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Assessment and management strategies for soil pollution in Pakistan: A review

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Abstract

Soil pollution is a pressing environmental issue in Pakistan, with adverse implications for agriculture, human health, and ecosystem sustainability. This review paper provides a comprehensive analysis of soil pollution in Pakistan, focusing on assessment, management strategies, policy frameworks, remediation techniques, contamination sources, monitoring, and research priorities. The study highlights the urgency of addressing soil pollution and its detrimental impacts on the environment and human health. It explores various assessment methods, including soil sampling, laboratory analysis, remote sensing, and geospatial technologies, emphasizing the importance of data interpretation and mapping for understanding the extent and severity of soil pollution. The review discussed the role of robust policy frameworks and regulatory mechanisms in preventing and controlling soil pollution, with a particular emphasison industrial pollution control, agricultural practices, waste management, and the use of hazardous substances. It further investigates innovative approaches and technologies for soil remediation, such as bioremediation, electrokinetic remediation, and nanotechnology. Additionally, the review highlights the significance of research priorities, including soil pollution characterization, emerging contaminants, socio-economic impacts, and policy and governance aspects. The findings of this review contribute to enhancing knowledge and informing effective soil pollution management strategies in Pakistan, while also providing valuable insights for researchers, policymakers, and practitioners worldwide.

Keywords: Contamination sources, Ecosystem sustainability, Monitoring, Policy frameworks, Remediation techniques, Research priorities

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Introduction

Pakistan is located in southern Asia and shares borders with India to the east, Iran and Afghanistan to the west, and China to the north (shown in Fig 1). It covers a total area of 803,940 square kilometers. The geographical features of the country include the flat Indus Plainin the east, the mountainous regions of the Himalayas, Karakoram, and Hindukush in the north, hilly areas in the northwest reaching up to 4761 meters, and the upland Baluchistan plateau in the west. The elevations range from K2, the second highest peak in the world at 8611 meters, to sea level at the Indian Ocean. Link: https://geology.com/world/pakistan-satellite-image.shtml
The climate of Pakistan is predominantly arid to semi-arid, although the conditions aretemperate in the northwest and arctic in the northern mountains. The average annual rainfall varies from less than 125 mm in the southwest (western Baluchistan) to over 1000 mm in Islamabad, but it again decreases to less than 125 mm in the northern mountains. Monsoon rains are mainly experienced in July and August. The mean annual temperature in the Indus Plain is around 18ºC, with monthly maximum temperatures exceeding 40ºC, but it decreases significantly in the northern mountains. Soil pollution is a pressing environmental issue that poses significant threats to ecosystems, human health, and agricultural productivity (Siddique et al., 2016; Raza & Ahmed, 2018). It is characterized by the contamination of soil with pollutants, such as heavy metals, pesticides, industrial chemicals, and other harmful substances (Ali et al., 2013). The accumulation of these pollutants in the soil can have long-lasting effects on soil quality, waterresources, and the overall environment (Siddique et al., 2016). In the framework of Pakistan, soil pollution has emerged as a major concern due to various anthropogenic activities and natural factors (Ahmed & Aslam, 2020). The country's rapid industrialization, intensive agricultural

practices, urbanization, and inadequate waste management systems contribute to the increasing levels of soil pollution (Zahir et al., 2015; Munir et al., 2019). Additionally, factors like geological characteristics, climate variations, and geological formations also influence the extent and nature of soil pollution in different regions of Pakistan (Ahmed & Aslam, 2020). Globally, pollution from heavy metals in water, air, soil, plants and aquatic species is a significant environmental problem because they enter the human food chain.

Understanding the background and causes of soil pollution in Pakistan is crucial for developing effective mitigation strategies, preserving ecosystem health, and ensuring sustainable development (Siddique et al., 2016; Raza & Ahmed, 2018). This review paper aimsto provide an in-depth analysis of soil pollution in Pakistan, exploring its sources, types, impacts, monitoring techniques, remediation strategies, and future perspectives. By examiningthe current state of soil pollution in Pakistan, this review paper helps to enhance knowledge and promote informed decision-making for sustainable soil management in the country (Zahir et al., 2015; Munir et al., 2019).

Importance of studying soil pollution in Pakistan

In recent years, there has been a growing recognition of the importance of addressing soil pollution in Pakistan. Numerous studies have focused on identifying and assessing soil pollution hotspots in specific regions of the country. These studies have provided valuable insights into the extent, nature, and sources of soil pollution, which have informed targeted remediation strategies and policies. The findings from these studies highlight the urgent need for comprehensive soil monitoring, assessment, and management approaches to safeguard soil quality and protect the environment and human health. (Iqbal et al., 2020). Soil pollution has far-reaching implications for human health. Contaminated soil can lead to the accumulation of toxic substances in food crops, posing risks to those who consume (Rizwan et al., 2016). Exposure to heavy metals, pesticides, and other pollutants present in the soil can lead to various health issues, including organ damage, developmental disorders, and an increased risk of chronic diseases (Arain et al., 2017). By studying soil pollution in Pakistan, we can identify hotspots of contamination, assess exposure risks, and develop strategies to mitigate health hazards associated with polluted soils (Murtaza et al., 2017). Soil pollution has ecological consequences that extend beyond agricultural lands. Contaminated soils can negatively impact soil organisms, plant diversity, and ecosystem functioning (Raza et al., 2021 a). It can disrupt soil microbial communities, impair nutrient cycling, and lead to the loss of biodiversity (Khan et al., 2020). By studying soil pollution, we may better understand its effects on ecosystems, identify vulnerable habitats, and develop conservation strategies to preserve biodiversity and ecosystem services (Ali et al., 2019). Furthermore, soil pollution has socioeconomic implications. The costs associated with remediating polluted soils, treating contaminated water, and addressing health issues can impose a significant burden on the economy. By studying soil pollution, we can assess the economic impacts, estimate the costs of pollution-related damages, and guide policymakers in implementing sustainable practices and regulations to prevent further soil degradation (Khan et al., 2020).

Sources and causes of soil pollution in Pakistan

Industrial activities

Industrial activities in Pakistan contribute significantly to soil pollution. The rapid industrialization and expansion of manufacturing sectors have led to the release of various hazardous substances into the environment, including the soil. The following are some key sources and causes of soil pollution related to industrial activities in Pakistan:

Chemical manufacturing

The production of chemicals, such as fertilizers, pesticides, pharmaceuticals, and dyes, involves the use and disposal of toxic substances. Accidental spills, improper waste management, and inadequate treatment facilities can result in the contamination of soil with heavy metals, organic compounds, and other harmful chemicals (Shahid et al., 2016; Ullah et al., 2019).

Mining and extraction

Pakistan is rich in natural resources, and mining activities are prevalent across the country. Mining operations, particularly those involving minerals like coal, lead, and copper, can generate tailings and waste materials that contain high levels of heavy metals and other pollutants. Improper disposal and storage of mining waste can lead to the contamination of nearby soils (Arif et al., 2017; Rehman et al., 2020).

