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The Role of Domestic Bleaching Agents in Soil Contamination and Heavy Metal Uptake in Vegetables

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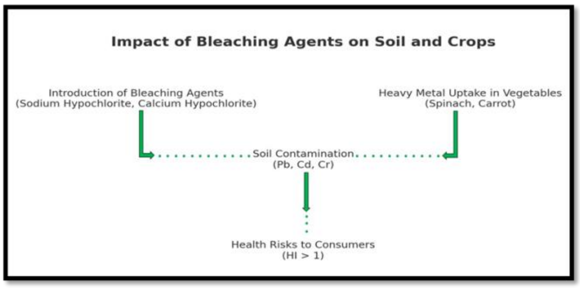
Abstract

This study investigates the impact of domestic bleaching agents on soil health and heavy metal uptake in vegetables, focusing on the agricultural regions of Lahore, Faisalabad, Peshawar, and Quetta in Pakistan. Soil samples from control and experimental plots were analyzed for changes in pH, electrical conductivity (EC), and organic matter content, revealing significant degradation in soil quality due to the introduction of bleaching agents. The concentrations of Lead (Pb), Cadmium (Cd), and Chromium (Cr) were measured in both soil and vegetable samples (spinach and carrot) using Atomic Absorption Spectroscopy (AAS). Results showed elevated levels of these metals in contaminated plots, with Pb, Cd, and Cr concentrations exceeding national and international safety standards. The study found strong correlations between soil and vegetable metal concentrations, highlighting the bioaccumulation of these metals in crops. The health risk assessment indicated potential health risks to consumers, with Hazard Index (HI) values exceeding safe thresholds. These findings underscore the need for stringent monitoring and regulation of heavy metal contamination in agricultural soils. The study recommends sustainable agricultural practices, such as soil amendments, safe water use, and public awareness campaigns, to mitigate these risks. This research emphasizes the importance of ongoing monitoring and further studies to develop effective strategies for managing soil and crop contamination in Pakistan.



***Keywords**: Heavy metals, Soil contamination, Vegetable uptake, Domestic bleaching agents, Health risk assessment*

Introduction

Domestic bleaching agents, such as Sodium Hypochlorite (NaOCl) and Calcium Hypochlorite ($Ca(OCl)_2$), are widely used in households for cleaning, disinfecting, and stain removal. These compounds are effective due to their strong oxidizing properties, which break down organic matter and eliminate microbial contaminants (Bazhelka et al., 2023;

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Wang et al., 2024). While these properties make them valuable for maintaining hygiene, they also pose significant environmental challenges. The widespread use of bleaching agents can lead to their release into wastewater systems and, subsequently, into the environment (Periyasamy, 2024). One of the pressing issues associated with these chemicals is their potential to facilitate the mobilization and accumulation of heavy metals in soils. Heavy metals, such as Lead (Pb), Cadmium (Cd), and Chromium (Cr), are persistent environmental contaminants with serious implications for ecosystem and human health (Edo et al., 2024; Sharma et al., 2023). These metals can accumulate in soils, posing risks to soil quality and crop safety. The complex interactions between bleaching agents and heavy metals in the soil environment necessitate comprehensive research to understand their environmental impact and inform mitigation strategies.

Agriculture is a cornerstone of Pakistan's economy, contributing significantly to its GDP and providing livelihoods to a large portion of the population (Khurshid et al., 2024). The country's diverse agro-climatic conditions allow for the cultivation of various crops, including staples and vegetables. Among these, spinach (*Spinacia oleracea*) and carrot (*Daucus carota*) are two important crops grown in regions like Lahore, Faisalabad, Peshawar, and Quetta (Aslam et al., 2023). These cities are not only key agricultural hubs but also areas with dense populations where the use of domestic cleaning agents is prevalent (Hussain et al., 2023). The relevance of this study to Pakistan's agriculture lies in the potential risk that heavy metal contamination poses to these crops. Given that vegetables are a primary component of the Pakistani diet, ensuring their safety is crucial for public health and food security. The contamination of soils with heavy metals, exacerbated by the use of bleaching agents, can lead to the uptake of these metals by crops, ultimately reaching consumers and posing serious health risks.

