms before the water reaches consumers. The process generally involves the following steps:

- (a) **Addition of Chlorine:** Chlorine is added to the water supply at treatment plants or drinking storage systems [118].
- (b) **Mixing and Contact Time:** The chlorine mixes thoroughly with water and remains in contact with microorganisms for a specific period, usually 15–30 min [119].
- (c) **Oxidation and Disinfection:** Chlorine oxidizes cellular components of microbes, killing or inactivating them [120].
- (d) **Residual Protection:** A small amount of chlorine remains in the water after treatment, known as residual chlorine. This residual chlorine continues to protect the water from microbial contamination during storage and distribution through pipelines [121].

3.3.3. Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is an increasingly important oxidizing agent used in drinking water treatment due to its ability to generate reactive oxygen species and its environmentally benign decomposition into water and oxygen, leaving no harmful residuals. In aqueous systems, its disinfecting action is based on both direct oxidation and indirect radical-mediated processes. Although hydrogen peroxide can inactivate microorganisms on its own, antimicrobial efficiency is generally moderate because it is less reactive than radical-based oxidants. It can be rapidly decomposed or scavenged by natural organic matter and catalase-positive microorganisms present in water [122]. Its main strength lies in its ability to form highly reactive hydroxyl radicals (OH) under specific activation conditions, which significantly enhance its disinfection and pollutant degradation capacity [123].

In drinking water treatment applications, hydrogen peroxide is rarely used alone at large scale due to its relatively limited standalone disinfecting power [124]. Instead, it is most commonly applied in combination with ultraviolet radiation, ozone, or iron catalysts in advanced oxidation processes. These integrated systems significantly improve both microbial inactivation and the removal of emerging contaminants such as pharmaceuticals, pesticides, and taste- and odor-causing compounds [125].

The effectiveness of hydrogen peroxide is significantly enhanced when it is converted into hydroxyl radicals, which are among the most powerful and non-selective oxidants used in water treatment. This transformation occurs through various activation pathways, including ultraviolet (UV) irradiation, ozone interaction and transition metal catalysis [126]. Under UV light, hydrogen peroxide undergoes photolysis, producing two hydroxyl radicals from each molecule. In the presence of ferrous ions, the classical Fenton reaction occurs, in which hydrogen peroxide reacts with Fe^{2+} to generate hydroxyl radicals, hydroxide ions, and Fe^{3+} . The ferric ions can be subsequently reduced back to ferrous ions, especially under light irradiation in the photo-Fenton process, sustaining radical production [127]. These reactions collectively form the basis of advanced oxidation processes, where hydrogen peroxide acts as a precursor for continuous radical generation.

The efficiency of hydrogen peroxide-based treatment systems depends on several physico-chemical and operational factors. Water pH plays a crucial role, especially in Fenton and photo-Fenton reactions, where acidic conditions favor optimal radical generation. Temperature influence's reaction kinetics, generally enhancing the decomposition rate of hydrogen peroxide and radical formation [128]. The presence of natural organic matter can significantly reduce treatment efficiency because it competes for hydroxyl radicals, thereby lowering their availability for microbial inactivation. Similarly, inorganic ions such as bicarbonates and chlorides can act as radical scavengers and reduce overall oxidation capacity. Hydrogen peroxide dosage and contact time are also critical parameters, as insufficient concentrations lead to incomplete disinfection, while excessive doses may increase cost without proportional improvements in performance [129].

3.3.4. Ultraviolet Light

Ultraviolet (UV) light is an advanced physical water disinfection technology widely used for improving drinking water quality. UV technology is highly important because it provides rapid and effective microbial disinfection without altering the taste, odor, or chemical composition of water. It is capable of achieving high log reductions in pathogens within seconds of exposure. Unlike chlorination, UV treatment does not generate harmful disinfection by-products such as trihalomethanes (THMs) or halo acetic acids, which are associated with long-term health risks. Additionally, UV treatment is environmentally friendly because it does not require chemical storage or handling [130].