Industrial waste disposal

Improper handling and disposal of industrial waste contribute significantly to soil pollution. Industries often discharge untreated effluents and waste materials directly into water bodies or onto land, leading to the infiltration of pollutants into the soil. Common contaminants include heavy metals, organic compounds, and toxic by-products (Nadeem et al., 2017; Imran et al., 2019).

Atmospheric deposition

Industrial emissions, such as gases, particulate matter, and combustion by-products, can be deposited onto the soil surface through air pollution. These pollutants can then leach into the soil and accumulate over time, affecting soil quality and plant growth.

Industrial accidents and incidents

Accidental spills, leaks, and industrial accidents can release large quantities of hazardous substances into the surrounding environment, including soil. Chemical spills or leaks from storage tanks, pipelines, or transportation vehicles can result in immediate soil contamination and pose long-term risks to soil health (Ahmad et al., 2018; Iqbal et al., 2020).

Agricultural practices

Agricultural practices in Pakistan play a significant role in soil pollution. The country's agricultural sector, which includes crop cultivation, livestock farming, and the use of agrochemicals, can contribute to soil contamination through various sources and causes. The following factors contribute to soil pollution in Pakistan's agricultural practices:

Excessive use of fertilizers and pesticides

In an effort to enhance crop yields, farmers often apply excessive amounts of chemical fertilizers and pesticides. Over time, these inputs can accumulate in the soil, leading to nutrient imbalances, soil acidification, and the contamination of groundwater resources. Some fertilizers when applied to soils, they add certain heavy metals (Table 1). Theleaching and runoff of excess fertilizers and pesticides can also result in soil pollution, especially in areas with poor drainage or improper irrigation practices (Iqbal et al., 2019; Ali et al., 2020).

Table 1 Heavy metal content of fertilizers (μg/gm) (Naz et al., 2022)

Fertilizers	Mn	Cu	Ni	Cr	Mo	Pb	Co	Zn
Potassiumsulphate	Tracesto 0.33	0.33-80	<5	<5	0.09	<50	<5	<50
Ammoniumsulphate	0.80	0.800	<5	<5	<0.05-0.22	Traces to 200	<5	0.800
Super phosphate	Tracesto 2842	Tracesto 1000	Traces to 32	0-1000	Tracesto 35	Traces to 92	0.02-13	70-3000
Nitrochalk	24	22	2	_	_	_	_	15
Potassiumchloride	Traces to 8	0-10	<1	_	<0.05	<1	001	0-3

Improper waste management

Livestock farming in Pakistan generates substantial amounts of animal waste, including manure and slurry. Improper handling and disposal of these wastes can lead to the contamination of nearby soil. When manure is over-applied or improperly stored, it can release excess nutrients, pathogens, and organic pollutants into the soil, negatively impacting soil quality and posing risks to human health (Azizullah et al., 2017).

Irrigation practices

Inadequate irrigation practices, such as excessive or improper use of water, can contribute to soil pollution. Over-irrigation can lead to waterlogging and the accumulation of salts in the soil, causing soil salinization and alkalization. Additionally, the use of contaminatedwater for irrigation, such as water polluted with industrial effluents or untreated sewage, can introduce harmful substances into the soil (Saleem et al., 2018; Abbas et al., 2022).

Deforestation and land degradation

Deforestation and land degradation, often driven by unsustainable agricultural practices, contribute to soil erosion and the loss of topsoil. When the protective vegetation cover is removed, soil erosion rates increase, leading to the loss of valuable nutrients and organic matter. The exposed soil becomes more susceptible to pollution as it comes into directcontact with pollutants from various sources, including agricultural runoff and industrial emissions (Saeed et al., 2016).

Municipal waste and landfill sites

Municipal waste and landfill sites are significant sources of soil pollution in Pakistan. Improper waste management practices, including inadequate waste collection, open dumping, and poorly designed landfills, contribute to soil contamination (Akhtar et al., 2018; Naeem et al., 2020). The disposal of untreated municipal waste in landfills leads to the generation of leachate, a liquid that contains a range of pollutants, including heavy metals, organic compounds, and pathogens (Nasreen et al., 2019; Ullah et al., 2021). Over time, this leachate can percolate into the underlying soil layers, polluting the soil and potentially contaminating groundwater resources. Furthermore, the decomposition of organic waste in landfills produces methane gas, which can migrate through the soil and contribute to air pollution (Kumar et al., 2018; Khalid et al., 2020). Addressing soil pollution from municipal waste and landfill sites requires the implementation of proper waste management practices, including waste segregation, recycling, composting, and the establishment of well-engineered landfill facilities with appropriate liningsystems and leachate collection and treatment measures (Hameed et al., 2019; Rasool et al., 2022).

Urbanization and construction

Urbanization and construction activities in Pakistan contribute to soil pollution through various sources and causes. The rapid expansion of urban areas, accompanied by infrastructure development and construction projects, can have significant impacts on soil quality. The following factors contribute to soil pollution in the context of urbanization and construction in Pakistan. (Naz et al., 2022).

Construction waste

The generation and improper disposal of construction waste can lead to soil pollution. Construction debris, such as concrete, bricks, and asphalt, may contain contaminants, including heavy metals, asbestos, and chemicals (Chen et al., 2019). If these materials are not properly managed or recycled, they can leach pollutants into the surroundingsoil, posing risks to ecosystems and potentially contaminating groundwater sources.

Urban runoff

Urban areas are characterized by impervious surfaces, such as roads, pavements, and buildings, which limit the infiltration of water into the soil. As a result, rainwater and urban runoff carry various pollutants, including heavy metals, petroleum products, and microplastics, from streets and rooftops into the soil (Galli et al., 2009). This runoff can introduce pollutants and contaminants into the soil, contributing to soil pollution in urban areas.

Landfills and waste disposal

Improper waste management practices, particularly in urban areas, can lead to soil pollution. Landfills that are poorly designed or managed can release leachate, a liquid containing a mixture of organic and inorganic pollutants, into the soil (Akhtar & Ahmad, 2019). Over time, these pollutants can infiltrate the groundwater and contaminate the surrounding soil, posing risks to human health and the environment.

Industrial and commercial activities

Urban areas often house industrial and commercial activities, which can be a source ofsoil pollution. Industries located in urban areas may release pollutants, such as heavy metals, chemicals, and organic compounds, into the soil through improper waste disposal or accidental spills (Siddique et al., 2015). Similarly, commercial activities, such as gas stations or automotive repair shops, can contribute to soil pollution through the leakage of petroleum products and other hazardous substances.

Types of soil pollution in Pakistan

Heavy metal contamination

Heavy metal contamination is a significant type of soil pollution in Pakistan. Various industrial activities, including mining, manufacturing, and improper waste disposal, release heavy metals such as lead, cadmium, arsenic, mercury, and chromium into the soil (Bashir et al., 2016; Shahid et al., 2016; Tariq et al., 2018). These metals persist in the soil forextended periods and pose serious risks to ecosystems and human health. Heavy metals can accumulate in the food chain, as they are absorbed by plants and subsequently consumed by animals and humans (as shown in Fig. 1), leading to toxic effects (Hussain et al., 2017). Long-term exposure to heavy metals can result in detrimental health effects, including organ damage, neurological disorders, and increased cancer risks (Khan et al., 2020; Ullah et al., 2019). Managing heavy metal contamination requires implementing strict regulations on industrial emissions and waste disposal, promoting proper waste management practices, and adopting remediation techniques such as phytoremediation and soil stabilization to reduce the levels of heavy metals in contaminated soils (Nawab et al., 2018; Shahid et al., 2020; Yaseen et al., 2021).