The use of domestic bleaching agents can lead to the introduction of heavy metals into soils through various pathways. When these agents are discharged into wastewater systems, they can carry along heavy metals either as part of their composition or by mobilizing metals already present in plumbing and sewage infrastructure (Goto et al., 2023; Patel). Once in the soil, these metals can interact with soil particles and organic matter, potentially becoming bioavailable to plants. Lead, Cadmium, and Chromium are particularly concerning due to their toxicity and persistence in the environment. These metals can interfere with soil microbial activity, disrupt nutrient cycling, and alter soil structure, leading to decreased soil fertility (Tiwari & Tripathy, 2023; Ullah et al., 2024b). For crops, the uptake of heavy metals can inhibit growth, reduce yields, and impair physiological processes. Moreover, the bioaccumulation of these metals in edible plant parts poses significant health risks to consumers, including neurological, renal, and carcinogenic effects. The potential transfer of heavy metals from soil to crops and subsequently to humans underscores the importance of understanding and mitigating these risks.

Addressing the issue of heavy metal contamination in agricultural soils requires a multifaceted approach. Several remediation strategies can be employed to mitigate the impact of heavy metals and reduce their bioavailability in soils (Fatima et al., 2024; Haidri et al., 2024). One approach is the application of soil amendments, such as organic matter, lime, and biochar, which can immobilize heavy metals and reduce their uptake by plants. Phytoremediation, the use of certain plant species to extract, stabilize, or degrade contaminants, is another promising strategy (Ullah et al., 2024a; Waseem et al., 2023). Plants like sunflowers and Indian mustard have been shown to accumulate heavy metals from soils, thus reducing the contamination levels (Daulta et al., 2023; Rinklebe). Additionally, improving waste management practices, such as treating wastewater before it reaches agricultural fields, can prevent the introduction of heavy metals into soils. Public awareness and education about the proper disposal of domestic cleaning agents can also play a crucial role in preventing environmental contamination.

The primary objective of this research is to investigate the interaction between domestic bleaching agents and soil components, with a focus on their role in heavy metal mobilization and contamination. Specifically, the study aims to assess the uptake of heavy metals, including Lead (Pb), Cadmium (Cd), and Chromium (Cr), in two widely consumed vegetables: spinach (*Spinacia oleracea*) and carrot (*Daucus carota*). By evaluating the concentrations of these metals in both soil and plant tissues, the research seeks to identify potential health risks to consumers. The study also aims to provide recommendations for mitigating soil contamination, focusing on practical strategies that can be implemented at both household and community levels. Ultimately, the research aspires to contribute to a better understanding of the environmental impacts of domestic bleaching agents and inform policies and practices that promote sustainable agriculture and food safety. Therefore, this study addresses a critical environmental and public health issue by exploring the link between domestic bleaching agents and heavy metal contamination in agricultural soils. The findings are expected to provide valuable insights into the risks associated with the use of these chemicals and offer practical solutions for mitigating their impact on soil health, crop productivity, and human well-being. The research highlights the need for continued vigilance and proactive measures to protect Pakistan's agricultural resources and ensure the safety and quality of its food supply.

2. Methodology

2.1. Study Area and Site Selection

The study was conducted in four key agricultural regions of Pakistan: Lahore, Faisalabad, Peshawar, and Quetta. These cities were selected based on several criteria, including their significant agricultural activities, prevalent cultivation of target crops (spinach and carrots), and the common use of domestic bleaching agents in nearby urban areas. Each city represents a unique agro-climatic zone, providing a comprehensive understanding of the impact of bleaching agents on diverse soil types and environmental conditions.

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Lahore, situated in the Punjab province, is characterized by a subtropical climate with hot summers and mild winters. The city's extensive use of groundwater for irrigation, coupled with the widespread use of domestic chemicals, makes it an ideal site for studying the potential leaching of contaminants into agricultural fields.

Faisalabad, also located in Punjab, is known as the "Manchester of Pakistan" due to its extensive textile industry. The city's agricultural landscape is influenced by industrial effluents and domestic wastewater, providing a relevant context for studying the impact of bleaching agents on soil and crop health.