UV radiation is a part of the electromagnetic spectrum located between visible light and X-rays, with wavelengths ranging from 100–400 nm. For water treatment, the most effective germicidal range is UV-C (200–280 nm), particularly around 254 nm, which is strongly absorbed by microbial DNA and RNA. UV treatment has become an important alternative to conventional chemical disinfectants such as chlorine because it effectively inactivates pathogens without producing harmful chemical residues or disinfection by-products [131].

The working principle of UV water treatment is based on exposing contaminated water to UV radiation inside a reactor chamber equipped with UV lamps. As water flows through the chamber, microorganisms such as bacteria, viruses, and protozoa absorb UV photons. These photons penetrate microbial cells and damage their nucleic acids (DNA and RNA), disrupting their genetic structure as mentioned in Figure 8. The most important mechanism involves the formation of pyrimidine dimers (especially thymine dimers) in DNA, which blocks replication and transcription processes. As a result, microorganisms lose their ability to reproduce and infect humans [132]. Unlike chemical disinfectants, UV does not “kill” microorganisms chemically; instead, it inactivates them biologically by preventing cellular reproduction. This mechanism makes UV highly effective against chlorine-resistant pathogens such as *Cryptosporidium* and *Giardia* [34].

UV water treatment systems mainly use two lamp technologies, i.e., (i) low-pressure UV lamps-emit monochromatic light at 254 nm and are energy efficient and (ii) medium-pressure UV lamps-emit polychromatic UV light with higher intensity and are used in large-scale water treatment plants. Recently, UV-LED technology has emerged as an innovative alternative due to lower energy consumption and mercury-free operation. In advanced oxidation processes (UV/H₂O₂), UV also helps degrade organic micropollutants such as pesticides, pharmaceutical residues, and industrial chemicals by generating hydroxyl radicals (•OH), which are strong oxidizing agents [133]. This makes UV valuable not only for disinfection but also for contaminant degradation.

3.4. Advanced and Emerging Treatment

3.4.1. Membrane Processes

Membrane processes are a group of pressure-driven or gradient-driven separation techniques widely used in modern water treatment, to remove physical, chemical, and biological contaminants from water [134]. These processes rely on a semi-permeable barrier that selectively allows certain components, mainly water molecules, to pass through while retaining suspended solids, microorganisms, organic compounds, and dissolved ions depending on the membrane type and operating conditions. In water treatment applications, membrane processes have become central due to their high efficiency, modular design, relatively low chemical requirement, and ability to produce consistent water quality suitable for drinking, irrigation, and industrial use [135].