Pesticide and herbicide residues

Pesticide and herbicide residues contribute to soil pollution in Pakistan. Intensive agricultural practices rely on the use of pesticides and herbicides to control pests and weeds. However, improper application, overuse, and inadequate management of these chemicals leadto their accumulation in the soil (Ashraf et al., 2017; Chaudhry et al., 2018). Pesticide and herbicide residues can persist in the soil for extended periods, posing risks to soil organisms, groundwater quality, and human health. These residues can contaminate food crops, resulting in potential health hazards when consumed (Mahar et al., 2019; Siddique et al., 2021). To mitigate pesticide and herbicide contamination, promoting integrated pest management approaches, educating farmers about proper application techniques, and encouraging the use of environmentally friendly alternatives are crucial. Additionally, monitoring pesticide usage, implementing safe disposal practices, and adopting sustainable farming practices can help reduce soil pollution from pesticide and herbicide residues in Pakistan (Sohail et al., 2018; Ullah et al., 2021).

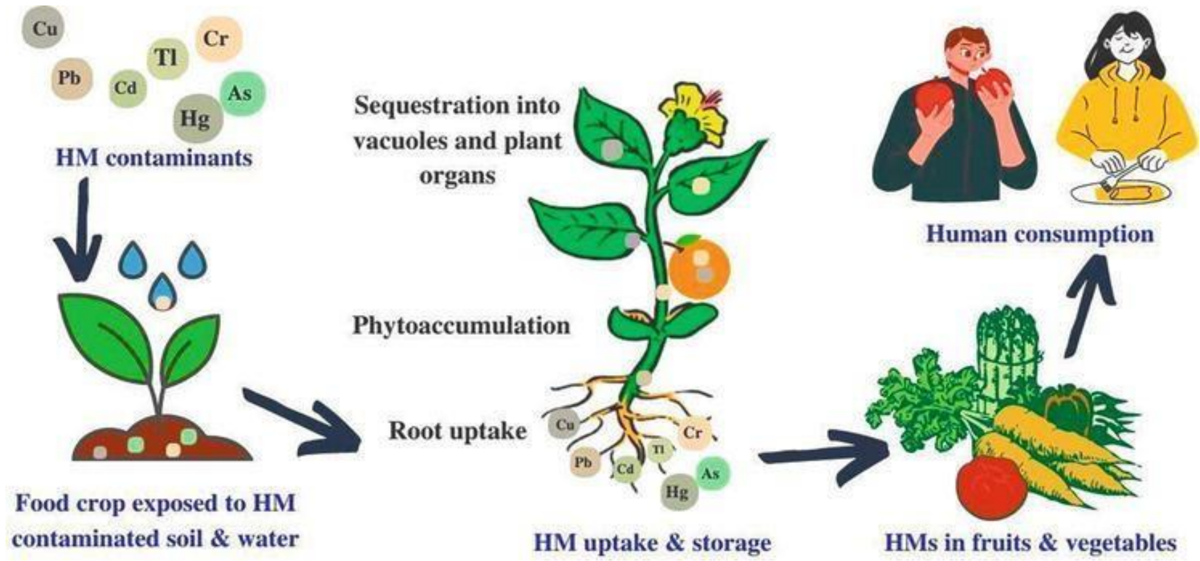

Fig. 1 Heavy metal uptake and transportation to food chain

Organic pollutants

Organic pollutants contribute to soil pollution in Pakistan. These pollutants include various organic compounds such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and industrial chemicals. Organic pollutants can enter the soil through industrial activities, improper waste disposal, agricultural practices, and urban runoff (Khan et al., 2019). These compounds are persistent and can accumulate in the soil, posing risks to soil health, groundwater quality, and the overall environment (Nisar et al., 2018; Raza et al., 2021 a). Organic pollutants can disrupt soil microbial communities, impair nutrient cycling, and have adverse effects on soil fertility. They can also leach into groundwater, potentially contaminating water sources (Naeem et al., 2020).Managing organic pollutants requires implementing strict regulations on chemical usage, improving waste management practices, promoting organic farming practices, and adopting remediation techniques like bioremediation and soil vapor extraction to reduce the presence of organic pollutants in contaminated soils in Pakistan.

Soil salinity and alkalinity

Soil salinity and alkalinity are prevalent forms of soil pollution in Pakistan. These conditions often arise due to improper irrigation practices, inadequate drainage systems, and natural factors such as arid climate and high evaporation rates (Bashir et al., 2019; Hussain et al., 2020). Excessive salts and minerals accumulate in the soil, leading to increased salinity, which hinders plant growth and reduces agricultural productivity. Alkaline soils, characterized by high pH levels, also pose challenges for crop cultivation as they affect nutrient availability and soil microbial activity (Ganie et al., 2017; Tahir et al., 2020). Addressing soil salinity and alkalinity requires implementing improved irrigation techniques, such as drip irrigation and proper water management practices, promoting soil amendments to enhance soil structure, and utilizing salt-tolerant crop varieties (Hussain et al., 2018; Iqbal et al., 2022). Furthermore, measures such as land levelling, drainage systems, and soil leaching can help mitigate the adverse effects of soil salinity and alkalinity, allowing for sustainable agriculture in Pakistan.

Soil erosion and degradation

Soil erosion and degradation are significant forms of soil pollution in Pakistan. Unsustainable land use practices, deforestation, improper agricultural practices, and natural factors like rainfall intensity contribute to soil erosion and degradation (Bashir et al., 2020). Erosion removes the topsoil layer, which is rich in nutrients, organic matter, and beneficial microorganisms, leading to a decline in soil fertility and productivity. Additionally, soil degradation occurs when the soil's physical, chemical, and biological properties deteriorate, affecting its ability to support plant growth and sustain ecosystems (Raza et al., 2021 b). Implementing soil conservation measures, such as terracing, contour plowing, afforestation, and conservation tillage, is essential to prevent soil erosion and degradation, preserve soil quality, and maintain sustainable land management practices in Pakistan.

Industrial pollution

An important environmental problem worldwide including in Pakistan, is industrial pollution. A variety of pollutants are released into the environment because of several industrial processes such waste disposal, chemical processing, and manufacturing. These pollutants can have a negative impact on the quality of soil, water, and air. They include heavy metals, hazardous compounds, and industrial effluents (Mustafa et al., 2021). Industrial pollutants can seriously endanger human health and cause long-term ecological harm when they remain in the environment. Adopting sustainable waste management techniques, greener production technology, and stringent regulatory enforcement are all necessary for controlling industrial pollution. To reduce the effects of industrial pollution and promote sustainable industrial practices, cooperation between industries, regulatory agencies, and the community is essential (Siddique et al., 2020).

