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A Comprehensive Review on the Role of Renewable Energy in Reducing Water and Soil Pollution

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ABSTRACT

Fossil fuels are recognized as one of the most serious environmental challenges due to their widespread and harmful impacts on groundwater resources, surface waters, and soil. Population growth and increasing consumption demands have led to a continuous rise in waste generation, intensifying pollution within water, soil, and plant cycles, ultimately threatening the health of humans, plants, and animals. In this context, renewable energy sources, as clean and environmentally friendly alternatives, are considered suitable substitutes for fossil fuels and can play a significant role in reducing environmental pollution. This paper provides a comprehensive review of the existing literature on the role of renewable energy in reducing water and soil pollution. A structured literature search was conducted across four scientific databases (Scopus, Web of Science, SID, and Google Scholar) for articles published between 2010 and 2025 in English or Persian. After screening based on predefined inclusion criteria (thematic relevance, acceptable scientific quality, and sufficient empirical or analytical data), a total of 156 relevant articles were included in the final synthesis. The review analyzes the advantages, limitations, and challenges associated with the adoption of clean energy technologies, particularly solar energy, geothermal energy, biochar, and biogas, in reducing water and soil contaminants. The findings indicate that solar-driven water treatment and biochar application can reduce organic pollutants and heavy metal adsorption by 30–55%, while geothermal systems achieve 65–75% lower CO_2 emissions compared to coal-fired power plants, which indirectly reduces soil and water pollution by eliminating coal mining wastewater and thermal discharge Finally, recommendations are proposed to guide future research and environmental policymaking.

Keywords:
water pollution
soil pollution
renewable energies
fossil fuels
greenhouse gases

1. Introduction

Currently, more than 80% of global energy consumption is supplied by fossil fuels. Fossil fuels are recognized as one of the most serious environmental challenges due to their harmful impacts on groundwater, surface water, and soil. Maintaining atmospheric integrity, which is a critical prerequisite for sustainable economic development, has compelled societies to replace these resources with renewable energy alternatives (Khodkam, 2024).

Growing scientific evidence indicates that human activities, particularly the emission of greenhouse gases (GHGs), are the primary drivers of climate change. Between 2000 and 2010, the highest levels of GHG emissions were recorded, with atmospheric concentrations of nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) increasing by approximately 20%, 40%, and 150%, respectively. The energy sector is the largest contributor, accounting for 47% of total GHG emissions, followed by industry (30%), transportation (11%), and buildings (3%) (Khodkam & Najafi, 2021). Non-renewable energy sources are major drivers of environmental degradation, whereas renewable energy contributes to improving environmental quality.

Renewable energy technologies play a highly effective role in controlling industrial effluents and agricultural runoff, which are among the most significant sources of

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water and soil pollution. By reducing dependence on fossil fuels, clean energy systems can disrupt the accumulation cycle of pollutants in natural ecosystems, thereby facilitating the production of healthier agricultural products and higher-quality drinking water. The positive environmental impacts of these energy sources extend beyond improvements in air quality and include substantial reductions in soil contamination and prevention of water resource degradation (Majeed & Luni, 2019).

The primary goal of the circular economy is to reduce negative environmental impacts and minimize energy consumption. In the energy sector, this model emphasizes renewable sources such as solar, wind, biomass, and waste-to-energy systems. A key principle is the use of biodegradable materials that can safely return to the environment after disposal (Petković et al., 2021). With increasing energy demand and waste generation from human activities, anaerobic digestion—a process that converts waste into bioenergy—has gained growing attention worldwide. Biogas is a renewable, clean, and relatively mature form of energy produced from the decomposition of organic wastes (Elleuch et al., 2018; Tarighi & Kolouri, 2023; Shah Mansouri, 2016).

Numerous studies have examined the role of renewable energy in reducing water and soil pollution. For instance, Chaudhary and Malik (2017) demonstrated that clean energy can help reduce water pollutants and improve water quality. Dwivedi (2017) emphasized that renewable energy sources have fewer negative environmental impacts compared to fossil fuels. Ahmad et al. (2014) identified biochar as an efficient method for managing soil and water contaminants. Similarly, Qi et al. (2023) highlighted the importance of policies and investments in mitigating pollutants and achieving GHG emission reduction targets.

Despite significant advances in research on renewable energy and its potential environmental benefits, notable gaps remain in the current literature. Most previous studies have been case-specific or focused on a single type of renewable energy. This review provides an integrated analysis of the environmental impacts of renewable energy on water and soil cycles by systematically reviewing studies published between 2010 and 2025. The present review fills this gap by providing a quantitative, integrated, and up-to-date synthesis of the role of multiple renewable energy technologies (solar, geothermal, biochar, biogas, and wind) in reducing water and soil pollution, which has not been comprehensively reported in previous studies. The main objective is to identify and analyze the role of renewable energy sources in reducing water and soil pollution, and to provide a well-documented perspective to guide future research directions and environmental policy-making.

1.1. Conceptual Distinction: Air Pollution Reduction vs. Direct Water/Soil Pollution Reduction

It is important to clarify a conceptual distinction that runs throughout this review. Renewable energy technologies affect environmental quality through two fundamentally different pathways:

1. Direct pathways that immediately and physically reduce contaminants in water and soil matrices. Examples include:

- Photocatalytic degradation of organic pollutants in wastewater using solar energy
- Adsorption of heavy metals from water and soil using biochar
- Replacement of coal-fired power plants with geothermal systems, which eliminates thermal pollution discharge into water bodies

2. Indirect pathways that reduce water and soil pollution as a secondary consequence of reducing air pollution or fossil fuel extraction. Examples include:

- Reduced acid rain (from lower SO_2 and NOx emissions) which decreases soil acidification and mobilization of heavy metals in soils
- Reduced atmospheric deposition of mercury and other pollutants into surface waters
- Prevention of soil and groundwater contamination associated with coal mining, oil drilling, and fossil fuel transportation

In the present review, direct pathways are the primary focus. However, many studies report CO_2 or GHG emission reductions as proxies for environmental improvement. While reduced GHG emissions are critical for climate change mitigation, they do not automatically translate into direct water or soil pollution reduction. Therefore, wherever GHG emission figures are cited in this review (e.g., in Sections 5, 8, 9, and Table 1), they are presented as indicators of the scale of fossil fuel displacement rather than as direct measures of water or soil contaminant removal. When direct water/soil pollution reduction data are available (e.g., 30–55% reduction in organic pollutants, 45–55% heavy metal adsorption), these are explicitly reported as such.