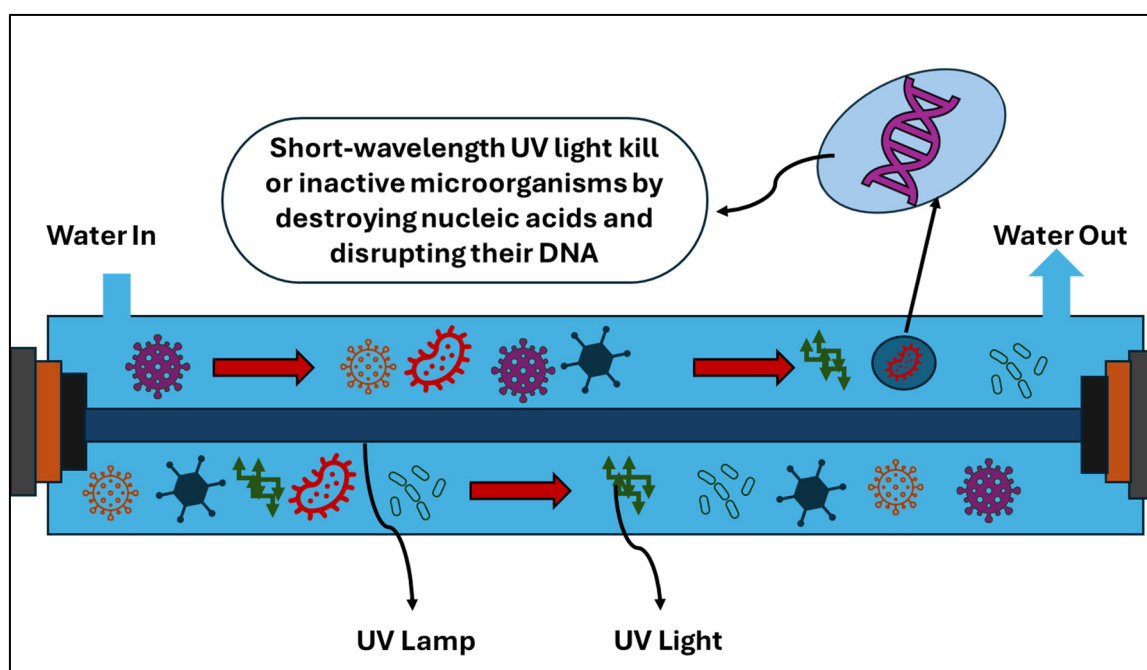


Figure 8. Representation of the mechanisms of ultraviolet technology in drinking water contamination (created with BioRender.com and power point).

In general water treatment systems, membrane processes are integrated into multi-barrier approaches where raw water first undergoes pretreatment to remove large particles and reduce fouling potential. This pretreatment may include screening, coagulation-flocculation, sedimentation, or sand filtration, depending on the quality of the feed water. After pretreatment, water is directed to membrane modules where separation occurs under controlled hydraulic pressure or concentration gradients [136]. The performance of these systems depends strongly on membrane material, pore size distribution, surface charge,

hydrophobicity, operating pressure, temperature, and feed water composition. Polymeric membranes such as polyethersulfone, polysulfone and polyamide are widely used due to their flexibility and cost-effectiveness, while ceramic membranes are applied in more demanding conditions due to their chemical and thermal stability [137].

Membrane filtration processes are generally classified according to pore size and the type of contaminants they target. Microfiltration is the least selective among pressure-driven membrane processes and typically operates with pore sizes ranging from approximately 0.1 to 10 micrometers. It is mainly used for the removal of viruses, fungi, algae, protozoa, and most bacteria. Microfiltration is often applied as a pretreatment step before more advanced membrane processes because it reduces turbidity and particulate load, thereby protecting downstream membranes from rapid fouling. Ultrafiltration operates at a smaller pore size range, typically between 0.01 and 0.1 micrometers [138], and is capable of removing viruses, colloidal particles, and high-molecular-weight organic compounds. Due to its higher selectivity, ultrafiltration is widely used in drinking water treatment plants and wastewater reuse systems, where microbial safety is a primary concern.

Nanofiltration represents an intermediate membrane process between ultrafiltration and reverse osmosis. It typically operates at pore sizes in the range of 1 nanometer and is particularly effective in removing divalent and multivalent ions such as calcium and magnesium, as well as small organic molecules and certain pesticides [139]. Nanofiltration is often referred to as a “softening membrane process” because it can reduce water hardness while maintaining partial mineral content, which is advantageous in drinking water applications. It operates at moderate pressures compared to reverse osmosis, making it more energy-efficient while still achieving significant contaminant removal [140].

Reverse osmosis is the most selective, approximately 0.1 to 1 nm (non-porous) and advanced membrane process used in water treatment [141]. It operates on the principle of applying hydraulic pressure greater than the osmotic pressure of the feed solution, forcing water molecules through a dense non-porous membrane while rejecting nearly all dissolved salts, heavy metals, pathogens, and organic contaminants. The transport mechanism in reverse osmosis is based on the solution-diffusion model, where water dissolves into the membrane material and diffuses through it, while solutes are largely excluded [142].