Household pollution

Domestic activities generate household pollution, which is a substantial and frequently underappreciated factor in environmental deterioration and public health problems. Numerous pollutants can be released into the air and water by routine household activities like heating, cooking, and improper trash disposal. When solid fuels like wood or coal are used for cooking, indoor air pollution can result in respiratory illnesses and other negative health impacts. This is especially true in developing nations (Smith et al., 2014). Improper disposal of household waste, including plastic and electronic waste, contributes to soil and water pollution, affecting ecosystems and aquatic life (Baldé et al., 2017). Additionally, the use of certain cleaning products and pesticides in households can introduce harmful chemicals into the environment (Zota et al., 2018). Efficaciously addressing household pollutants requires promoting sustainable practices, encouraging using cleanser cooking technologies, and enforcing proper waste control strategies. Public consciousness and schooling campaigns are critical to inform people approximately the environmental effect of household sports activities and promote behavior change toward more sustainable and eco-friendly practices (Das et al., 2019).

Impact of soil pollution in Pakistan

Agricultural productivity and food security

Soil pollution in Pakistan has a significant impact on agricultural productivity and food security. Contaminated soils can lead to reduced crop yields, poor plant growth, and lower nutrient content in agricultural produce (Shahid et al., 2018; Ullah et al., 2020). Heavy metal contamination, pesticide residues, and soil salinity can hinder the growth and development of crops, resulting in decreased agricultural productivity. Moreover, the presence of toxic substances in food crops can pose risks to human health when consumed, compromising food safety and security (Aslam et al., 2021; Tariq et al., 2023). Addressing soil pollution is crucial to ensure sustainable agriculture, improve crop productivity, and safeguard the availability of safe and nutritious food for the population of Pakistan. Implementing soil remediation measures, promoting sustainable agricultural practices, and enforcing regulations to minimize soil pollution are essential steps in safeguarding agricultural productivity and enhancing food security in the country (Arshad et al., 2017; Nadeem et al., 2022).

Human health risks

Soil pollution in Pakistan poses significant risks to human health. Contaminated soil can release harmful substances into the environment, potentially contaminating water sources, crops, and ultimately affecting human exposure (Qasim et al., 2021). Heavy metals, pesticides, and organic pollutants present in polluted soils can accumulate in food crops, leading to potential ingestion of toxic substances by humans. Long-term exposure to these pollutants can result in various health problems (as shown in Fig. 2), including organ damage, developmental issues, neurological disorders, and increased cancer risks (Saleem et al., 2023). Furthermore, contaminated soil can impact the quality of groundwater, a vital source of drinking water in many areas, further exacerbating the health risks. Implementing measures to prevent soil pollution, promoting safe agricultural practices, and conducting regular monitoring and testing of soil and water quality are crucial in minimizing human health risks associated with soil pollution in Pakistan (Anwar et al., 2022).

Water pollution and contamination

Soil pollution in Pakistan has a significant impact on water quality and contributes to water pollution and contamination. Contaminants present in polluted soils can leach into the groundwater or runoff into nearby water bodies, leading to the contamination of water sources (Sohail et al., 2020). Heavy metals, pesticides, and organic pollutants from soil pollution can enter rivers, lakes, and streams, affecting aquatic ecosystems and potentially harming aquatic life. Moreover, the leaching of nutrients from fertilizers used in agriculture can result in eutrophication, leading to the excessive growth of algae and harmful algal blooms in water bodies (Khalid et al., 2019; Rehman et al., 2022). This degrades water quality and poses risks to aquatic organisms and human health. Soil pollution is essential in preserving water quality, maintaining the ecological balance of water ecosystems, and ensuring access to clean and safe water for the population of Pakistan. Implementing sustainable farming practices, promoting proper waste management, and regulating industrial activities are crucial steps in preventing soil pollution and mitigating its impacts on water pollution and contamination (Majid et al., 2019).

Economic implications

Soil pollution in Pakistan has significant economic implications on various sectors of the economy. The agricultural sector, which is a major contributor to Pakistan's economy, suffers from decreased crop yields and reduced productivity due to soil pollution. This leads to financial losses for farmers and a decline in agricultural output, affecting food availability and increasing food prices (Ali et al., 2019; Khan et al., 2020). Soil pollution also affects the quality and marketability of agricultural produce, resulting in lower profits for farmers and impacting the overall agricultural value chain (Khalid et al., 2018; Rizwan et al., 2021).

Moreover, contaminated soil can lead to increased costs for soil remediation and clean-up efforts, putting a burden on public and private resources (Ahmad et al., 2017; Nawaz et al.,2022). Likewise, industries that rely on clean soil for their operations, such as construction, may face challenges due to the need for soil remediation and the associated costs.

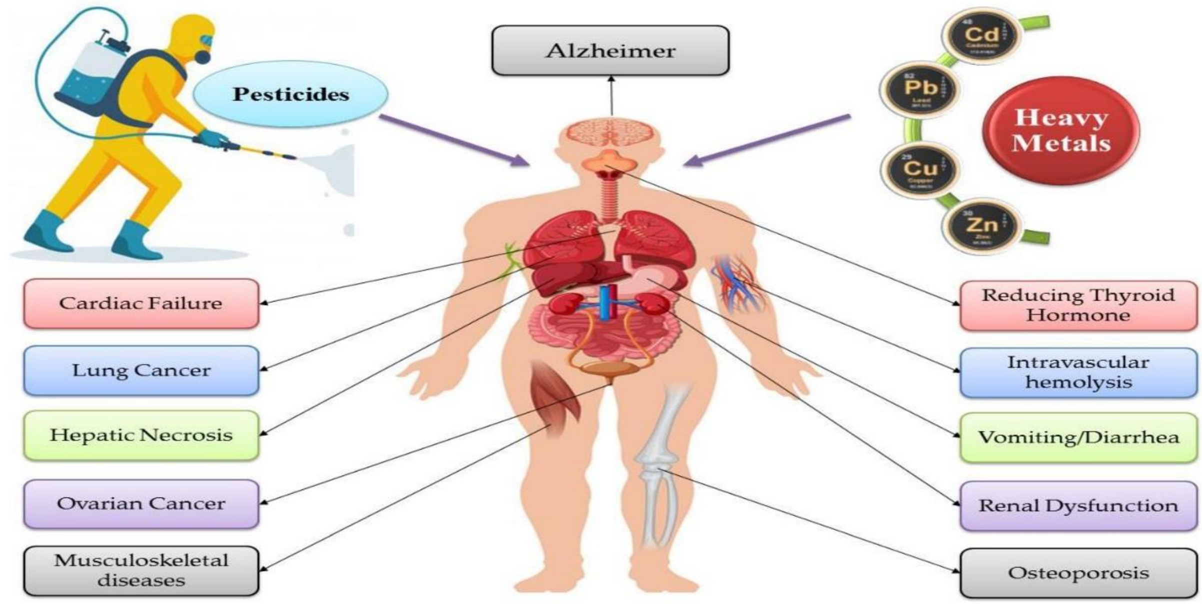

Fig. 2 Heavy metal and pesticide effect on human health

Monitoring and assessment of soil pollution in Pakistan

Soil sampling techniques

Random sampling

This technique involves collecting soil samples from various locations within a given area to obtain representative data. Random sampling ensures that the collected samples are unbiased and provide a comprehensive understanding of soil pollution across the area of interest (Arora et al., 2018; Zhang et al., 2020).