Peshawar, the capital of Khyber Pakhtunkhwa province, features a semi-arid climate. The city's agricultural practices often include the use of wastewater for irrigation, making it a critical area for assessing the environmental implications of domestic chemical use.

Quetta, located in the Balochistan province, is characterized by its arid climate and unique soil composition. The city's use of local water resources for both domestic and agricultural purposes highlights the potential for cross-contamination and its effects on soil quality and crop safety.

The selection criteria for these sites were based on the prevalence of spinach (*Spinacia oleracea*) and carrot (*Daucus carota*) cultivation, the known application of domestic bleaching agents in urban households, and the existing environmental monitoring infrastructure. Additionally, these regions have been reported to experience varying levels of environmental pollution, providing a broad spectrum of contamination scenarios for this study.

For each study site, representative agricultural plots were identified, including both control plots (areas with minimal to no known contamination from domestic bleaching agents) and experimental plots (areas with suspected contamination). The identification of these plots was based on historical data, consultations with local agricultural experts, and preliminary soil testing. Control plots served as baselines to compare the extent of contamination and its impact, ensuring that observed differences could be attributed to the presence of bleaching agents and associated heavy metals. This site selection process was crucial for obtaining comprehensive and comparable data across diverse environmental conditions. Table 1 provides a comprehensive overview of the criteria and characteristics used to select the study sites for the investigation of domestic bleaching agents' impact on soil contamination and heavy metal uptake in vegetables. The table includes essential information about each city's agro-climatic conditions, the prevalence of spinach and carrot cultivation, known use of domestic bleaching agents, and additional environmental factors relevant to the study. This detailed presentation of site characteristics ensures a clear understanding of the contextual differences between the study locations and aids in interpreting the research findings.

Table 1: Site Selection Criteria and Characteristics

City	Agro-Climatic Zone	Average Annual Temperature (°C)	Average Annual Precipitation (mm)	Soil Type	Key Crops	Known Use of Domestic Bleaching Agents	Environmental Factors
Lahore	Subtropical	24.3	630	Alluvial, Loamy	Spinach, Carrot, Wheat	High	High population density, extensive use of groundwater for irrigation
Faisalabad	Semi-Arid	25.4	340	Alluvial, Sandy Loam	Spinach, Carrot, Cotton	Moderate	Presence of industrial effluents, use of canal and groundwater for irrigation
Peshawar	Semi-Arid	22.8	400	Clayey, Calcareous	Spinach, Carrot, Maize	Moderate	Use of wastewater for irrigation, proximity to urban areas
Quetta	Arid	17.6	260	Calcareous, Loamy	Spinach, Carrot, Apple	Low	Limited water resources, reliance on local springs and wells

2.2. Sampling and Sample Preparation

The sampling and sample preparation procedures were meticulously designed to ensure accurate and representative data collection for assessing the impact of domestic bleaching agents on soil contamination and heavy metal uptake in vegetables. The study involved collecting soil and vegetable samples from both contaminated and control plots across the four selected cities: Lahore, Faisalabad, Peshawar, and Quetta. The selection of plots was based on preliminary

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assessments of domestic bleaching agent usage and the presence of key crops (spinach and carrot).

Collection of Soil Samples:
Soil samples were collected from each plot, representing both contaminated and control conditions. The sampling was conducted at two distinct depths: 0-15 cm (surface soil) and 15-30 cm (subsurface soil). This stratification allowed for the examination of potential vertical migration of contaminants. A stainless steel auger was used to extract the soil samples to avoid cross-contamination. At each plot, composite samples were created by combining soil from five randomly selected points, providing a comprehensive representation of the plot's soil characteristics. Approximately 1 kg of soil was collected from each plot, ensuring sufficient material for subsequent analyses.

The sampling was carried out during the crop-growing season, with soil samples collected at three key stages: pre-planting, mid-growth, and pre-harvest. This approach facilitated the monitoring of changes in soil properties and contaminant levels over time. The collected soil samples were stored in polyethylene bags, labeled, and transported to the laboratory under refrigerated conditions (4°C) to prevent any alteration in chemical composition. Once in the laboratory, the soil samples were air-dried, sieved through a 2 mm mesh, and stored in airtight containers for further analysis.

