

Pollutant Sources, Removal Techniques and their Impacts on Environmental Quality and Ecological Sustainability

¹Peace Onya Ali, ²Ikechukwu Sampson Chikwe, ³Olubunmi Abiola Adewusi, ⁴Tasie Chimezie Michael, ⁵Boniface Tersoo Iorhuna, ⁶Edjere Akpoobaro Obadejire, ⁷Erienu Obruché Kennedy

¹Department of SLT, Petroleum Training Institute, Effurun

²Department of SLT, Imo State Polytechnic, Omuma

³Department of Chemistry, Lagos State University, Ojo, Lagos, Nigeria

⁴Department of Agricultural Economics, Ignatius Ajuru University of Education, Port Harcourt

⁵Department of Chemical Sciences, Taraba State University, Jalingo

⁶Department of Physics, Delta State College of Education, Mosogar

⁷Department of Chemistry, Delta State College of Education, Mosogar

Abstract — Environmental pollution is a major global challenge that threatens environmental quality, human health, biodiversity, and ecological sustainability. This review examines the sources of environmental pollutants, pollutant removal techniques, their effectiveness, and their impacts on environmental quality and ecological sustainability. Major sources of pollution include industrial activities, agricultural practices, domestic waste, petroleum operations, transportation, and improper waste disposal. Common pollutants include heavy metals, petroleum hydrocarbons, pesticides, plastics, particulate matter, and emerging contaminants. Conventional removal techniques, such as filtration, adsorption, chemical precipitation, and biological treatment, are discussed alongside emerging approaches, including phytoremediation, nanotechnology, membrane filtration, electrochemical treatment, and advanced oxidation processes. The review highlights that the effectiveness of these techniques depends on pollutant characteristics, treatment conditions, operational costs, and environmental requirements. Although pollutant removal technologies can improve air, water, and soil quality, some generate secondary waste, consume substantial energy, or produce potentially harmful transformation products. These limitations emphasize the need for integrated treatment strategies, effective waste management, pollution prevention, and continuous environmental monitoring. Sustainable pollution control should prioritize affordable, energy-efficient, and environmentally safe technologies that support ecosystem restoration, biodiversity conservation, and resource recovery. The review concludes that combining conventional and emerging remediation techniques with stronger environmental regulations and sustainable production practices is essential for reducing pollution and promoting long-term ecological sustainability.

Keywords— Pollutant, Techniques, Environmental, Ecological, Sustainability

I. INTRODUCTION

Environmental pollution is a major global challenge that threatens human health, ecosystem stability, biodiversity, and the sustainable use of natural resources (Obruché et al., 2019; Ugochukwu et al., 2025). It occurs when harmful substances or forms of energy enter the environment at concentrations that adversely affect living organisms and natural processes (Odimgbe et al., 2026). Rapid industrialization, urbanization, agricultural intensification, population growth, and inadequate waste management have increased the release of pollutants into the air, water, and soil (United Nations Environment Programme [UNEP], 2019; WHO, 2021). Environmental pollutants include heavy metals, petroleum hydrocarbons, pesticides, plastics, particulate matter, and emerging

contaminants such as pharmaceuticals. These substances differ in their toxicity, persistence, mobility, and potential to accumulate in living organisms. Some pollutants degrade naturally, while others remain in the environment for extended periods, disrupting ecological processes and reducing environmental quality (Gavrilescu, 2005; Schwarzenbach et al., 2006; Umudi et al., 2025). Pollutant removal techniques are therefore essential for reducing contamination and restoring environmental quality. Conventional methods, including filtration, sedimentation, chemical precipitation, and biological treatment, are widely used to manage pollution. Emerging approaches, such as nanotechnology, advanced oxidation, phytoremediation, and biochar adsorption, offer additional opportunities for treating complex pollutants and improving resource recovery (Crini & Lichtfouse, 2019; R. K. Gautam et

al., 2014; Nathan et al., 2025). However, pollutant removal does not always eliminate environmental risks. Some treatment processes generate contaminated sludge, transformation products, or other residues that require further management. Consequently, pollution control should be assessed not only by the amount of contaminant removed but also by its effects on ecosystem health, energy consumption, waste generation, and long-term sustainability (Kümmerer, 2010; Umudi et al., 2025). This review examines the sources and types of environmental pollutants, conventional and emerging removal techniques, their effectiveness and limitations, and their implications for environmental quality and ecological sustainability (Etus and Erienu, 2026). It also identifies major challenges and future opportunities for developing effective, affordable, and environmentally responsible pollution-control strategies.