Grid sampling

In grid sampling, the sampling area is divided into a grid pattern, and soil samples are collected from predetermined points within each grid. This technique allows for systematic coverage of the sampling area, ensuring representative data collection.

Composite sampling

Composite sampling involves collecting multiple soil samples from different locations within a specific area and combining them to create a composite sample. This technique isuseful when the area of interest is large or when there are variations in soil properties within the sampling area. Composite sampling provides an average representation of soil characteristics.

Depth-specific sampling

This technique involves collecting soil samples at different depths within the soil profile. It helps assess vertical variations in soil pollution and allows for a better understanding of the distribution of contaminants in the soil (Huang et al., 2018; Zhang et al., 2021).

Auger sampling

Auger sampling involves using an auger, a cylindrical tool, to collect soil samples. This technique is suitable for collecting samples from relatively shallow depths and is commonlyused in areas with easy soil penetration.

Core sampling

Core sampling utilizes a cylindrical core sampler to extract intact soil cores from the ground. This technique allows for the collection of undisturbed soil samples, particularly useful for assessing soil structure, compaction, and pollutant distribution within specific soil layers (Lu et al., 2017; Tang et al., 2020).

Soil sample preservation

After collection, soil samples should be properly preserved to maintain their integrity for laboratory analysis. Preservation techniques include air-drying, refrigeration, or freezing, depending on the specific analysis requirements.

Documentation

It is crucial to accurately document the sampling locations, depths, and other relevant information during the sampling process. This documentation helps in proper interpretation and analysis of the collected data (Jiang et al., 2018; Wu et al., 2021). Effective soil sampling techniques are essential for monitoring and assessing soil pollution in Pakistan. By employing these techniques, scientists, researchers, and environmental professionals can gather reliable data on soil quality, identify contamination hotspots, and develop appropriate remediation strategies to mitigate soil pollution.

Laboratory analysis methods

pH measurement

pH measurement is a fundamental analysis method that determines the acidity or alkalinity of the soil. It provides information on soil fertility, nutrient availability, and potential impacts of soil pollution on pH levels (Brevik et al., 2018).

Nutrient analysis

Nutrient analysis involves testing soil samples for essential elements such as nitrogen (N), phosphorus (P), potassium (K), and other micronutrients. This analysis helps assess the nutrient status of the soil, which can be affected by soil pollution and impact plant growth and productivity (Olsen et al., 2020).

Heavy metal analysis

Heavy metal analysis is crucial for assessing soil pollution. Laboratory techniques such as atomic absorption spectroscopy (AAS) or inductively coupled plasma mass spectrometry (ICP-MS) are commonly used to quantify the concentration of heavy metals like lead, cadmium, arsenic, mercury, and chromium in soil samples (Alloway, 2013; Basta and Gradwohl, 2017).

Organic pollutant analysis

Organic pollutant analysis involves the detection and quantification of various organiccompounds present in soil, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), pesticides, and industrial chemicals. Gas chromatography (GC), high-performance liquid chromatography (HPLC), and mass spectrometry (MS) are commonly employed techniques for organic pollutant analysis.

Microbiological analysis

Microbiological analysis focuses on assessing the presence and activity of soil microorganisms, which play a vital role in nutrient cycling and soil health. Techniques such as plate counting, DNA sequencing, and enzyme activity assays can provide insights into the microbial diversity, abundance, and functional potential in soil samples (Bünemann et al., 2018; Singh et al., 2020).

Soil texture analysis

Soil texture analysis determines the proportions of sand, silt, and clay particles in the soil, which influence soil structure, water-holding capacity, and nutrient retention. This analysis is typically conducted using the hydrometer method or laser diffraction techniques.

Contaminant mobility and leaching potential

Laboratory experiments can be conducted to evaluate the mobility and leaching potential of contaminants in soil samples. Techniques such as column leaching tests or batch leaching tests can simulate the movement of contaminants in soil and provide valuable information on their potential to migrate to groundwater (Liu et al., 2014; Parket al., 2019).

Data interpretation and analysis

Laboratory analysis results are interpreted and analyzed to assess the extent and severity of soil pollution. Statistical analysis, geospatial mapping, and comparison with regulatory standards or guidelines are commonly used approaches to interpret and analyze soil pollution data (Khan et al., 2021). Laboratory analysis methods play a crucial role in monitoring and assessing soil pollution in Pakistan. These methods enable the quantification of various parameters, including pH, nutrients, heavy metals, organic pollutants, microbiological activity, and soil texture, providing valuable insights into the contamination levels and potential impacts on soil quality. Accurate and reliable laboratory analysis is essential for informed decision-making, remediation planning, and the implementation of effective soil pollution management strategies.

Remote sensing and geospatial technologies

Satellite imagery

Satellite imagery provides valuable data for monitoring and assessing soil pollution over large areas. Remote sensing satellites capture images of the Earth's surface, enabling the identification of land cover changes, vegetation health, and potential sources of soil pollution. Spectral analysis of satellite images can help detect patterns related to soil contamination, such as changes in vegetation reflectance or anomalies in surface temperature (Canty and Nielsen, 2017; Singh et al., 2019).

Hyperspectral imaging

Hyperspectral imaging involves capturing images across a wide range of wavelengths, allowing for detailed spectral analysis of the Earth's surface. This technology can identify specific soil properties associated with pollution, such as heavy metal concentrations or organic matter content. By analyzing the unique spectral signatures of different pollutants, hyperspectral imaging enables the mapping and monitoring of soil pollution (Krishna et al., 2019).

Geographic information systems (GIS)

GIS technology combines spatial data with attribute information, allowing for the creation of detailed maps and spatial analysis of soil pollution. GIS can integrate various data sources, such as soil sampling results, satellite imagery, land use data, and environmental monitoring data, to visualize and analyze the extent and distribution of soil pollution in Pakistan. GIS also enables the identification of potential pollution sources, the assessment of pollution hotspots, and the development of targeted remediation strategies (Chen et al., 2017; Panda et al., 2020).

Soil quality indices

Geospatial technologies can be used to develop soil quality indices by integrating multiple soil properties and pollution-related parameters. These indices provide a comprehensive assessment of soil quality and pollution levels across different areas, allowing for the identification of priority areas for remediation and land management.

Digital elevation models (DEMs)

DEMs provide elevation data that can be used to analyze the topographic characteristics of an area and its influence on soil pollution. By identifying areas with poor drainage or high runoff potential, DEMs can help predict the transport of pollutants and the area’s most susceptible to soil pollution (Bilgili et al., 2018).

Land cover classification

Remote sensing techniques combined with image classification algorithms can categorize land cover types, including agricultural fields, urban areas, and natural vegetation. This information helps in understanding the relationships between land use patterns, human activities, and soil pollution, thereby assisting in targeted pollution control measures.

Change detection analysis

Remote sensing and geospatial technologies enable change detection analysis by comparing multiple images taken at different time points. This analysis helps identify temporal changes in land cover, vegetation health, or pollution sources, aiding in the assessment of soil pollution trends and the effectiveness of pollution mitigation efforts (Huang et al., 2020).