The efficiency of membrane processes in water treatment is influenced by several key mechanisms. Size exclusion is the primary mechanism in microfiltration and ultrafiltration, where particles larger than the membrane pores are physically retained. In nanofiltration and reverse osmosis, in addition to size exclusion, electrostatic interactions between charged solutes and membrane surfaces play a significant role. Many membranes carry a surface charge that affects the rejection of ions through Donnan exclusion, where similarly charged ions are repelled, enhancing separation efficiency. In reverse osmosis, the dominant mechanism is not simple sieving, but a diffusion-based process governed by chemical potential differences, where water movement is driven by pressure gradients against osmotic equilibrium conditions as mentioned in Figure 9.

3.4.2. Photocatalysis

Photocatalysis is an advanced oxidation technology that uses light-activated semiconductor materials, most commonly titanium dioxide (TiO_2), to degrade organic contaminants and inactivate pathogens in drinking water [143]. Upon UV or visible-light irradiation, the semiconductor generates electron-hole pairs, which react with water and oxygen to produce highly reactive hydroxyl and superoxide radicals. These radicals non-selectively oxidize organic pollutants, breaking them down into simpler, less toxic byproducts and ultimately mineralizing them into carbon dioxide and water [144]. Photocatalysis has demonstrated strong efficacy against pesticides, pharmaceuticals, dyes, and endocrine-disrupting com-

pounds, as well as microbial pathogens including bacteria and viruses [145]. Visible-light-active photocatalysts, such as doped TiO_2 and heterojunction composites, are increasingly explored to reduce reliance on UV light and improve energy efficiency. Key limitations include catalyst recovery and reuse, reduced efficiency in turbid or high-organic-load water, and the need for further pilot- and full-scale validation before widespread adoption.

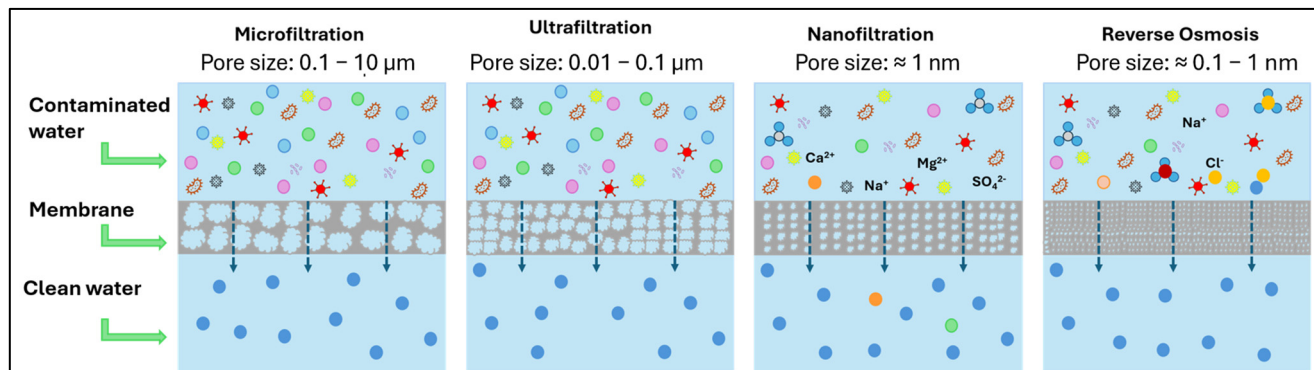


Figure 9. Schematic illustration of the mechanisms of membrane processes technology in drinking water contamination (created with [BioRender.com](https://www.biorender.com) and power point).