II. SOURCES AND TYPES OF ENVIRONMENTAL POLLUTANTS

Environmental pollutants originate from both human activities and natural processes (figure 1). Anthropogenic sources are particularly important because they can release large quantities of contaminants into the environment within relatively short periods (Micheal et al., 2026). Industrial activities contribute pollutants through manufacturing emissions, wastewater discharge, chemical processing, mining, and petroleum production (Abeokuta et al., 2025). These activities may release heavy metals, acids, solvents, hydrocarbons, and particulate matter. When industrial effluents are discharged without adequate treatment, they can alter water chemistry, contaminate sediments, and expose aquatic organisms to toxic substances (Alloway, 2013; Tchounwou et al., 2012; Umudi et al., 2025). Agricultural activities are another significant source of pollution. Fertilizers introduce excess nitrogen and phosphorus into water bodies, potentially causing eutrophication, algal blooms, oxygen depletion, and aquatic ecosystem deterioration. Pesticides can contaminate soil and surface water, affecting non-target organisms and disrupting ecological interactions (Carpenter et al., 1998; Stehle & Schulz, 2015).

Domestic and municipal waste contributes organic matter, pathogens, detergents, plastics, pharmaceuticals, and other contaminants. Inadequate sanitation and poorly managed landfills may facilitate the movement of pollutants into groundwater and surface water. Plastic waste is particularly concerning because it can fragment into microplastics that persist in aquatic and terrestrial environments (Geyer et al., 2017; Jambeck et al., 2015; Umudi et al., 2025). Oil exploration, petroleum refining, transportation, and accidental oil spills release hydrocarbons into soil and water. These

compounds can reduce soil fertility, interfere with plant growth, damage aquatic organisms, and alter microbial communities responsible for nutrient cycling. Petroleum contamination is especially difficult to manage when pollutants become trapped in soil pores or bind strongly to organic matter (Atlas, 1981). Air pollution originates from transportation, fossil fuel combustion, industrial emissions, open waste burning, and certain agricultural activities. Pollutants such as particulate matter, nitrogen oxides, sulfur dioxide, and ground-level ozone affect respiratory health, vegetation, atmospheric chemistry, and climate. Natural sources, including volcanic eruptions, dust storms, and wildfires, can also contribute significantly to environmental contamination (WHO, 2021). For effective pollution management, pollutants should be classified according to their chemical characteristics, environmental medium, toxicity, and persistence. Understanding their sources and behaviour helps determine the most appropriate removal technology and prevents the transfer of contamination from one environmental compartment to another.



Figure 1: Sources and Types of Environmental Pollutants

III. CONVENTIONAL AND EMERGING POLLUTANT REMOVAL TECHNIQUES

Pollutant removal techniques are processes designed to reduce the concentration, toxicity, mobility, or environmental availability of contaminants. The selection of a suitable technique depends on the pollutant type, concentration, contaminated medium, treatment cost, available infrastructure, and required environmental standards (Jacintha et al., 2025). Conventional methods include sedimentation, filtration, adsorption, chemical precipitation, and biological wastewater treatment (Okpanachi et al., 2025). These methods are widely applied because many are technically established and can be adapted to different treatment capacities. However, their performance varies according to pollutant characteristics and

operating conditions (Crini & Lichtfouse, 2019). Emerging techniques include advanced oxidation processes, nanomaterial-based treatment, phytoremediation, electrochemical treatment, and improved adsorbents such as biochar (Etus and Erienu, 2026). These approaches may

improve the removal of persistent contaminants, although some require additional energy, specialized equipment, or careful management of treatment residues (Fu & Wang, 2011; R. K. Gautam et al., 2014; Obruche et al., 2025).