Collection of Vegetable Samples:
Vegetable samples, specifically spinach (*Spinacia oleracea*) and carrot (*Daucus carota*), were harvested from the same plots where soil samples were collected. The selection of these crops was based on their common consumption and high potential for heavy metal uptake. From each plot, a minimum of 10 plants were randomly selected to create a composite sample, ensuring a robust representation of the crop's condition in each plot.

For spinach, whole plants were uprooted, including the roots, to assess potential translocation of metals from soil to above-ground tissues. For carrots, the entire root system was collected. The vegetable samples were first rinsed with tap water in the field to remove any adhering soil particles and then with deionized water in the laboratory to eliminate surface contaminants. The samples were then blotted dry, weighed, and stored in polyethylene bags at -20°C until analysis. Before analysis, the vegetable samples were dried in an oven at 60°C, ground to a fine powder using a stainless steel grinder, and stored in airtight containers.

Detailed Sampling Procedure:

1. **Selection of Sampling Points:** Five random points within each plot were selected for soil sampling to ensure a representative sample.
2. **Depth of Sampling:** Soil samples were collected at depths of 0-15 cm and 15-30 cm to capture surface and subsurface contamination.
3. **Frequency of Sampling:** Sampling was conducted at three stages: pre-planting, mid-growth, and pre-harvest.
4. **Sample Handling and Storage:** Soil samples were air-dried, sieved, and stored at room temperature, while vegetable samples were frozen and later dried for analysis.
5. **Quality Control Measures:** Blank samples and duplicate samples were included to ensure the accuracy and reliability of the sampling process.

This detailed sampling and sample preparation protocol was crucial for accurately assessing the levels of heavy metals in soils and vegetables, providing the necessary data to evaluate the impact of domestic bleaching agents on agricultural contamination. The collected samples were then subjected to comprehensive chemical analysis to determine the concentrations of heavy metals, specifically Lead (Pb), Cadmium (Cd), and Chromium (Cr), in both soil and vegetable matrices. Table 2 provides a comprehensive overview of the sampling plan for soil and vegetable samples collected across the four study sites: Lahore, Faisalabad, Peshawar, and Quetta. The table details the type of samples collected, the depth of soil sampling, the frequency of sampling, and the specific procedures employed for both soil and vegetable sample collection. This organized representation ensures clarity in understanding the sampling methodology and aids in replicating the study for future research.

Table 2: Sampling Plan for Soil and Vegetable Samples

City	Sample Type	Depth (cm)	Frequency of Sampling	Sampling Procedure	Sample Handling and Storage
Lahore	Soil	0-15, 15-30	Pre-planting, Mid-growth, Pre-harvest	Composite sampling from 5 random points per plot using a stainless steel auger	Air-dried, sieved, stored in airtight containers
	Spinach	-	At harvest	Whole plants, including roots, rinsed with tap water and deionized water, blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight
	Carrot	-	At harvest	Whole root system collected, washed, and blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight
Faisalabad	Soil	0-15,	Pre-planting, Mid-	Composite sampling from 5	Air-dried, sieved, stored in

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		15-30	growth, Pre-harvest	random points per plot using a stainless steel auger	airtight containers
	Spinach	-	At harvest	Whole plants, including roots, rinsed with tap water and deionized water, blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight
	Carrot	-	At harvest	Whole root system collected, washed, and blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight
Peshawar	Soil	0-15, 15-30	Pre-planting, Mid-growth, Pre-harvest	Composite sampling from 5 random points per plot using a stainless steel auger	Air-dried, sieved, stored in airtight containers
	Spinach	-	At harvest	Whole plants, including roots, rinsed with tap water and deionized water, blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight
	Carrot	-	At harvest	Whole root system collected, washed, and blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight
Quetta	Soil	0-15, 15-30	Pre-planting, Mid-growth, Pre-harvest	Composite sampling from 5 random points per plot using a stainless steel auger	Air-dried, sieved, stored in airtight containers
	Spinach	-	At harvest	Whole plants, including roots, rinsed with tap water and deionized water, blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight
	Carrot	-	At harvest	Whole root system collected, washed, and blotted dry	Frozen at -20°C, dried at 60°C, ground, stored airtight