Data interpretation and mapping

Data interpretation and mapping are critical components of monitoring and assessing soil pollution in Pakistan. Once data from various sources, such as soil sampling, laboratory analysis, remote sensing, and geospatial technologies, are collected, they need to be interpretedand analyzed to understand the extent and severity of soil pollution (Seshadri et al., 2020; Deng et al., 2021). Statistical analysis, geospatial mapping techniques, and the comparison of data with regulatory standards or guidelines help in identifying pollution hotspots, trends, and potential sources of contamination (Wu et al., 2021). By effectively interpreting and mapping the data, decision-makers and environmental experts can make informed decisions, prioritize areas for remediation, and implement targeted soil pollution management strategies to protect soil quality and mitigate the adverse impacts of pollution on the environment and human health.

Soil pollution management and remediation in Pakistan

Policy and regulatory framework

The effective management and remediation of soil pollution in Pakistan rely on a robustpolicy and regulatory framework (Bhat et al., 2020). A comprehensive set of policies and regulations is essential to establish guidelines, standards, and enforcement mechanisms to prevent soil pollution, control pollutant emissions, and ensure responsible waste management practices (National Environmental Quality Standards, 2008; Ministry of Climate Change Pakistan, 2014). The policy framework should address various aspects, including industrial pollution control, agricultural practices, urban development, waste management, and the use of hazardous substances. Additionally, the framework should promote sustainable practices, incentivize the adoption of clean technologies, and encourage public-private partnerships for soil pollution management Sustainable Development Policy Institute, 2019; Ministry of Climate Change Pakistan, 2018). A strong policy and regulatory framework will provide a solid foundation for effective governance, coordination, and implementation of soil pollution management strategies, ultimately safeguarding soil quality, protecting the environment, and ensuring the well-being of the population in Pakistan.

Best management practices in agriculture and industry

Sustainable farming techniques

Promoting sustainable farming practices, such as organic farming, integrated pest management, and crop rotation, reduces reliance on chemical inputs and minimizes soil pollution risks.

Proper nutrient management

Implementing balanced nutrient management practices, including the judicious use of fertilizers, organic amendments,

and soil testing, helps prevent nutrient imbalances and reducesthe risk of nutrient leaching and soil degradation.

Conservation agriculture

Encouraging practices like conservation tillage, cover cropping, and agroforestry helpsenhance soil health, reduce erosion, and improve water infiltration, thereby mitigating soil pollution risks.

Irrigation management

Efficient irrigation practices, such as drip irrigation or precision irrigation, minimize water wastage and prevent the accumulation of salts and pollutants in the soil.

Pollution control measures

Industries should adopt advanced pollution control technologies, such as air filters, wastewater treatment systems, and proper waste disposal methods, to prevent the release of pollutants that can contaminate soil.

Hazardous waste management

Proper management and disposal of hazardous waste generated by industries are crucial to prevent soil contamination. Industries should adhere to strict regulations and guidelines for handling and disposing of hazardous substances.

Environmental monitoring

Regular monitoring and reporting of emissions, waste generation, and pollutant levels are essential for industries to assess their environmental impact and take corrective actions to prevent soil pollution.

Cleaner production techniques

Promoting cleaner production practices, such as resource efficiency, waste reduction, and the use of eco-friendly technologies, helps minimize pollution at its source and reduces thepotential for soil contamination.

By implementing these best management practices in agriculture and industry, Pakistan can significantly reduce soil pollution risks, protect soil quality, and contribute to sustainable land management. The adoption of these practices requires collaboration among farmers, industry stakeholders, policymakers, and environmental agencies to ensure widespread implementation and adherence to regulations.

Soil remediation techniques

Soil remediation techniques are essential for the effective management of soil pollutionin Pakistan. Various methods can be employed to restore contaminated soil to a healthy and productive state. These techniques include:

Bioremediation

Bioremediation utilizes microorganisms, such as bacteria, fungi, and plants, to degradeor metabolize pollutants (shown in Fig. 3) present in the soil (Mishra and Kumar, 2020; Singhet al., 2021). These organisms break down contaminants into less harmful substances through natural biological processes. Bioremediation can be enhanced through techniques like bioaugmentation (introducing specialized microorganisms) or phytoremediation (using plantsto extract, stabilize, or degrade contaminants).

Soil washing

Soil washing involves the physical separation of contaminants from soil particles through mechanical or chemical means. The technique typically employs water or other solvents to flush out and remove pollutants from the soil matrix. Soil washing can be effective for treating soils contaminated with heavy metals, pesticides, and hydrocarbons.

Thermal desorption

Thermal desorption is a process that uses heat to vaporize organic contaminants from soil. The technique involves heating the contaminated soil to volatilize the pollutants, which are then collected and treated separately. Thermal desorption is particularly useful for removing persistent organic pollutants and volatile contaminants from the soil.

Soil vapor extraction

Soil vapor extraction (SVE) is a technique that involves the extraction of volatile contaminants from the soil using a vacuum system. By applying a vacuum to the soil, the technique promotes the volatilization of contaminants, which are then collected and treated. SVE is effective for soils contaminated with volatile organic compounds (VOCs) and fuels.

Solidification and stabilization

Solidification and stabilization techniques aim to immobilize contaminants in the soil, reducing their mobility and potential for leaching or spreading. This method involves adding binders or chemicals to the contaminated soil, forming a solid mass that encapsulates the pollutants and prevents their movement.

Phytoremediation

Phytoremediation utilizes plants to remove, degrade, or stabilize contaminants in the soil (Ali et al., 2013; Khan et al., 2019). Plants can absorb and accumulate pollutants through their roots (shown in Fig. 4), thus reducing their concentration in the soil. Additionally, plants can promote the breakdown of contaminants through natural processes or provide a conducive environment for microbial activity that aids in bioremediation.