Table 1. Conventional and emerging techniques for pollutant removal

Removal technique	Main mechanism	Target pollutants	Major advantages	Limitations
Filtration and sedimentation	Physical separation of particles	Suspended solids and particulate matter	Simple operation and established technology	Limited removal of dissolved pollutants
Adsorption	Binding of contaminants to solid surfaces	Dyes, metals and some organic pollutants	Flexible and potentially efficient	Spent adsorbents require regeneration or safe disposal
Chemical precipitation	Conversion of dissolved contaminants into insoluble solids	Heavy metals and selected inorganic pollutants	Effective under suitable chemical conditions	Produces sludge and requires chemical inputs
Biological treatment	Microbial degradation and transformation	Biodegradable organic matter and selected contaminants	Can reduce organic pollution with relatively low chemical demand	Sensitive to operating conditions and contaminant toxicity
Phytoremediation	Plant uptake, stabilization or transformation	Selected metals and organic pollutants in soil and water	Can support ecological restoration and reduce site disturbance	Often slow and dependent on plant and site conditions
Advanced oxidation	Generation of reactive species that transform contaminants	Persistent organic compounds and selected emerging contaminants	Can break down compounds resistant to conventional treatment	Energy and chemical requirements; by-products may form
Membrane separation	Selective separation through membrane barriers	Suspended solids, microorganisms and selected dissolved contaminants	Produces high-quality treated water under suitable conditions	Fouling, energy use and concentrate management
Nanotechnology-based treatment	Adsorption, catalytic transformation or separation using nanomaterials	Selected metals and organic contaminants	High surface area and tunable properties	Material recovery, potential toxicity and cost concerns
Electrochemical treatment	Electrocoagulation, electrode reactions or electro-oxidation	Metals, dyes and selected industrial pollutants	Can combine several treatment mechanisms	Electricity demand, electrode consumption and residue management
Biochar-based treatment	Sorption and surface interactions	Selected metals, nutrients and organic contaminants	Potentially low-cost and supports waste valorization	Performance depends on feedstock and production conditions

Source: Synthesized from Fu and Wang (2011), Crini and Lichtfouse (2019), R. K. Gautam et al. (2014), Ali et al. (2012), and V. K. Gupta et al. (2012).

Table 1 demonstrates that pollutant removal techniques differ in their mechanisms, applications, benefits, and limitations. Physical processes such as filtration and sedimentation are useful for removing suspended materials but generally require additional treatment when dissolved pollutants are present. Chemical precipitation can remove selected metals effectively,

although the resulting sludge must be handled to prevent secondary contamination (Ogwuche and Obruche, 2020; Erienu et al., 2022). Adsorption is versatile because it can be applied to a range of pollutants using activated carbon, biochar, mineral materials, and engineered adsorbents. Its effectiveness depends on surface properties, pH, contact time, and competition between contaminants. Ali et al. (2012) describe the potential of agricultural waste-derived adsorbents as lower-cost alternatives for removing certain pollutants, while Crini and Lichtfouse (2019) emphasize the importance of selecting

adsorbents according to the treatment objective. Biological treatment and phytoremediation offer opportunities to reduce pollution through microbial activity and plant-mediated processes (Sarah et al., 2026). These methods can be valuable where contamination is treatable under natural or controlled biological conditions. However, they may be slower than some chemical processes, and plants or microbial communities may be affected by high contaminant concentrations (Festus-Amadi et al., 2021). Advanced oxidation and nanotechnology-based methods can address certain contaminants that resist conventional treatment. Nevertheless, their benefits must be weighed against energy demand, chemical consumption, potential by-product formation, and the fate of engineered materials after treatment. Membrane and electrochemical processes can provide effective separation or transformation, but their long-term performance depends on operational costs, maintenance, and residue management. Overall, no single technique is suitable for all pollution scenarios. Combining complementary methods can improve treatment performance, particularly where wastewater or contaminated soil contains mixtures of pollutants. The most appropriate approach is therefore one that achieves the required contaminant reduction while minimizing secondary pollution, cost, and adverse ecological effects.

IV. EFFECTIVENESS AND LIMITATIONS OF POLLUTANT REMOVAL TECHNIQUES

The effectiveness of pollutant removal techniques is determined by their ability to reduce contaminant concentrations, toxicity, mobility, and potential ecological harm. Important performance indicators include removal efficiency, treatment time, operational cost, energy consumption, and the environmental safety of treatment residues. A technology that performs well under laboratory conditions may not achieve the same results when applied to complex industrial wastewater or contaminated soils (Saravanan et al., 2022). Adsorption is widely investigated because of its operational simplicity and effectiveness against various dissolved contaminants. Its performance depends on adsorbent characteristics, pollutant concentration, pH, temperature, and contact time. Nevertheless, adsorption generally transfers pollutants from water to a solid material rather than destroying them. Consequently, regeneration, recovery, or safe disposal of the spent adsorbent is necessary (Crini & Lichtfouse, 2019). Membrane filtration can produce high-quality treated water, but membrane fouling, energy requirements, and the management of concentrated waste streams can increase treatment costs. Chemical oxidation processes can transform persistent organic pollutants, although

incomplete oxidation may produce intermediate compounds whose toxicity must be assessed (Miklos et al., 2018; Shannon et al., 2008). Bioremediation and phytoremediation are potentially sustainable because they use microorganisms or plants to degrade, transform, extract, or immobilize selected pollutants. However, their effectiveness depends on environmental conditions, contaminant bioavailability, microbial activity, plant tolerance, and treatment duration (Ali et al., 2013; Pilon-Smits, 2005).