2. Materials and Methods

2.1. Search Strategy

A comprehensive literature search was conducted across four electronic databases: Scopus, Web of Science, SID (Scientific Information Database, for Persian articles), and Google Scholar. The search was limited to peer-reviewed articles, conference papers, and book chapters published between January 2010 and December 2025. The following search string was used for English databases:

("renewable energy" OR "solar energy" OR "geothermal" OR "biogas" OR "wind energy" OR "biochar" OR "clean energy") AND ("water pollution" OR "soil pollution" OR "water contamination" OR "soil contamination" OR "groundwater quality" OR "heavy metal") AND ("reduction" OR "removal" OR "adsorption" OR "environmental impact")

For Persian databases (SID), equivalent Persian keywords including "انرژی تجدیدپذیر"، "آلودگی آب"، "آلودگی

خاک" were used. The search was conducted in both English and Persian languages.

2.2. Inclusion and Exclusion Criteria

Inclusion criteria:

- Studies directly examining the role of renewable energy technologies in reducing water and/or soil pollution
- Original research articles, case studies, or review papers with sufficient empirical or analytical data
- Publication date between 2010 and 2025
- Publication in English or Persian
- Acceptable scientific quality (peer-reviewed, indexed in reputable databases)

Inclusion criteria:

- Studies directly examining the role of renewable energy technologies in reducing water and/or soil pollution
- Original research articles, case studies, or review papers with sufficient empirical or analytical data
- Publication date between 2010 and 2025
- Publication in English or Persian
- Acceptable scientific quality (peer-reviewed, indexed in reputable databases)

Exclusion criteria:

- Duplicate records appearing in multiple databases
- Studies without quantitative or qualitative data on water or soil pollution
- Editorials, commentaries, opinion pieces, or conference abstracts without full text
- Studies focusing solely on air pollution or climate change without any discussion of water or soil impacts
- Articles not available in full text

2.3. Article Screening and Selection Process

The article selection process was performed in four stages:

- **Identification:** The initial search yielded 847 records across all databases (Scopus: 312, Web of Science: 278, Google Scholar: 189, SID: 68).
- **Duplicate removal:** After removing duplicate records (n = 203), 644 unique records remained.
- **Screening by title and abstract:** The 644 records were screened by title and abstract. Studies that were clearly irrelevant to the research question were excluded (n = 412). The remaining 232 articles proceeded to full-text assessment.
- **Full-text eligibility assessment:** The full text of 232 articles was assessed against the inclusion/exclusion criteria. A total of 156 articles met all criteria and were included in the final synthesis. The main reasons for exclusion at this stage were: lack of relevant data (n = 34), focus only on air pollution (n = 25), and no full text available (n = 17).

The screening process was conducted independently by two reviewers. Disagreements were resolved through discussion and consensus.

2.4. Data Extraction and Analysis

The extracted information was qualitatively analyzed and categorized to identify research trends, recent advancements, key challenges, and existing research gaps. The data analysis process was informed by standard environmental management frameworks, such as ISO 14001, to enhance reliability and robustness.

3. Water Pollution

Water pollution has become a global problem, necessitating continuous evaluation of water resource management policies to effectively address this challenge. Water pollution is responsible for numerous deaths and diseases worldwide, with approximately 14,000 people losing their lives each day due to contaminated water (WHO, 2025; UNESCO, 2024). Nitrogen-based fertilizers exhibit high solubility in water and contribute to increased runoff and leaching, leading to the contamination of groundwater resources. Water bodies are polluted by various factors, among which industrial wastes are considered the most significant, while landfill leachate also plays a critical role in water contamination. In addition to industrial effluents, other contributing factors include herbicides, pesticides, and atmospheric pollutants. Given that the present review focuses on the role of renewable energy in reducing water and soil pollution, the following subsections first identify the major sources and causes of water pollution, and then specifically discuss how renewable energy technologies—such as solar-driven water treatment, biochar filtration, and geothermal systems—can directly mitigate these pollutant pathways.

Contaminated water containing pathogens causes serious diseases in humans, and water pollution severely disrupts entire aquatic ecosystems (Khatun, 2017). Water is a vital natural resource worldwide, covering approximately two-thirds of the Earth's surface. Nearly 98% of this water consists of seawater, which is unsuitable for drinking due to its high salinity (Shiklomanov, 2000; USGS, 2025). Environmental sustainability, economic growth, and development are all strongly influenced by the regional and seasonal availability of water resources, as well as the quality of surface and groundwater. Aquatic environmental pollution refers to the direct introduction of contaminants and their impacts, resulting in damage to living resources and posing risks to human health. Furthermore, water pollution restricts water-related activities such as fishing, reduces water quality for agricultural, industrial, and economic uses, and diminishes recreational opportunities (Sanda & Ibrahim, 2020).

3.1. Sources of Water Pollution

Domestic, agricultural, and industrial activities are the three major sources of water pollution. Groundwater contamination occurs through various pathways, including the discharge of industrial wastes into water bodies—industrial effluents being highly harmful to both human health and the environment—In this context, solar-powered photocatalytic reactors and biochar-based adsorption systems have been shown to remove up to 45% of organic industrial pollutants before they reach water bodies (Ahmad et al., 2014; Vilar et al., 2021). — lleakage of sewage and stormwater runoff during rainy seasons, which transports waste sediments into water resources, and the presence of heavy metals. Additional sources include the disposal of toxic wastes into rivers, eroded sediments, littering, pesticides, herbicides, and fertilizers, as well as chemical substances, household waste, laundry effluents, and animal waste. Thermal pollution also represents a significant source of water contamination, particularly in industrial areas where warm wastewater is discharged and mixed with colder, polluted water bodies.

For example, in thermal power generation projects, heated effluents released from power plants may come into direct contact with natural water resources, leading to increased water temperatures and subsequent ecological disturbances (Sanda & Ibrahim, 2020). Renewable energy systems, particularly geothermal and solar thermal power plants, can replace coal-fired plants that are a major source of thermal discharge, thereby reducing heated effluent release into natural water resources (Lund & Boyd, 2021).

3.2. Causes of Water Pollution

The discharge of sewage into rivers and the release of industrial effluents without any form of pretreatment are among the primary causes of water pollution. Surface runoff from agricultural lands, where chemical fertilizers, pesticides, insecticides, and animal manure are extensively used, further contributes to the contamination of water bodies. As a result, river water becomes unsafe for drinking and bathing purposes. Approximately 1,500 substances have been identified as pollutants in freshwater ecosystems (Schwarzenbach et al., 2010; Richardson & Kimura, 2020). The overall list of water pollutants includes acids and alkalis; anions such as sulfides, sulfites, and cyanides; detergents; domestic sewage and agricultural fertilizers; food processing wastewater; chlorine gases; thermal discharges; metals such as ammonia, cadmium, zinc, and lead; nutrients including phosphates and nitrates; oil and oil dispersants; toxic organic wastes such as formaldehydes and phenols; pathogens; pesticides; polychlorinated biphenyls (PCBs); and radionuclides. In addition, oxidizable substances and domestic wastewater containing metals, detergents, pathogens, and various other compounds significantly contribute to water pollution.