3.4.3. Electrochemical Treatment

Electrochemical treatment uses electrical current to drive contaminant removal directly at electrode surfaces, without requiring large chemical inputs [146]. The main approaches include electrocoagulation, in which sacrificial metal electrodes (typically aluminum or iron) dissolve to generate coagulant species in situ, destabilizing and aggregating suspended and colloidal contaminants for removal by sedimentation or flotation; and electrooxidation, in which contaminants are directly oxidized at the electrode surface or indirectly via electrochemically generated reactive species. Electrochemical disinfection can also inactivate pathogens through direct electron transfer and in situ generation of oxidants such as chlorine or hydrogen peroxide. These methods are effective against heavy metals, emerging organic contaminants, and microbial pathogens, and offer a compact, chemical-reagent-free footprint suited to decentralized treatment [147]. Limitations include electrode fouling and passivation, relatively high energy consumption compared to conventional coagulation, and the need for periodic electrode replacement.

3.4.4. Nanotechnology-Based Systems

Nanomaterials are increasingly applied in drinking water treatment due to their high surface-area-to-volume ratio, tunable surface chemistry, and enhanced reactivity compared to bulk materials [148]. Beyond the magnetite/maghemite nanoparticles used in magnetic separation, nanotechnology applications include nanocomposite membranes incorporating graphene oxide or carbon nanotubes for improved permeability, fouling resistance, and contaminant rejection; silver and metal-oxide nanoparticles for antimicrobial disinfection; and engineered nanoadsorbents for selective removal of heavy metals, PFAS, and emerging organic contaminants [149]. These materials can be integrated into existing filtration and adsorption systems to enhance removal efficiency at lower material loadings. Despite promising lab-scale performance, key challenges remain around production cost and scalability, potential nanomaterial release and ecotoxicity, and the absence of standardized protocols for evaluating long-term stability and safety in drinking water applications.

Beyond inorganic nanomaterials, biopolymer-based nanocomposites represent an emerging and more environmentally sustainable class of adsorbents and membrane materials. Natural biopolymers such as chitosan, alginate, cellulose, and starch are combined with

nanofillers, including graphene oxide, carbon nanotubes, and nanoclays, to enhance adsorption capacity, selectivity, and mechanical stability while retaining the biodegradability and low toxicity of the base polymer [150]. Chitosan-based composites have demonstrated particularly strong performance for heavy metal and dye removal; a chitosan-activated carbon composite achieved 98.7% removal efficiency for hexavalent chromium, while a graphene oxide- Fe_3O_4 -chitosan composite removed 98% of dye contaminants while retaining magnetic separability for reuse [151]. Complementing these engineered composites, eco-friendly nano-adsorbents derived from natural or agro-industrial waste materials, such as algae, cellulose-based sawdust, and biochar, are being explored as lower-cost, more sustainable alternatives to conventional activated carbon, though their large-scale adoption remains limited by production consistency and characterization standards [152].

3.5. Biological and Resource-Recovery Treatment

Bioremediation

Conventional drinking water treatments are becoming increasingly expensive, energy-intensive, and often generate secondary pollutants or sludge that require further disposal. At the same time, intensified human activities such as industrial manufacturing and intensive agriculture have significantly contributed to the contamination of water resources with a wide range of chemical pollutants and heavy metals. In this context, bioremediation technology has emerged as a sustainable and cost-effective alternative for addressing drinking water contamination, particularly in regions where conventional treatment methods are economically unfeasible, operationally demanding, or environmentally harmful [153]. This approach harnesses the natural metabolic and physicochemical capabilities of bacteria, fungi, algae, and higher plants to degrade, transform, or immobilize contaminants directly within aquatic systems, thereby minimizing the generation of additional waste or harmful by-products.

The mechanisms of bioremediation are generally categorized into four main biological processes, each contributing differently depending on environmental conditions and pollutant types. The first is biodegradation and biotransformation, in which microorganisms utilize specific enzymes to metabolize organic contaminants such as pesticides, pharmaceuticals, and industrial chemicals, using them as sources of carbon or energy. Under aerobic conditions, these enzymatic reactions typically involve oxidative pathways that break complex aromatic structures into simpler, less toxic compounds as mentioned in Figure 10 [154]. In contrast, in anaerobic environments such as deep groundwater, specialized microbial communities facilitate reductive processes, including dehalogenation, which progressively remove toxic functional groups like chlorine until the compounds become environmentally benign [155].