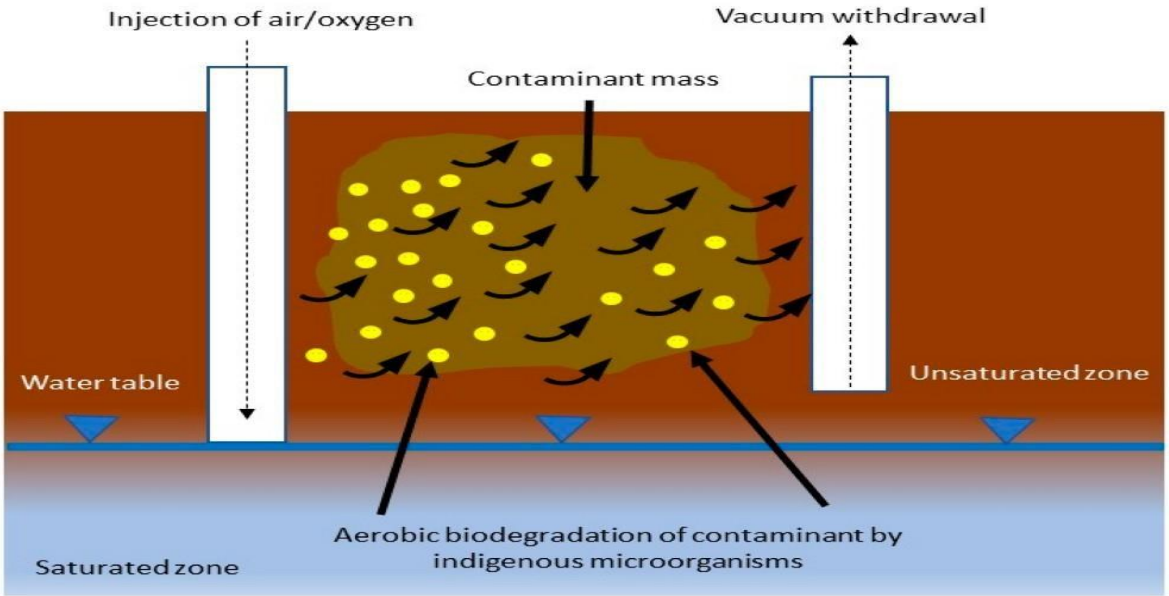

Fig. 3 Soil bioremediation to degrade pollutants

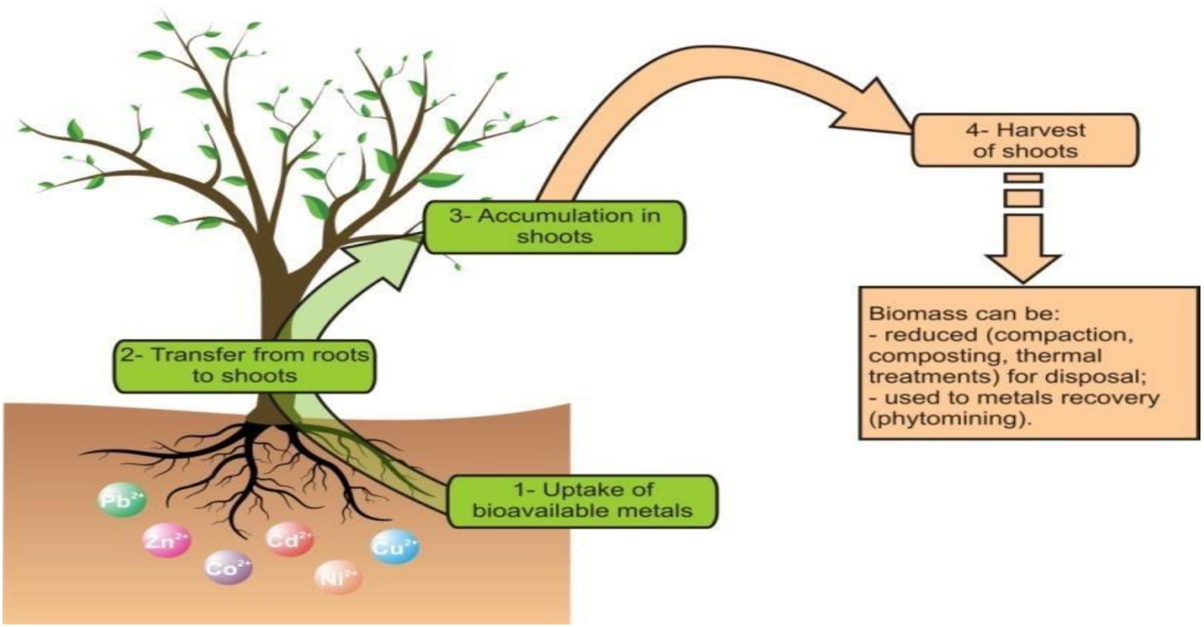

Fig. 4 Phytoremediation of contaminated soil

Electrokinetic remediation

Electrokinetic remediation involves the application of an electric current to the soil, which enhances the movement of contaminants towards electrodes for subsequent removal (Fernández et al., 2017). The method is effective for soils contaminated with heavy metals, ionic pollutants, and certain organic compounds (Hu et al., 2015; Hwang et al., 2020). These soil remediation techniques offer potential solutions for mitigating soil pollution in Pakistan. The selection of the appropriate technique depends on factors such as the type and extent of contamination, site-specific conditions, and regulatory requirements (Singh et al., 2018). Successful soil remediation requires careful planning, site characterization, and regular monitoring to ensure the effectiveness of the chosen technique and the restoration of soil quality to acceptable levels.

Public awareness and education

Public awareness and education play a crucial role in soil pollution management and remediation efforts in Pakistan. It is essential to raise awareness among the public, farmers, industries, policymakers, and other stakeholders about the impacts of soil pollution onhuman health, the environment, and sustainable development. Through targeted awareness campaigns, workshops, and educational programs, individuals can be informed about best practices to prevent soil pollution, such as proper waste disposal, responsible use of chemicals, and sustainable agricultural techniques. Furthermore, educating the public about the importance of soil conservation, the significance of soil testing, and the availability of soil remediation techniques can empower communities to actively participate in soil pollution management initiatives. By fostering a sense of ownership and responsibility towards soil health, public awareness and education efforts can contribute to long-term sustainable practices, increased compliance with regulations, and the preservation of healthy soils in Pakistan.

Case studies and research efforts

Studies on soil pollution hotspots in Pakistan

Several case studies and research efforts have focused on identifying and assessing soilpollution hotspots in Pakistan (Rasool et al., 2020). These studies aim to understand the extent, nature, and sources of soil pollution in specific regions and provide valuable insights for targeted remediation strategies. Through comprehensive soil sampling and analysis, researchers have identified contaminated sites associated with industrial activities, agricultural practices, and urbanization (Shahid et al., 2019). These studies have revealed elevated levels of heavy metals, pesticide residues, organic pollutants, and salinity in certain areas, highlighting the urgency for remedial actions. By mapping and documenting soil pollution hotspots, researchers contribute to the development of evidence-based policies and interventions to address soil pollution challenges. These studies also emphasize the importance of continuous monitoring and evaluation to track changes in pollution levels, assess the effectiveness of remediation measures, and inform future soil pollution management strategiesin Pakistan (Ali et al., 2018; Ashraf et al., 2021).

Innovative approaches and technologies for soil remediation

Case studies and research efforts have been instrumental in exploring innovative approaches and technologies for soil remediation in Pakistan (Abbas et al., 2017; Mahmood et al., 2020). Researchers and environmental professionals have been actively investigating and experimenting with new techniques to remediate contaminated soils effectively and efficiently. These innovative approaches include the use of nanotechnology, biochar application, microbial remediation, and soil amendments (Ahmad et al., 2016; Rizwan et al., 2019). Nanotechnology offers the potential for targeted and efficient removal of contaminants through processes like nanoparticle-enhanced sorption or photocatalysis. Biochar, a carbon-rich material, has shown promise in sequestering pollutants and improving soil fertility. Microbial remediation techniques harness the power of microorganisms to degrade or detoxify contaminants in the soil. In addition, various soil amendments, such as activated carbon, phytoremediation enhancers, and natural zeolites, have been explored for their ability to bind, immobilize, or enhance the degradation of pollutants. These case studies and research efforts provide valuable insights into the feasibility and effectiveness of these innovative approaches and technologies in the context of soil remediation in Pakistan. They contribute to expanding the toolbox of soil remediation strategies and pave the way for more sustainable and cost-effective solutions to combat soil pollution.