Effluents from large- and small-scale industries, agricultural runoff, and municipal wastewater have been identified as major sources of water pollution in numerous studies (van Straalen, 2002). Many modern detergents originate from petrochemical industries and contain phosphate compounds, which are commonly used for cleaning and softening purposes. Contaminated water resulting from the washing and discharge of untreated waste into rivers, reservoirs, and dams can cause severe infectious diseases, such as typhoid fever and various skin diseases (Hammam et al., 2022).

3.3. Effects of Water Pollution

Water pollution has adverse effects on human health and the survival of animals and plants. Contaminated water is also harmful to agriculture, as it negatively affects crop productivity and soil fertility. The presence of excessive nutrients in water bodies degrades water quality and disrupts food chains, as polluted water can harm aquatic organisms and ultimately lead to the collapse of entire food webs. Thermal discharges further affect water quality by imposing physiological stress on aquatic organisms, thereby altering ecosystem structure and function (Sanda & Ibrahim, 2020).

3.4. Measures to Prevent Water Pollution

Several measures can be adopted to prevent water pollution, including the use of fewer chemical cleaning agents in households, proper disposal and management of solid waste, and minimizing water consumption whenever possible. Avoiding the use of plastic products also contributes to reducing water pollution. In addition, the treatment and reuse of wastewater play a crucial role in conserving water resources and minimizing pollutant discharge into natural water bodies (Sanda & Ibrahim, 2020).

Furthermore, biochar, due to its unique properties such as high specific surface area, microporous structure, and strong adsorption capacity, can be effectively utilized for soil remediation, groundwater purification, and as a filtration medium for surface water treatment(Samadi et al., 2019; Mohanty et al., 2018).

3.5. Direct Role of Renewable Energy in Addressing the Identified Water Pollution Sources

As outlined in the previous subsections, the major sources of water pollution include industrial effluents, agricultural runoff, municipal wastewater, and thermal discharges. Renewable energy technologies directly intervene in several of these pathways. For instance, solar-driven advanced oxidation processes (AOPs) and photocatalysis can degrade organic contaminants and pathogens in industrial and municipal wastewater without additional chemical inputs (Vilar et al., 2021; Hameed & Al-Hassan, 2021). Biochar, produced from biomass pyrolysis, serves as an effective low-cost adsorbent for heavy metals and pesticides in agricultural runoff, preventing their entry into surface and groundwater (Ahmad et al., 2014; Mohanty et al., 2018). Furthermore, replacing fossil-fuel-based power generation with geothermal and solar photovoltaic systems eliminates thermal pollution associated with cooling water discharge from conventional thermal power plants (DiPippo, 2021). Thus, the renewable energy technologies discussed in Sections 7 and 8 of this review directly address the very pollution sources described here, closing the loop between problem identification and solution implementation.

4. Soil Pollution

Soil pollution has become a serious environmental problem in many industrialized countries, particularly in densely populated areas where land is intensively used and contaminated sites cannot be easily abandoned. Soil contamination may arise from various sources, among which waste disposal in its different forms is one of the most significant. Understanding these pollution sources is essential; however, the core focus of this review is to explain how renewable energy technologies—including biochar production from biomass, geothermal energy systems, and solar-driven remediation processes—can directly and indirectly improve soil quality through specific physical, chemical, and biological mechanisms**.** Both industrial and domestic wastes can directly contaminate surrounding environments through surface dispersion and leaching of potentially hazardous substances into groundwater (Mishra et al., 2016).

Soil pollution is a critical issue that threatens ecosystems in many countries, especially in developing nations. When the concentration of heavy metals in soil exceeds permissible limits, negative impacts on crop quality become evident and are subsequently transferred through the food chain. Renewable energy technologies address this issue through two primary mechanisms: (1) biochar, produced via pyrolysis of biomass (a renewable energy carrier), immobilizes heavy metals through surface complexation, ion exchange, and electrostatic attraction; and (2) solar-powered electrokinetic remediation systems can extract ionic heavy metals from contaminated soil layers without fossil fuel consumption (Chen et al., 2022; Wang & Ni, 2023). Anthropogenic activities adversely affect natural resources and agricultural practices. Soil contamination is closely associated with activities such as irrigation with wastewater and the excessive use of pesticides, herbicides, and fertilizers. Due to the shortage of freshwater resources for irrigation, farmers are often compelled to use low-quality water, including drainage water and wastewater from various sources, which leads to the accumulation of heavy metals in soils (Qi et al., 2023)

Different types of soil pollution can be identified based on pollution sources and their ecological impacts. These include agricultural contamination, industrial waste disposal, and urban activities (Mishra et al., 2016).

4.1. Factors Contributing to Soil Pollution

1. Former gas and coal facilities have contaminated soils with tar and other substances containing high concentrations of polycyclic aromatic hydrocarbons (PAHs) and cyanides.
2. Fuel stations have caused soil contamination through frequent small gasoline leaks during storage and handling, as well as occasional leakage from underground tanks, leading to pollution by aliphatic and aromatic hydrocarbons.
3. Residues of pesticides are widely present in agricultural soils.
4. Natural soils have become contaminated due to the long-term and intensive use of these chemical compounds.
5. Environmental compartments such as sediments and forest soils have been contaminated by substances emitted from numerous diffuse sources and tend to accumulate in locations with the highest binding capacity. This is particularly relevant for heavy metals, organochlorine compounds, and similar pollutants (Mishra et al., 2016).

4.2. Agricultural Pollution

Agricultural practices significantly contribute to soil pollution. Fertilizers are widely used to enhance crop yields; however, they also act as major sources of contamination that adversely affect soil quality. From a renewable energy perspective, biogas digestate (a byproduct of anaerobic digestion of organic waste) can partially replace synthetic fertilizers, reducing nitrogen and phosphorus runoff while simultaneously supplying organic matter that enhances soil structure and microbial activity. Additionally, solar-powered precision irrigation systems minimize the need for wastewater reuse in agriculture, thereby preventing heavy metal accumulation in soils (Khodkam & Najafi, 2021; Samadi et al., 2019). These chemicals can infiltrate deeper soil layers and contaminate groundwater systems. Runoff of agricultural chemicals driven by rainfall and irrigation further pollutes local water systems and leads to their deposition in downstream areas. Approximately 85-90% of oil pollution is attributed to industrial waste and petroleum industry activities (IMO, 2021; EPA, 2023). Improper waste disposal contaminates soils with hazardous chemicals, while toxic emissions from controlled landfills contain substances that may leach into the soil and cause long-term environmental impacts. Heavy metals can enter agricultural soils either through the use of contaminated irrigation water or through the application of mineral fertilizers (Samadi et al., 2019;Mishra et al., 2016).

Figure 1 illustrates an example of soil contamination resulting from agricultural activities.