The most effective strategy is therefore not necessarily the one with the highest immediate removal percentage. Instead, the selected technique should achieve the required environmental quality while considering life-cycle costs, secondary waste, treatment reliability, and ecological safety. Combining complementary methods may improve overall performance, particularly when pollutants differ in their chemical properties and resistance to degradation (Kato & Kansha, 2024; Shannon et al., 2008).

V. IMPACTS OF ENVIRONMENTAL POLLUTANTS ON ENVIRONMENTAL QUALITY

Environmental quality describes the condition of air, water, soil, and ecosystems in relation to their ability to support human health, biodiversity, and ecological processes. Pollutants can deteriorate this quality by changing the physical, chemical, and biological characteristics of the environment. Air pollution is associated with respiratory and cardiovascular diseases, premature mortality, reduced visibility, and damage to vegetation. Fine particulate matter and ground-level ozone are particularly important because they affect both human health and ecosystem functioning. The World Health Organization (2021) identifies air pollution as a major environmental health risk requiring coordinated emission reduction and air-quality management.

Water pollution results from the introduction of pathogens, nutrients, heavy metals, petroleum hydrocarbons, pesticides, and other contaminants into rivers, lakes, groundwater, and coastal environments. Excess nutrients can cause eutrophication, leading to algal blooms, oxygen depletion, and changes in aquatic community structure (Carpenter et al., 1998). Heavy metals can persist in sediments and enter food webs, potentially causing toxic effects in organisms and increasing risks to humans through contaminated food and water (Tchounwou et al., 2012).

Soil pollution reduces soil quality by altering microbial activity, nutrient cycling, soil structure, and plant growth. Persistent contaminants can reduce agricultural productivity and move into groundwater or crops. Heavy metals are particularly concerning because they cannot be biodegraded, although their chemical forms and mobility can change through environmental processes (Alloway, 2013). Plastic pollution introduces persistent debris and microplastics into terrestrial, freshwater, and marine environments. These materials can be ingested by organisms, affect feeding and habitat quality, and

transport certain associated chemicals. The accumulation of plastic waste reflects the environmental consequences of production, consumption, and inadequate waste management (Geyer et al., 2017; Jambeck et al., 2015). Persistent organic pollutants may remain in the environment for extended periods and accumulate in organisms. Their movement through food webs can expose organisms far from the original contamination source, making monitoring and remediation especially important (Jones & de Voogt, 1999).

Table 2. Major environmental pollutants and their impacts on environmental quality

Environmental pollutant	Major sources	Environmental impacts	Implications for ecological sustainability
Heavy metals, including lead, cadmium and mercury	Mining, industries, batteries and industrial wastewater	Soil and water contamination; toxicity to plants and animals	Disruption of food webs and long-term contamination
Petroleum hydrocarbons	Oil spills, refineries and fuel leakage	Soil degradation, aquatic toxicity and reduced oxygen exchange	Habitat damage and slower ecosystem recovery
Pesticides	Agricultural application and improper disposal	Harm to non-target organisms and contamination of water and soil	Reduced biodiversity and disruption of ecological interactions
Excess nitrogen and phosphorus	Fertilizers, sewage and livestock waste	Eutrophication, algal blooms and oxygen depletion	Loss of aquatic biodiversity and impaired ecosystem functioning
Plastics and microplastics	Municipal waste, packaging, textiles and industrial activities	Persistent litter, ingestion by organisms and habitat deterioration	Long-term waste accumulation and ecological stress
Particulate matter and gaseous air pollutants	Transport, industries, fuel combustion and waste burning	Respiratory illness, vegetation damage and atmospheric changes	Reduced ecosystem health and increased environmental pressure
Pharmaceuticals and personal care products	Domestic sewage, healthcare and industrial discharges	Potential biological effects on aquatic organisms and incomplete removal during treatment	Uncertain long-term ecological effects and chronic exposure
Persistent organic pollutants	Certain industrial processes, legacy chemicals and accidental releases	Long-term contamination and potential bioaccumulation	Persistent exposure and disruption of ecosystem stability

Source: Synthesized from Alloway (2013), Carpenter et al. (1998), Jones and de Voogt (1999), Geyer et al. (2017), Tchounwou et al. (2012), and Schwarzenbach et al. (2006).