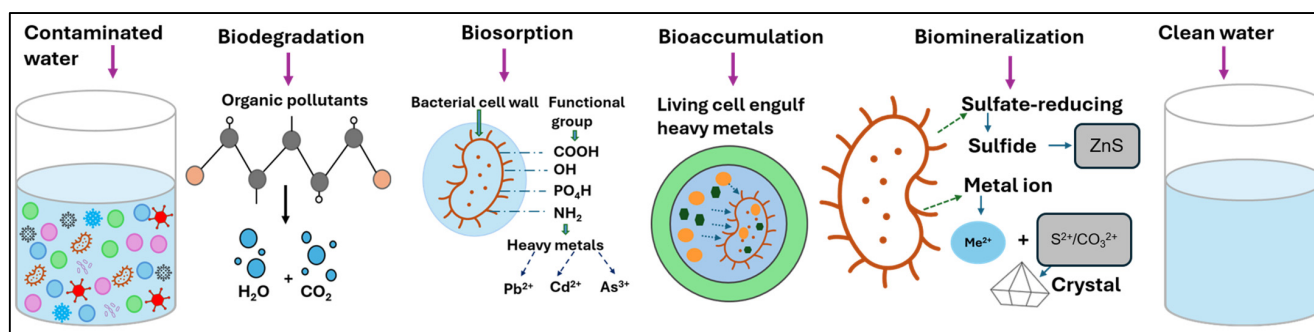


Figure 10. Schematic visualization of the mechanisms of bioremediation technology in drinking water contamination (created with [BioRender.com](https://www.biorender.com) and power point).

The second mechanism is biosorption, a rapid and largely passive process that does not require metabolic activity and can therefore occur in both living and dead biomass. The cell walls of algae, fungi, and bacteria contain functional groups such as carboxyl, hydroxyl, phosphate, and amine groups, which act as natural binding sites for metal ions [156]. Through electrostatic attraction and ion exchange, these structures efficiently capture heavy metals including lead, cadmium, and arsenic from contaminated water as mentioned in Figure 10.

The third process, bioaccumulation, is an energy-dependent mechanism in which living cells actively transport contaminants across their membranes and sequester them internally. Once inside the cell, pollutants may be compartmentalized, transformed into less toxic forms, or bound to intracellular proteins for detoxification as mentioned in Figure 10 [157]. Although highly effective for removing heavy metals and certain organic compounds, this method requires careful management of the biomass, as cell death or improper disposal can lead to the re-release of accumulated toxins back into the environment.

The fourth mechanism is biomineralization, where microorganisms induce chemical reactions that convert dissolved toxic metals into stable, insoluble mineral forms. For instance, some bacteria facilitate the precipitation of metal ions through metabolic by-products such as sulfides or carbonates, leading to the formation of solid particles that settle out of the water column [158]. In other cases, microbial activity promotes the formation of calcium carbonate crystals that can encapsulate heavy metals within their structure, effectively immobilizing them in a stable, rock-like matrix as mentioned in Figure 10. This process not only reduces metal mobility but also enhances long-term stabilization of contaminants, making subsequent removal from water systems more efficient [159]. Together, these mechanisms provide an integrated and sustainable approach for restoring and maintaining safe drinking water quality.

Table 10 brings together the treatment technologies discussed in this review to allow direct comparison across methods.

Table 10. Key operational parameters and sustainability-related considerations of conventional, advanced, and emerging drinking-water treatment technologies.