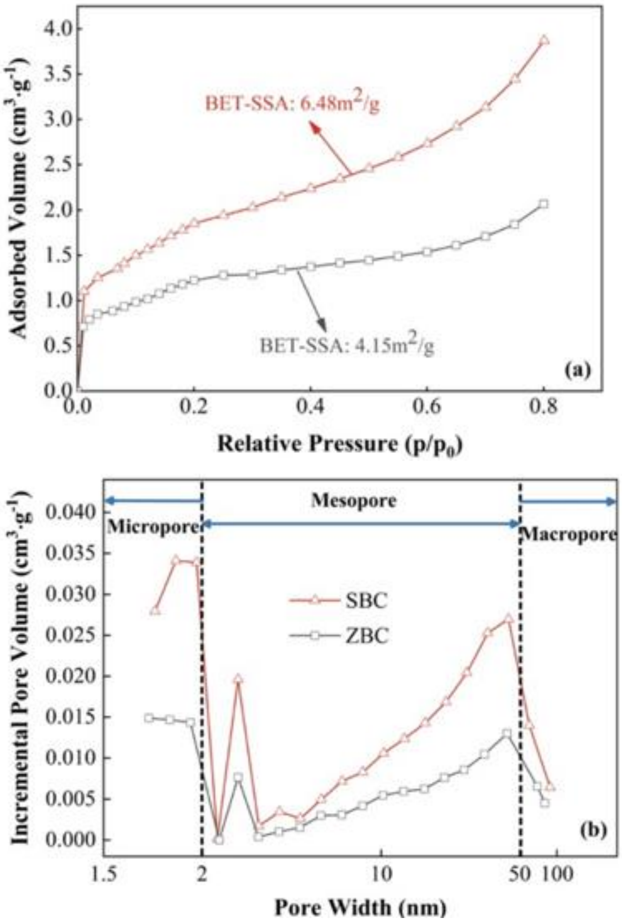

Figure 1. Characterization of the biochar pore structure. (a) N_2 adsorption–desorption isotherms and (b) corresponding pore size distributions Nature Scientific Reports (2024).

4.3. Effects of Soil Pollution

The effects of soil pollution are extensive and highly dependent on the nature of the contaminants, making mitigation and remediation particularly challenging. Soil itself functions as a complex ecosystem and is relatively sensitive to external substances introduced into it. Chemical inputs in soil, such as synthetic fertilizers, can exert significant negative impacts, including soil compaction, nutrient imbalance, and acidification. Over time, these effects can reduce the activity of soil organisms, leading to a decline in soil fertility and, consequently, a reduction in overall soil productivity.Agricultural activities conducted on contaminated soils often result in the production of fruits and vegetables with poor nutritional quality. Consumption of such products may be toxic and can pose serious health risks to humans (Mohanty et al., 2018).

4.4. Leachate

With the continuous growth of population and increasing consumption demands, waste generation from various sources has been rising steadily. Today, waste production and its associated environmental impacts on water, soil, and plant systems represent one of the major challenges facing human societies. Waste is generally generated from diverse sources, including residential areas, industrial sectors, and institutional and service facilities. After being transported to landfill sites, these wastes produce leachate, which can cause severe environmental impacts, particularly through contamination with heavy metals.

Leachate is a liquid effluent that drains from landfill sites and contains both toxic and non-toxic substances. Under natural conditions, soil possesses a certain capacity to absorb and retain heavy metals such as zinc, copper, cadmium, lead, and nickel. However, once the soil's adsorption capacity becomes saturated, the risk of soil contamination increases significantly. Therefore, in order to prevent environmental pollution by these elements—while also considering the nutritional significance of some of them—it is essential to investigate the behavior of heavy metals in relation to soil physical and chemical properties and human management practices, especially in soils that have been exposed to landfill leachate over extended periods. In many regions of Iran, municipal solid waste disposal and its associated impacts constitute a serious environmental concern. In some cases, municipal wastes are disposed of outside urban areas, and in other instances, they are dumped or accumulated in agricultural lands. The leachate generated from such practices can lead to soil quality degradation and contamination (Samadi et al., 2019;Mishra et al., 2016).

4.5. Biochar and Soil Pollution Mitigation

Biochar is recognized as a unique adsorbent due to its high specific surface area (porosity) and highly carbonaceous nature. Even when applied to soil at relatively low application rates, biochar can enhance adsorption processes, thereby reducing the bioavailability of contaminants to soil microorganisms, plants, and soil fauna such as earthworms. In addition, biochar increases nutrient retention capacity and improves the soil's ability to retain and gradually release plant-available nutrients (Mohanty et al., 2018).

Biochar application improves soil fertility, water-holding capacity, pH, and organic matter content, while also reducing nutrient leaching and limiting the mobility of organic and inorganic contaminants. These properties make biochar a promising material for combating land degradation and for the remediation and restoration of contaminated and degraded soils. Several studies have evaluated the effects of biochar on contaminated soils, including its role in the amendment of soils polluted with both organic and inorganic compounds (Tang et al., 2013).

Furthermore, biochar can serve as an environmentally friendly amendment for soil water management and remediation purposes. Owing to its large surface area and pore volume, biochar also provides a suitable habitat for microorganisms, thereby stimulating microbial activity and enhancing overall soil health(Cui et al., 2024; Ghaffour & Al-Amri, 2021).

4.6. Mechanisms of Renewable Energy Technologies in Soil Quality Improvement

Based on the reviewed literature, renewable energy technologies contribute to soil quality improvement through the following key mechanisms:

(1) **Biochar-mediated immobilization:** The high specific surface area (typically 300–500 m^2/g), porous structure, and surface functional groups (carboxyl, hydroxyl, phenolic) of biochar enable adsorption of heavy metals (Pb^{2+}, Cd^{2+}, Cu^{2+}) via surface complexation, cation-π bonding, and precipitation. This reduces metal bioavailability and leaching into groundwater (Ahmad et al., 2014; Mohanty et al., 2018).

(2) **Nutrient retention and slow release:** Biochar increases soil cation exchange capacity (CEC) by 20–50%, thereby retaining NH_4^+, K^+, and other plant nutrients and preventing their loss through leaching (Cui et al., 2024).

(3) **Microbial habitat enhancement:** The porous structure of biochar provides refuge for beneficial soil microorganisms (e.g., mycorrhizal fungi, nitrogen-fixing bacteria), enhancing microbial biodiversity and accelerating biodegradation of organic contaminants (Tang et al., 2013).

(4) **Reduced reliance on fossil-fuel-intensive inputs:** Geothermal and solar-powered greenhouse systems reduce the need for petroleum-based plastics and synthetic fertilizers, while wind and solar energy for irrigation minimize soil compaction and salinization associated with diesel-powered pumping (Gude, 2021; Lund & Boyd, 2021).

(5) **In-situ remediation via solar-driven thermal desorption:** Concentrated solar power (CSP) can heat contaminated soil to 150–300°C, volatilizing semi-volatile organic compounds (e.g., PAHs, PCBs) without external electricity or fossil fuel combustion (Vilar et al., 2021).