Table 2 shows that environmental pollutants differ in their sources, behaviour, and ecological consequences. Heavy metals and persistent organic pollutants are particularly challenging because they may remain in environmental systems for long periods. Although metals cannot be destroyed through

conventional biological degradation, their mobility and toxicity can sometimes be reduced through immobilization, chemical treatment, or removal from contaminated media. Nutrients such as nitrogen and phosphorus illustrate how substances that are essential for biological growth can become pollutants when present in excessive quantities. Their accumulation in water bodies can stimulate algal growth, reduce dissolved oxygen, and damage aquatic ecosystems. Effective control therefore requires both the removal of excess nutrients and the prevention

of their release from agricultural and wastewater sources (Carpenter et al., 1998). Petroleum hydrocarbons, pesticides, and plastics present different environmental challenges. Petroleum contamination can damage habitats and reduce soil functionality, while pesticides may affect organisms that are not intended targets. Plastics can persist and fragment into smaller particles, complicating environmental collection and monitoring. These differences demonstrate why pollution management should be tailored to the pollutant rather than relying on a single universal method. Air pollutants also have implications beyond their immediate location of release. Their effects can extend to vegetation, climate-related processes, human health, and the deposition of contaminants onto soil and water. Similarly, pharmaceuticals and personal care products require attention because some may pass through conventional wastewater treatment and enter aquatic ecosystems (Schwarzenbach et al., 2006). The table further indicates that ecological sustainability depends on preventing long-term contamination, protecting biodiversity, and maintaining ecosystem functions. Effective environmental management must therefore combine pollution prevention, appropriate treatment, regular monitoring, and responsible waste disposal. Reducing pollutant releases at their sources is particularly important because it limits the burden placed on downstream treatment systems and natural ecosystems.

VI. IMPACTS OF POLLUTANT REMOVAL TECHNIQUES ON ECOLOGICAL SUSTAINABILITY

Pollutant removal techniques can improve ecological sustainability by reducing toxic exposures, restoring degraded habitats, protecting biodiversity, and supporting the responsible use of natural resources (figure 2). However, the environmental benefits depend on the treatment method, its operating conditions, and the management of residues produced during treatment. Biological remediation and phytoremediation can contribute to ecosystem restoration by reducing selected contaminants while minimizing disturbance to the environment (Ikechukwu et al., 2026). Plants may extract, stabilize, or transform certain pollutants, while microorganisms can degrade biodegradable organic compounds. These methods can be particularly useful for contaminated soils and wetlands when site conditions support biological activity (Ali et al., 2013; Pilon-Smits, 2005). Adsorption and membrane technologies can improve water quality by removing contaminants from wastewater and industrial effluents. Adsorption materials derived from agricultural residues may also support waste valorization by converting some forms of biomass into useful treatment materials. Nevertheless, spent adsorbents and

membrane concentrates require appropriate management to prevent contaminants from re-entering the environment (Crini & Lichtfouse, 2019; Shannon et al., 2008). Advanced oxidation and electrochemical treatment can help remove or transform persistent pollutants that resist conventional biological treatment. However, their sustainability must be assessed against electricity consumption, chemical requirements, equipment costs, and the possible formation of harmful transformation products. Treatment effectiveness should therefore be evaluated alongside the environmental burdens associated with operating the technology (Martínez-Huitle & Brillas, 2009; Miklos et al., 2018). Ecologically sustainable pollution management also requires the prevention of secondary pollution. For example, removing heavy metals from wastewater does not eliminate the hazard if the metals remain concentrated in sludge that is subsequently disposed of improperly. Similarly, pollutants accumulated in plant biomass may require controlled harvesting and disposal. Remediation should consequently be viewed as a complete process that includes contaminant removal, residual management, and verification of environmental recovery (Itodo et al., 2021; Ekpo et al., 2023). The principles of a circular economy can strengthen sustainability by promoting water reuse, nutrient recovery, material recycling, and energy recovery where these practices are safe and appropriate. Industrial wastewater treatment can thus contribute not only to pollution reduction but also to resource conservation and more efficient production systems (Kato & Kansha, 2024).