Technology	Key Parameters Affecting Performance	Sustainability Indicators and Critical Considerations
Coagulation–flocculation	pH, coagulant type and dose, water chemistry, mixing intensity, contact time	Chemical consumption, energy requirements for mixing, sludge generation and management
Activated alumina	pH, surface charge, adsorbent dose, contact time, contaminant concentration and competing ions	Adsorbent consumption, regeneration/reuse potential, spend-media management and contaminant disposal
Activated carbon	Adsorbent characteristics, surface area, contact time, contaminant concentration and water matrix	Adsorbent production and consumption, regeneration/reuse requirements, spent-carbon management and material replacement
Ozonation	Ozone dose, contact time, pH, dissolved organic matter and water matrix	Electricity requirement for ozone generation, ozone dose, potential oxidation/disinfection by-product formation and off-gas management
Chlorination	Chlorine dose, contact time, pH, temperature and water chemistry	Chemical demand, storage/handling requirements and formation of disinfection by-products
Membrane processes	Membrane material, pore size, transmembrane pressure, temperature, feed composition and fouling	Energy demand, membrane fouling, cleaning chemicals, membrane replacement, concentrate generation and management
Magnetic separation	Magnetic material properties, particle size, surface functionalization, magnetic-field strength and separation conditions	Material synthesis and consumption, recovery/reuse potential; material stability and limited full-scale quantitative sustainability data

Table 10. Cont.

Technology	Key Parameters Affecting Performance	Sustainability Indicators and Critical Considerations
Bioremediation	Microbial population, contaminant concentration, pH, temperature, nutrients, hydraulic retention time and environmental conditions	Potentially low chemical demand and energy consumption; treatment time, biomass management and process stability are important considerations
Photocatalysis	Catalyst type and loading, light intensity/wavelength, irradiation time, pH, contaminant concentration and water matrix	Energy demand associated with light irradiation, catalyst production and recovery/reuse, catalyst stability and potential secondary-product formation
Electrochemical treatment	Current density, applied voltage, electrode material, electrolyte concentration, treatment time and water chemistry	Electricity consumption, electrode consumption/passivation, electrode replacement and possible secondary oxidant/by-product formation
Nano-technology-based systems	Nanomaterial type, particle size and surface properties, material loading, contaminant concentration and contact time	Nanomaterial production and material requirements, recovery/reuse, long-term stability, potential release/ecotoxicity and limited full-scale validation
UV/H ₂ O ₂	UV fluence, H ₂ O ₂ dose, UV transmittance, contact time, pH and water matrix	Electricity and H ₂ O ₂ consumption, treatment efficiency, radical scavenging by natural organic matter and potential transformation by-products
Distillation	Temperature, pressure, heating rate, evaporation/condensation conditions, feed composition and recovery ratio	High thermal-energy requirement, dependence on energy source, scaling, concentrate/brine management and potential integration with waste heat or renewable energy

Quantitative sustainability indicators are not directly comparable across all technologies because energy consumption, material requirements, operating costs and environmental burdens are strongly dependent on treatment objectives, contaminant concentration, water-matrix characteristics, process configuration, operating conditions and treatment scale; therefore, technology-specific sustainability indicators and limitations are emphasized rather than assigning universal numerical values.

4. Emerging Trends

Beyond established and advanced treatment technologies, several emerging trends are shaping the next generation of drinking water purification. Smart water treatment systems integrate Internet-of-Things (IoT) sensors, real-time contaminant monitoring, and artificial intelligence-based process control to enable continuous water quality assessment and predictive maintenance. Machine learning models are increasingly applied to forecast contaminant loads, optimize membrane operation, and detect anomalies in distribution networks before they compromise water safety, reducing reliance on fixed treatment schedules in favor of responsive, data-driven operation [160].

Advanced functional materials are also transforming contaminant removal at the material level. Metal–organic frameworks (MOFs), molecularly imprinted polymers, biochar-based composites, and two-dimensional materials such as graphene oxide offer high surface area, tunable selectivity, and enhanced adsorption or catalytic capacity for trace and emerging contaminants, including pharmaceuticals, PFAS, and endocrine-disrupting compounds. Their engineered porosity and surface chemistry allow selective binding of target pollutants even at low concentrations, though production scalability and cost remain limiting factors [161].