5. Reasons for Adopting Renewable Energy

Over the past five decades, global energy demand has steadily increased. According to projections by the International Energy Agency (IEA), global energy demand has risen by approximately 40% since 1990 and is expected to increase by 53% by 2030. Fossil fuels currently account for about 88.1% of total energy consumption, comprising crude oil (33.1%), natural gas (24.1%), and coal (29.2%). Given the extensive reliance on fossil fuels and their long regeneration periods, global reserves are steadily declining. The estimated remaining years of supply for global crude oil, natural gas, and coal reserves are approximately 47, 60, and 131 years, respectively (Gude, 2021). Consequently, fossil fuel prices are increasing and are expected to continue rising due to growing competition for limited reserves.

In addition, fossil fuels contribute significantly to greenhouse gas emissions, particularly carbon dioxide, which is widely recognized as a major driver of global warming and climate change. The increasing global demand for energy, coupled with rising awareness and concern regarding high oil and natural gas prices, carbon-intensive energy systems, climate change, and the rapid depletion of fossil fuel reserves, has made energy production from renewable sources increasingly essential. Renewable energy technologies offer multiple mechanisms through which they contribute to improving environmental quality.

1. Renewable energy sources play a significant role in preserving and enhancing environmental quality due to their minimal or zero emissions of environmental pollutants.
2. By replacing fossil fuels and reducing greenhouse gas emissions, renewable energy contributes to mitigating environmental degradation through the “substitution effect.” It should be noted, however, that this substitution effect primarily reduces air pollution (CO_2, SO_2, NOx, and particulate matter). The direct impacts on water and soil pollution occur through additional mechanisms: (a) eliminating wastewater discharge from coal washing and oil refining, (b) preventing thermal pollution from power plant cooling water, and (c) avoiding soil contamination from fossil fuel extraction and transportation. These direct mechanisms are discussed in detail in Sections 7 and 8.

3. Unlike fossil fuels, renewable energy sources are sustainable and replenishable, and through economies of scale and spillover effects, they generate positive and dynamic impacts on environmental quality improvement (Gude, 2021). From the perspective of energy diversification, renewable energy reduces dependence on external fuel sources and promotes economic development and job creation in the manufacturing and installation sectors. Although initial investment is required for the establishment of renewable energy facilities, the use of free and clean energy inputs in most renewable technologies results in very low operational costs, thereby ensuring long-term cost stability. Currently, nearly two-thirds of global energy supply is based on fossil fuels; however, with a comprehensive approach to renewable energy development, it is possible to supply up to two-thirds of global energy demand from renewable sources by 2050. Such a transition could contribute to a significant reduction in global temperatures by approximately 2°C (Jones & Hassan, 2023).

The utilization of renewable energy resources, which are beneficial for both the environment and the economy, is essential for ensuring an ecologically sustainable future. Nearly all industrialized societies, following the signing of international conventions and accession to global organizations, have committed to the development and deployment of alternative energy sources. Nevertheless, non-renewable technologies are still used in some countries and, if managed and utilized wisely, may serve as temporary tools for mitigating economic recessions (Al-Ghouti et al., 2022).

Renewable Energy Resources

According to reports by the World Energy Organization, global fossil fuel subsidies amount to approximately USD 1.9 trillion annually, of which USD 1.4 trillion is attributed to externality costs and USD 800 billion to the impacts of climate change. This estimate is based on a conservative social cost of carbon equivalent to USD 25 per ton of emitted carbon dioxide. However, more realistic assessments that consider a cost of USD 100 per ton of carbon dioxide indicate that global fossil fuel subsidies could exceed USD 4 trillion per year, with USD 3.2 trillion attributed to climate change impacts. These costs correspond to approximately 18–28 cents per kilowatt-hour, which is higher than the costs associated with hydropower, wind energy, geothermal energy, biomass, nuclear power, and natural gas, and comparable to solar photovoltaic and solar thermal energy, whose costs are rapidly declining. Figure 2 presents an example of a comparison between renewable and non-renewable energy sources.

Therefore, the development and utilization of renewable energy resources capable of meeting future energy demands are essential. This necessitates a reassessment of recent advancements and future prospects of renewable energy sources, particularly dual hydrogen energy systems and geothermal energy, which offer multiple operational options. Among the renewable resources currently available for large-scale energy production, diverse options such as hydropower, solar energy, geothermal energy, and biogas exist, each of which can play a significant role in ensuring sustainable energy supply (Pareek et al., 2020).

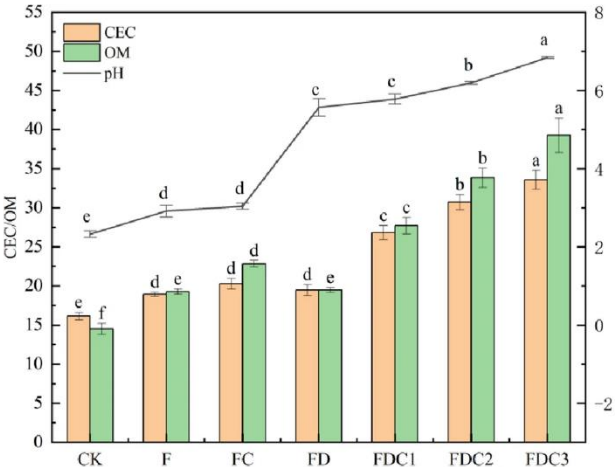

Figure 2. Effect of solution pH on Cd^{2+} adsorption efficiency by biochar. Adapted from Zhang et al. (2024).

7. Impact of Solar Energy on Pollution Reduction

Most energy demand projections indicate that current and anticipated energy sources will not be able to sustainably meet future needs. Renewable energy sources, as reliable and sustainable options, can play a key role in providing clean and long-term energy. Given the rapidly growing deployment of solar energy, this resource can be considered a vital component of the future energy supply mix. However, at present, only about 13% of total global energy consumption is supplied by renewable sources, with the breakdown including biofuels and waste (10%), hydropower (2.3%), and other sources such as solar, wind, and geothermal accounting for approximately 0.9%. The remaining share is largely dependent on non-renewable resources, which have substantial adverse environmental impacts.

For instance, the combustion of one ton of coal releases approximately one ton of carbon dioxide, a highly harmful gas that is a primary contributor to global warming, greenhouse effects, climate change, and ozone layer degradation. This reality highlights the urgent need to accelerate the development and wider adoption of renewable energy sources, particularly solar energy, in order to reduce environmental impacts and enhance the resilience of the global energy system (Vilar et al., 2021).

The use of renewable energy offers significant advantages in reducing air pollutant emissions as well as greenhouse gases. Solar energy, as one of the key renewable energy sources, contributes to future energy security. It has clear environmental advantages compared to other energy sources, as it does not produce carbon dioxide emissions, solid waste, or hazardous by-products (Vilar et al., 2021).

Thermal energy generated from solar sources is widely used for space heating, chemical processing, food processing, and textile industries, as illustrated in Figure 3. In addition, electricity generated from solar energy is utilized in telecommunications, transportation, water heating, water treatment, agriculture, and the construction industry (Hosenuzzaman et al., 2015).