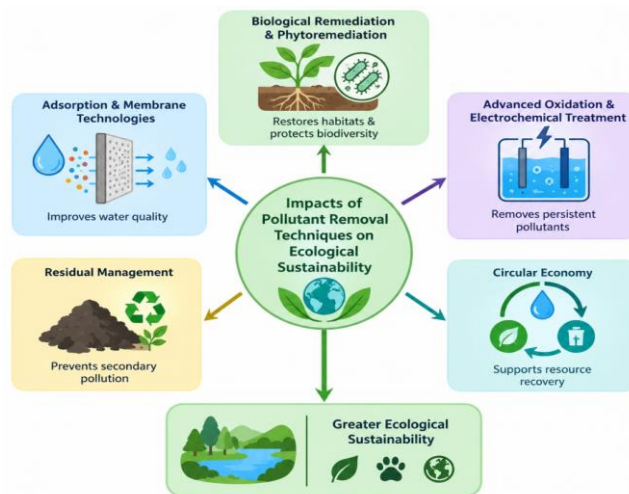


Figure 2: Impacts of Pollutant Removal Techniques on Ecological Sustainability

Challenges and Future Prospects of Sustainable Pollution Control

Despite advances in environmental remediation, several challenges limit the widespread application of effective pollution-control technologies. These include high capital costs, inadequate treatment infrastructure, limited technical expertise, inconsistent monitoring, and insufficient enforcement of environmental regulations. Such barriers can be especially significant in communities where waste collection, wastewater treatment, and industrial monitoring systems are underdeveloped. A major technical challenge is the presence of mixed contaminants. Industrial wastewater, contaminated soil, and municipal effluents may contain metals, organic compounds, nutrients, and microorganisms simultaneously. Because these pollutants respond differently to treatment, a process that effectively removes one contaminant may have limited effects on another. Integrated treatment systems are therefore increasingly important for complex pollution scenarios (Obruche et al., 2018; Saravanan et al., 2022; Ekpo et al., 2025).

Another concern is the gap between laboratory performance and practical implementation. Advanced materials may show promising removal efficiencies in controlled experiments but encounter difficulties involving regeneration, material recovery, fouling, treatment costs, and performance under real environmental conditions. Long-term pilot studies and field evaluations are needed before many emerging technologies can be widely adopted (Fu & Wang, 2011; Obruche et al., 2019). Future pollution control should prioritize affordable, energy-efficient, and low-waste technologies. Research into biochar, agricultural waste-derived adsorbents, microbial remediation, nature-based solutions, and renewable-energy-powered treatment could expand access to pollution management. Nanotechnology and advanced oxidation also offer potential benefits, provided that their environmental safety and life-cycle impacts are carefully evaluated.

Furthermore, pollution prevention should receive equal attention to remediation. Cleaner production, safer chemical substitution, improved agricultural practices, effective waste segregation, wastewater reuse, and stronger environmental monitoring can reduce pollutant releases before they require expensive treatment. The United Nations Environment Programme (2019) emphasizes the importance of addressing environmental challenges through coordinated action and more sustainable production and consumption. Future research should therefore focus on comparing treatment technologies using standardized indicators, evaluating secondary pollution, determining life-cycle environmental impacts, and establishing

long-term evidence of ecosystem recovery. Collaboration among researchers, industries, governments, and local communities will be necessary to ensure that technological advances translate into meaningful environmental improvements.

VII. CONCLUSION AND RECOMMENDATIONS

Environmental pollutants originate from industrial, agricultural, domestic, transportation, and petroleum-related activities, among other sources. Their effects on air, water, soil, and living organisms vary according to their toxicity, persistence, concentration, and environmental mobility. Effective pollution management requires a clear understanding of these characteristics to select suitable removal technologies. Conventional methods, including filtration, adsorption, precipitation, and biological treatment, remain important, while emerging techniques such as advanced oxidation, nanotechnology, and phytoremediation offer additional treatment opportunities. Nevertheless, no single technique is appropriate for every pollutant or environmental medium. Treatment selection should consider effectiveness, affordability, energy demand, secondary waste, and ecological safety. This review highlights that pollutant removal alone does not guarantee ecological sustainability. Sustainable pollution control must prevent contaminant transfer to other environmental compartments, manage treatment residues safely, protect biodiversity, and support the long-term recovery of ecosystems. It is recommended that industries and municipalities adopt integrated treatment systems, strengthen source reduction, improve waste management, and monitor environmental quality regularly. Governments should enforce environmental standards and support research into affordable remediation technologies. Future studies should also evaluate the long-term ecological effects and life-cycle performance of emerging treatment methods to ensure that pollution control contributes to durable environmental protection.

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