Success stories and lessons learned

Case studies and research efforts have led to several success stories and provided valuable lessons in the field of soil pollution management and remediation in Pakistan (Khan et al., 2020; Raza et al., 2021 d). These success stories highlight effective strategies, innovative approaches, and successful implementation of soil remediation projects. For instance, certain contaminated sites have been successfully remediated using a combination of techniques such as soil washing, bioremediation, and phytoremediation. These projects have demonstrated the feasibility and effectiveness of integrating multiple remediation techniques tailored to site- specific conditions. Lessons learned from these success stories include the importance of comprehensive site characterization, proper selection of remediation techniques, and regular monitoring to ensure the long-term effectiveness of remediation efforts (Hussain et al., 2018; Zahid et al., 2020). These case studies have underscored the significance of community involvement, stakeholder engagement, and collaborative partnerships in achieving successful soil pollution management outcomes (Shakeel et al., 2017; Waheed et al., 2022). By sharing these success stories and lessons learned, researchers, policymakers, and practitioners can enhance knowledge sharing, replicate successful approaches, and improve the overall effectiveness of soil pollution management and remediation initiatives in Pakistan.

Future perspectives and recommendations

Strategies for prevention and control of soil pollution

In order to address soil pollution effectively in Pakistan, it is crucial to implement strategies for prevention and control. These strategies can help mitigate the sources and causesof soil pollution, protect soil quality, and ensure sustainable land management practices. Some key recommendations for prevention and control of soil pollution include:

Strengthening regulatory frameworks

Enhance existing policies and regulations related to soil pollution, waste management, and the use of hazardous substances (Government of Pakistan, 2020). Ensure stringent enforcement and compliance mechanisms to prevent soil pollution and hold polluters accountable.

Promoting sustainable agricultural practices

Encourage farmers to adopt sustainable farming techniques such as organic farming, integrated pest management, and efficient use of fertilizers (Qadir et al., 2021). Provide education and training programs to raise awareness about responsible agricultural practices that minimize soil pollution risks.

Encouraging industrial pollution control measures

Industries should implement advanced pollution control technologies, adhere to emission standards, and follow proper waste management practices (Zahoor et al., 2020). Encourage industries to adopt cleaner production techniques and invest in eco-friendly technologies to minimize soil pollution.

Implementing proper waste management

Strengthen waste management systems to ensure proper disposal and treatment of municipal waste, industrial waste, and hazardous substances. Promote recycling and safe disposal practices to prevent the contamination of soil and water resources.

Monitoring and early warning systems

Establish robust soil monitoring programs to track changes in soil quality, identify pollution hotspots, and detect emerging contaminants (Zafar et al., 2018; Shahzad et al., 2022). Develop early warning systems to identify and respond to potential soil pollution risks promptly.

Encouraging research and innovation

Support research efforts to develop innovative techniques and technologies for soil remediation. Foster collaboration between researchers, policymakers, and industry stakeholders to drive innovation and find sustainable solutions for soil pollution management.

Enhancing public awareness and education

Promote public awareness campaigns and educational programs to educate communities about the importance of soil conservation, responsible waste management, and sustainable land practices (Arain et al., 2017). Encourage public participation and empower individuals to take proactive steps in preventing and controlling soil pollution.

Strengthening international collaboration

Engage in international cooperation and knowledge exchange to benefit from best practices and experiences from other countries in soil pollution prevention and control (Murtaza et al., 2018; Ullah et al., 2021). Collaborate with international organizations and participate in global initiatives focused on soil health and pollution management.

Collaboration and international cooperation

Collaboration and international cooperation are vital for addressing soil pollution challenges in Pakistan (Nisar et al., 2021). Given the transboundary nature of pollution, it is essential to foster partnerships and exchange knowledge and experiences with other countries facing similar issues. Collaboration can take various forms, including sharing best practices, research findings, and technological advancements in soil pollution management and remediation (Mirza et al., 2017; Ahmad et al., 2021). International cooperation enables accessto expertise, resources, and funding opportunities that can support Pakistan's efforts in tackling soil pollution. Collaborative initiatives can involve partnerships between government agencies, research institutions, non-governmental organizations, and international bodies specializing in soil health and pollution management (Ali et al., 2018). By leveraging international networks and platforms, Pakistan can learn from successful experiences of other nations, adopt relevant strategies, and adapt them to local contexts (Khan et al., 2019; Raza etal., 2021 c). By embracing collaboration and international cooperation, Pakistan can benefit from shared expertise, innovative solutions, and a collective effort to address soil pollution comprehensively (Siddique et al., 2022). It promotes the development of harmonized approaches, common frameworks, and coordinated actions that can have a significant positive impact on soil health and sustainable land management not only in Pakistan but also globally.

Research priorities and gaps

As Pakistan continues to address soil pollution, it is important to identify research priorities and address existing gaps to improve knowledge and inform effective soil pollution management strategies. Some key research priorities and areas of focus include:

Soil pollution characterization

Conduct comprehensive studies to understand the extent, distribution, and sources of soil pollution across different regions of Pakistan (Bashir et al., 2020; Iqbal et al., 2022). This includes identifying pollution hotspots, assessing contaminant levels, and mapping the spatial distribution of pollutants.

Emerging contaminants

Investigate the presence and impact of emerging contaminants, such as pharmaceuticals, microplastics, and nanoparticles, on soil quality. Understand their behaviour, fate, and potential risks to ecosystems and human health.

Remediation technologies

Explore and evaluate innovative soil remediation technologies suitable for local conditions in Pakistan (Akhtar et al., 2020; Shabbir et al., 2022). Focus on developing cost- effective and sustainable approaches that can efficiently remove or mitigate various types of contaminants from soil.

Socio-economic aspects

Investigate the socio-economic impacts of soil pollution, including its effects on agriculture, food security, livelihoods, and economic sustainability. Assess the cost-benefit analysis of soil pollution management and remediation measures.

Policy and governance

Analyze the effectiveness of existing policy frameworks and governance structures in addressing soil pollution (Zahid et al., 2019; Ali et al., 2021). Identify gaps and provide recommendations for improving regulatory mechanisms, enhancing enforcement, and promoting multi-stakeholder collaboration.

Conclusion

In conclusion, soil pollution poses significant challenges to Pakistan's environment, agriculture, human health, and overall sustainable development. The review paper has provideda comprehensive overview of the sources, causes, types, impacts, and management strategies of soil pollution in Pakistan. It has highlighted the importance of studying soil pollution in the country and the need for effective monitoring, assessment, and remediation approaches. The paper has emphasized the significance of collaboration, research, and international cooperation to address the complexities of soil pollution and develop sustainable solutions. By implementing strategies for prevention and control, promoting innovative approaches, and enhancing public awareness, Pakistan can mitigate the adverse effects of soil pollution and safeguard its soil resources for future generations. Moving forward, it is essential to prioritize research, fill knowledge gaps, and strengthen policy frameworks to ensure the long-term management and remediation of soil pollution in Pakistan. With collective efforts and a commitment to sustainable soil management, Pakistan can strive towards a healthier environment, improved agricultural productivity, and a sustainable future.

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