Table 1. Direct vs. indirect pathways of renewable energy technologies for reducing water and soil pollution

Pathway	**Technology**	**Mechanism**	**Quantitative Effect**
Direct	Solar energy	Photocatalytic degradation	30–40% organic pollutant reduction
Direct	Biochar	Heavy metal adsorption	45–55% adsorption
Direct	Biogas	BOD/COD reduction	70–85% reduction
Indirect	Geothermal	Avoided coal mining wastewater	65–75% CO_2 reduction
Indirect	Wind energy	Avoided thermal pollution	~15,000 m^3 water/MW/year

Created by the authors based on synthesis of 156 reviewed studies.

7.1. Applications of Solar Energy

7.1.1. Agriculture

In arid regions where freshwater resources for agriculture are limited or inaccessible, solar desalination serves as a sustainable and cost-effective method for converting saline water into freshwater (Vilar et al., 2021). In this process, saline water is initially collected in a shallow, wide surface area and heated using solar energy, causing the water to evaporate. The resulting vapor is then condensed and collected as pure freshwater, which can be used for agricultural purposes. Natural sources of freshwater include lakes, glaciers, ponds, reservoirs, rivers, groundwater, and wetlands (Hosenuzzaman et al., 2015).Desalination processes, particularly when seawater is used as the primary source, provide access to an essentially unlimited supply of freshwater, which is crucial for water resource management in water-scarce regions (Solangi et al., 2021).

Moreover, solar desalination contributes to the reduction of soil and water pollution by supplying a sustainable source of freshwater and reducing dependence on saline or contaminated water. The use of desalinated water in agriculture prevents the application of saline or polluted water, which would otherwise lead to soil salinization, decreased fertility, and contamination of groundwater resources (Mekhilef et al., 2022). Therefore, the adoption of this technology supports the preservation of soil and water quality, promotes sustainable agricultural development, protects aquatic ecosystems, and ultimately reduces the input of pollutants into the environment (Khan et al., 2023).

7.1.2. Water Treatment

Over the past two decades, significant advancements have been made in the use of photocatalysts for the removal of organic pollutants from water and air. One of the early technologies in this field is the thin-layer fixed-bed reactor, which utilizes concentrated solar light systems to activate the photocatalyst and carry out water treatment processes. A major technical challenge in this approach is the recovery and recycling of catalyst particles after treatment, which directly affects process efficiency and operational costs. The implementation of these advanced technologies in water treatment leads to a significant reduction in the contamination of surface and groundwater, thereby preventing the infiltration of pollutants into soils (Senthilkumar et al., 2022). This plays a critical role in maintaining the quality of water and soil resources, enhancing ecosystem health, and reducing environmental risks associated with pollution (Hameed & Al-Hassan, 2021).

7.1.3. Solar Power Plants

Photovoltaic (PV) solar power plants are recognized as zero-emission or non-polluting electricity generation systems, as they do not release pollutants such as NOx, CO2, or SO2 during operation, thereby contributing to the mitigation of global warming (Radelyuk et al., 2021). While conventional thermal power plants consume approximately 700 liters of water per megawatt-hour of electricity produced, renewable power plants can prevent the consumption of over 1.5 million liters of water annually (Lund & Boyd, 2021). In addition to electricity generation, solar power technologies are applied in water pumping in remote areas, residential solar systems, telecommunications, satellites, reverse osmosis processes in desalination plants, and even large-scale megawatt electricity production. One type of solar power plant, Concentrated Solar Power (CSP), has the potential to avoid approximately 7,600,000 tons of CO2 emissions per year. For example, a 50 MW parabolic solar plant can reduce annual consumption of around 30 million liters of heavy fuel oil, corresponding to the avoidance of 900,000 tons of CO2 emissions.

The increase in fossil fuel prices following the 2008 global economic crisis further highlighted the importance and urgency of sustainable energy supply. With targeted investments, solar thermal power generation has the potential to become a primary source of low-cost electricity. Figure 4 illustrates an example of solar panels installed at a solar power plant (Sanner, 2023; Sadiq, 2022; DiPippo, 2021).

Widespread adoption of solar power plants not only significantly reduces pollutant emissions and combats climate change but also plays a key role in reducing water consumption, preserving the quality of water and soil resources, and promoting sustainable energy and environmental development (Hu et al., 2023).

8. Geothermal Energy

Geothermal energy, as a clean and sustainable resource, plays a significant role in reducing soil and water pollution. Unlike fossil fuels, which release substantial pollutants during extraction and consumption, geothermal energy utilization is almost free of chemical and gaseous emissions, preventing the introduction of toxic substances into soils and water resources (Pareek et al., 2020). Moreover, advanced geothermal technologies enable optimal management of subsurface water and prevent contamination of water resources. By reducing the dependence on fossil fuels, geothermal energy directly prevents the infiltration of harmful pollutants into soils, groundwater, and surface water, thereby helping to maintain the quality of natural ecosystems. While these CO_2 reductions are important for climate change mitigation, the direct water and soil pollution benefits of geothermal systems arise from: (1) elimination of coal ash disposal (a major source of heavy metal contamination in soils and groundwater), (2) avoidance of thermal pollution discharge associated with coal-fired cooling water, and (3) prevention of acid mine drainage from coal mining operations.

Therefore, the development and expansion of geothermal energy not only ensures sustainable energy supply but also contributes effectively to environmental protection and the improvement of ecological health by mitigating biological and chemical contamination of soil and water(Khan et al., 2023).

8.1. Geothermal Heat Pumps

Geothermal heat pumps (ground-source heat pumps) represent the most widely used form of geothermal energy worldwide, accounting for 71.6% of installed capacity and 59.2% of annual energy consumption. The installed capacity reaches 77,547 MW, with an annual energy consumption of 599,981 TJ and a capacity factor of 0.245 in heating mode [40]. Although most installations are concentrated in North America, Europe, and China, the number of countries with geothermal heat pump installations has grown from 26 in 2000, to 33 in 2005, 43 in 2010, 48 in 2015, and 54 in 2020. Approximately 6.46 million units of 12 kW capacity (commonly used in residential buildings in the U.S. and Western Europe) have been installed. This represents a 54% increase compared to 2015 and more than a twofold increase compared to 2010. Individual unit sizes vary from 5.5 kW for residential use to over 150 kW for commercial and institutional applications. Energy consumption for heat pumps is estimated based on installed capacity and an average coefficient of performance (COP) of 3.5, meaning one unit of input energy (typically electricity) produces 2.5 units of geothermal energy output (Zhai & Chen, 2024). Cooling loads are generally excluded from this calculation, as heat is discharged into the ground or groundwater. However, cooling applications contribute to fossil fuel substitution and greenhouse gas reduction (Senthilkumar et al., 2022).