Renewable energy integration addresses the high energy demand of processes such as reverse osmosis and advanced oxidation. Solar-powered disinfection, solar-driven photo-

catalysis, and hybrid photovoltaic-membrane systems are being piloted for decentralized and off-grid treatment, particularly in resource-limited settings, lowering both operational cost and carbon intensity [162].

Circular water management strategies reframe treatment residuals as recoverable resources rather than waste. Wastewater reuse, nutrient and metal recovery from treatment sludge, and decentralized modular treatment units reduce net freshwater withdrawal and disposal burden while improving overall system resilience [163].

5. Future Directions

Ensuring universal access to safe drinking water will require a transition from conventional treatment approaches toward integrated, intelligent, and sustainable water purification systems capable of addressing increasingly complex contamination profiles. Future research should prioritize the development of multifunctional treatment technologies that simultaneously remove heavy metals, pathogens, emerging contaminants, microplastics, pharmaceuticals, and per- and polyfluoroalkyl substances (PFAS), as no single existing technology provides comprehensive contaminant removal under diverse water quality conditions.

Greater emphasis should also be placed on designing low-energy, cost-effective, and environmentally sustainable treatment processes suitable for decentralized and resource-limited settings. The use of advanced functional materials, including engineered adsorbents, biochar-based composites, metal–organic frameworks, nanomaterials, and photocatalysts, offers significant potential for improving contaminant removal efficiency while reducing operational costs and secondary waste generation. However, further studies are required to evaluate their long-term stability, regeneration, environmental safety, and large-scale applicability.

The integration of artificial intelligence, machine learning, Internet of Things (IoT)-based sensors, and real-time water quality monitoring is expected to transform drinking water management by enabling predictive maintenance, rapid contaminant detection, and optimization of treatment performance. Likewise, coupling renewable energy sources such as solar-powered membrane systems and advanced oxidation processes with water treatment facilities could substantially improve energy efficiency and reduce carbon emissions.

Future investigations should also adopt a circular economy perspective by promoting resource recovery, sustainable management of residual treatment, and life-cycle assessment of purification technologies. Finally, stronger international collaboration, harmonized regulatory frameworks, and long-term monitoring programs are needed to improve risk assessment for emerging contaminants and accelerate the translation of innovative laboratory-scale technologies into reliable, scalable, and economically viable solutions that support global water security and the achievement of Sustainable Development Goal 6.

6. Conclusions

This review highlights the diverse range of contaminants that compromise drinking water quality, including physical, chemical, microbiological, inorganic, organic, radiological, agricultural and industrial pollutants, all of which pose significant risks to human health and environmental sustainability. Conventional treatment technologies, such as coagulation–flocculation, filtration, adsorption, activated carbon, ion exchange, and disinfection, remain effective for removing many common contaminants. However, their performance is often limited when addressing persistent and emerging pollutants, including pharmaceuticals, PFAS, endocrine-disrupting compounds, and microplastics.

Advanced technologies, including membrane filtration, reverse osmosis, advanced oxidation processes, photocatalysis, electrochemical methods, and nanomaterial-based

treatments, demonstrate superior removal efficiencies for a broader range of contaminants but are frequently constrained by higher costs, energy demands, membrane fouling, and operational complexity. Therefore, integrated multi-barrier treatment systems that combine conventional and advanced processes represent the most effective strategy for ensuring safe and reliable drinking water.

Future research should focus on developing sustainable, energy-efficient, and economically viable purification technologies, while improving real-time water quality monitoring and treatment system resilience. Continued innovation, combined with effective water management and regulatory support, will be essential for safeguarding public health, protecting freshwater resources, and achieving long-term global water security.

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