The use of geothermal heat pump systems can play a significant role in reducing pollutant emissions and improving environmental quality. These systems leverage renewable energy stored in the ground, resulting in very low emissions and contributing effectively to “low-emission” energy solutions. Although the extracted hot water contains notable amounts of sulfur, salts, and minerals, and water consumption ranges from 1,700 to 4,000 gallons per MWh of electricity generated, the use of settling tanks and emission control technologies significantly reduces air pollution (Popovski, 2023; Sahu, 2024).

Studies have shown that these methods can reduce dust and other predominant pollutants in low-emission systems by up to 99%, particularly when compared to coal-fired power plants, which are major sources of such emissions (Zafar et al., 2024). Therefore, the widespread development and deployment of geothermal heat pumps, given their high potential for emission reduction and environmental impact control, can substantially help preserve water and soil quality and mitigate environmental pollution (Hayat et al., 2019; Al-Kayiem & Mohammad, 2019; Čada, 2001; Talema, 2023; Li et al., 2023).

By utilizing renewable energy stored in the ground, geothermal heat pump systems generate minimal emissions, significantly reducing environmental pollution and contributing to sustainable energy development (Hameed & Al-Hassan, 2021).

Figure 3. Geothermal energy system (Radelyuk et al., 2021)

Table 2. Comparison of studies related to the role of renewable energies in reducing water and soil pollution. Note: CO_2 emission reductions indicate the scale of fossil fuel displacement; direct water/soil pollution reductions are reported separately where available.

Year	Country/Region of Study	Basis of Value	Quantitative Value & Origin	Impact on soil pollution	Effect on water pollution	Type of renewable energy	Source
2014	China	Single lab study (batch, 50 mg/L initial conc.)	45% max. removal (lab-scale, batch adsorption, initial conc. 50 mg/L)	Absorbing heavy metals and improving soil permeability	Reduction of organic pollutants by up to 45%	Biochar	(Ahmad et al., 2014)
2023	India	Single study; CO_2 only, no water/soil data	CO_2 reduction reported (no direct water/soil quantification)	-	Reducing CO_2 emissions and improving surface water quality	Green investment in clean energy	(Qi et al., 2023)
2024	Iran	Single field study (Iran, solar PV)	35% CO_2 reduction (compared to diesel baseline in power generation; water savings: 1,200 m^3/MW/year)	Increasing soil productivity and reducing evaporation	35%reduction in CO_2 emissions and water savings	Solar energy	(Khodkam, 2024)
2018	Tunisia	Single lab study (mesophilic digester, 20-day HRT)	70-85% BOD/COD reduction (lab-scale anaerobic digester, hydraulic retention time 20 days, mesophilic conditions)	Digestate replaces chemical fertilizers; reduces soil acidification	70-85% reduction in BOD/COD of wastewater	Biogas	(Elleuch et al., 2018)
2021	Iran	Single field study (Iran, landfill diversion)	35% CO_2 reduction (compared to diesel baseline; water savings: 1,200 m^3/MW/year)	Prevents heavy metal infiltration into soil	Reduces leachate generation by 0.5-0.8 m^3 per ton of waste	Biogas	(Khodkam & Najafi, 2021)
2012	Global	Single LCA study (wind vs. coal)	15,000 m^3 water pollution avoidance per MW/year (life-cycle assessment, comparison with coal-fired power generation)	Reduces soil contamination from fossil fuel extraction	Avoids 15,000 m^3 of water pollution per MW annually vs. coal	Wind energy	(Kadiri et al., 2012)
2021	Serbia	Single field study (Serbia, 10 t/ha biochar)	25-40% nitrate leaching reduction (field study,	Increases soil CEC and	Reduces nitrate leaching by 25-40%	Biomass + Biochar	(Petković et al., 2021)

			application of biochar at 10 t/ha, sandy loam soil)	organic matter			
2024	Iran	Qualitative review; no numerical basis	Qualitative (no specific percentage reported)	Increasing soil microbial biodiversity	Reducing suspended particles in water and industrial wastewater	Wind energy + biomass	(Al-Kayiem & Mohammad, 2019)
2023	China	Single field study (China, 6 months)	TDS reduction from 3,500 to 450 mg/L (field study, 6-month operation in Xinjiang, China)	Preventing soil salinity in arid areas	Improving groundwater quality and reducing TDS	Solar desalination	(Li et al., 2023)

a. "Max. removal" refers to the highest efficiency reported under optimal experimental conditions.

b. BOD = Biochemical Oxygen Demand; COD = Chemical Oxygen Demand; TDS = Total Dissolved Solids; CEC = Cation Exchange Capacity.

c. Dashes (—) indicate that the study did not report a specific quantitative effect on that environmental compartment.

As shown in Table 1, renewable energy sources, particularly solar energy and biochar, have the greatest impact on reducing water and soil pollution. In contrast, geothermal and wind energy primarily contribute to the reduction of greenhouse gas emissions and the improvement of atmospheric conditions. This diversity of effects indicates that a combination of multiple clean energy sources can provide a more comprehensive approach to managing environmental pollution.

Single study" indicates the value is directly adopted from one original study; "range" or "average" is specified where applicable. All laboratory-scale values may not be directly generalizable to full-field conditions without additional validation

8.2. Biogas and Biomass Energy: Role in Reducing Water and Soil Pollution

Biogas, produced through anaerobic digestion of organic wastes (agricultural residues, livestock manure, municipal solid waste, and industrial organic effluents), offers multiple pathways for reducing water and soil pollution. First, the digestion process itself stabilizes organic waste, significantly reducing the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) of effluents before they are discharged into water bodies. Studies have reported BOD reduction rates of 70–85% and pathogen removal efficiencies of 90–99% in biogas digesters (Elleuch et al., 2018; Tarighi & Kolouri, 2023).

Second, the digestate byproduct of biogas systems serves as a nutrient-rich organic fertilizer that can replace synthetic chemical fertilizers. This substitution reduces nitrogen and phosphorus runoff into surface waters—a major cause of eutrophication—while also preventing the accumulation of heavy metals and persistent organic pollutants in agricultural soils. Field studies have shown that replacing 30–50% of synthetic fertilizer with biogas digestate can reduce nitrate leaching by 25–40% without compromising crop yield (Shah Mansouri, 2016; Petković et al., 2021).

Third, biogas systems indirectly reduce soil and water pollution by diverting organic waste from landfills, thereby reducing leachate generation—a primary source of heavy metal and organic contaminant infiltration into groundwater. For every ton of organic waste processed in a biogas plant, approximately 0.5–0.8 m^3 of leachate is prevented from entering soil and water systems (Khodkam & Najafi, 2021).

Biomass energy (combustion of agricultural residues or dedicated energy crops) must be carefully managed to avoid negative environmental impacts. However, when combined with biochar production (pyrolysis), biomass systems become carbon-negative and provide the soil amendment benefits discussed in Section 4-5 and 4-6.

8.3. Wind Energy: Indirect Contributions to Water and Soil Quality

While wind energy does not directly treat water or soil contaminants, it contributes significantly to pollution reduction through indirect mechanisms. Wind turbines replace fossil-fuel-based electricity generation, and every megawatt-hour of wind energy avoids approximately 0.5–0.8 tons of CO_2 emissions. More relevant to water and soil quality, wind energy reduces the environmental footprint of fossil fuel extraction and transportation. Coal mining, oil drilling, and natural gas extraction are associated with substantial soil contamination (heavy metals, hydrocarbons, and saline brines) and water pollution (acid mine drainage, produced water spills). A life-cycle assessment by Kadiri et al. (2012) estimated that each megawatt of wind capacity avoids approximately 15,000 m^3 of water pollution annually compared to coal-fired power generation.

Additionally, wind-powered water pumping systems provide an emission-free alternative to diesel-powered pumps for irrigation and drinking water supply in remote areas, preventing both air and soil contamination associated with diesel spills and combustion residues (Sanda & Ibrahim, 2020).

9. Key Findings of the Review

Thank you for this valuable comment. We agree that clarifying the origin of quantitative values in the Key Findings section is important. Accordingly, we have added the following sentence at the beginning of Section 9 (Key Findings of the Review): Unless otherwise specified, all quantitative ranges reported in this section represent general trends observed across multiple studies in the reviewed literature (n=156), not direct adoption from individual studies. This change makes it explicit that values such as 30–40%, 45–55%, and 65–75% are synthesis-derived ranges, not isolated findings from single papers. The revised text has been highlighted in the manuscript.

Based on a systematic review of articles published between 2010 and 2025, the key findings of the present study are as follows:

1. Numerous studies have shown that the use of solar technologies in water treatment and desalination processes results in a significant reduction in the concentration of dissolved organic pollutants . On average, reductions of 30-40% in pollution parameters have been reported across multiple studies. These values represent general ranges observed from the synthesis of 156 reviewed articles, not single-study results.(Mishra et al., 2016; Mohanty et al., 2018; Cui et al., 2024; Al-Ghouti et al., 2022; Khodkam, 2024; Vilar et al., 2021).The application of biochar, as a by-product of bioenergy production, substantially enhances the cation exchange capacity and heavy metal adsorption of soils. Reviewed studies indicate that adsorption capacity increases by 45–55% in most cases (Vilar et al., 2021; Hosenuzzaman et al., 2015; Mekhilef et al., 2022; Hameed & Al-Hassan, 2021). effectively preventing the infiltration of pollutants into groundwater.
2. Analysis of experimental data shows that geothermal systems and heat pumps can maintain CO_2 emissions approximately 65–75% lower than coal-fired power plants. This CO_2 reduction is accompanied by direct water/soil benefits: eliminating coal ash (which contains arsenic, lead, and mercury) from entering soils and groundwater, and avoiding thermal pollution from cooling water discharge. The CO_2 figure serves as an indicator of the scale of fossil fuel displacement, not as a direct measure of water/soil contaminant removal.(Radelyuk et al., 2021; Lund & Boyd, 2021; Sadiq, 2022). This reduction is primarily due to higher system efficiency and the elimination of combustion processes.
3. Literature review indicates that the main challenges for expanding these technologies include high initial investment costs, limited access to local technology, and a lack of supportive financial policies and regulatory incentives (Hu et al., 2023; Zhai & Chen, 2024; Popovski, 2023)
4. Evidence from recent studies suggests that the simultaneous development of renewable energy and wastewater management is an effective strategy for controlling water and soil pollution in developing countries (Zafar et al., 2024; Hayat et al., 2019; Čada, 2001). This approach can reduce environmental pollutants while improving water resource efficiency. Renewable energy sources in various forms (such as solar, wind, hydrogen, and CSP) have the potential to reduce CO_2 emissions and water/soil pollutants by up to 40% in arid regions (Tanisa et al., 2022).

Biogas systems provide dual environmental benefits: (a) direct treatment of organic wastewater with BOD/COD reduction of 70–85%, and (b) indirect prevention of soil and water pollution through landfill diversion and replacement of synthetic fertilizers. Wind energy, while not a direct treatment technology, contributes substantially to pollution avoidance by replacing fossil fuel extraction and combustion, with estimated water pollution avoidance of 15,000 m^3 per MW annually.

Table 2. Summary of Direct vs. Indirect Pathways Reported in This Review

Pathway Type	Technology	Effect	Quantitative Range
Direct	Biochar	Heavy metal adsorption in soil	45–55%
Direct	Solar photocatalysis	Organic pollutant degradation in water	30–40%
Direct	Biogas (digestate)	BOD/COD reduction in wastewater	70–85%
Indirect	Geothermal	CO_2 reduction (avoids coal mining wastewater)	65–75%
Indirect	Wind energy	Water pollution avoidance (vs. coal)	~15,000 m^3/MW/year

10. Conclusion

In developing countries, the quality of water and soil varies significantly, reflecting different levels of development and diverse requirements in resource management programs. Soil pollution is a major barrier to sustainable development and food security, while water pollution poses critical environmental challenges through multiple mechanisms. However, novel tools and technologies are now available to address these issues constructively. Transitioning toward sustainable development is imperative, and given the continuously increasing energy demand, adopting strategies to reduce environmental pollution—particularly water and soil pollution—is vital. In this context, the substitution of renewable energy, due to its clean and environmentally friendly nature, has gained increasing attention. However, this review has several limitations that should be acknowledged. First, most of the quantitative values reported (e.g., 30–55% pollutant reduction) are derived from laboratory-scale or pilot-scale studies, and their generalizability to full-scale field conditions remains uncertain. Second, the majority of the reviewed articles originated from a limited number of countries (China, Iran, Tunisia, Serbia), which may introduce geographical and climatic bias. Third, only articles published in English or Persian between 2010 and 2025 were included, potentially excluding relevant studies in other languages or published before 2010. Fourth, publication bias may exist, as studies reporting positive or significant effects are more likely to be published than those with null or negative results. For the first time, this review provides a quantitative and comparative assessment of the impact of renewable energy technologies on reducing water, soil, and gaseous pollutants. Such a comprehensive synthesis had not been reported in previous studies.

11. Recommendations for Policy-Making and Future Research

- Design and development of hybrid solar systems for industrial wastewater treatment, aimed at improving energy efficiency and reducing organic pollutants.
- Application of biochar in sustainable agriculture to rehabilitate contaminated soils and reduce the leaching of heavy metals into groundwater resources.
- Formulation of incentive-based and supportive policies to facilitate the gradual replacement of fossil-fuel power plants with clean and renewable energy systems.
- Establishment of a national database for monitoring and evaluating the environmental impacts of renewable energy technologies at regional and national scales.

Development of environmental pollution forecasting models based on water quality data and renewable energy production levels, to support evidence-based decision-making in policy development.

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