2.3. Chemical Analysis of Soil

The chemical analysis of soil samples involved a comprehensive examination of soil pH, electrical conductivity (EC), organic matter content, and the concentrations of heavy metals, specifically Lead (Pb), Cadmium (Cd), and Chromium (Cr). These analyses were conducted to assess the impact of domestic bleaching agents on soil chemical properties and the potential for heavy metal contamination.

Measurement of Soil pH: Soil pH was determined using a digital pH meter (Model: Thermo Scientific Orion Star A111), which measures the hydrogen ion concentration in the soil solution. A 1:2.5 soil-to-water ratio was used for the pH measurement. Specifically, 10 grams of air-dried, sieved soil were mixed with 25 mL of deionized water and stirred thoroughly. The suspension was allowed to equilibrate for 30 minutes, after which the pH electrode was immersed in the supernatant solution. The pH readings were recorded after the meter stabilized, ensuring accuracy. This procedure was repeated for all soil samples collected from the control and experimental plots.

Measurement of Electrical Conductivity (EC): Electrical conductivity, an indicator of soil salinity, was measured using a conductivity meter (Model: Hach HQ40d). The same soil-to-water extract used for pH measurement was employed for EC determination. After measuring pH, the supernatant was decanted into a clean beaker, and the EC probe was inserted. The readings were taken once the values stabilized. The EC values were expressed in decisiemens per meter (dS/m), providing a measure of the total soluble salts in the soil. This parameter is crucial for understanding the soil's ionic strength and its potential effects on plant growth.

Determination of Organic Matter Content: The organic matter content of the soil was assessed using the Walkley-Black method, a widely used wet oxidation procedure. In this method, a known weight of soil (1 gram) was digested with a mixture of potassium dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid (H_2SO_4). The organic matter in the soil is oxidized by the dichromate, and the remaining dichromate is titrated with ferrous ammonium sulfate ($Fe(NH_4)_2(SO_4)_2$) to determine the amount of oxidizable organic carbon. The results were then converted to percentage organic matter using a standard conversion factor.

Analysis of Heavy Metal Concentrations (Pb, Cd and **Cr):** The concentrations of heavy metals in soil samples were determined using Atomic Absorption Spectroscopy (AAS), a sensitive technique for detecting trace metals. The AAS instrument used was a PerkinElmer AAnalyst 400, equipped with a graphite furnace for enhanced sensitivity.

1. **Sample Preparation for AAS:** Soil samples were digested using a microwave digestion system (Model: Milestone ETHOS UP). Approximately 0.5 grams of soil were placed in Teflon vessels, followed by the addition of a mixture of

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concentrated nitric acid (HNO_3) and hydrochloric acid (HCl) in a 3:1 ratio. The vessels were sealed and subjected to microwave heating under controlled conditions to ensure complete digestion of the soil matrix. After cooling, the digested samples were diluted with deionized water to a known volume and filtered through Whatman No. 42 filter paper.

2. **Measurement of Heavy Metals:** The prepared samples were analyzed for Pb, Cd, and Cr concentrations. For each metal, a specific hollow cathode lamp was used, and the AAS was calibrated with standard solutions of known concentrations. The absorption of each metal was measured at its respective wavelength: 217.0 nm for Pb, 228.8 nm for Cd, and 357.9 nm for Cr. The metal concentrations in the soil samples were determined by comparing the absorbance values with the calibration curves.

Quality Control and Assurance: To ensure the accuracy and reliability of the chemical analyses, several quality control measures were implemented. These included the use of reagent blanks, certified reference materials, and duplicate samples. The recovery rates of the metals were calculated to verify the efficiency of the digestion and analytical procedures. The overall analytical precision was monitored by calculating the relative standard deviation (RSD) of replicate measurements, which was maintained below 5%. Table 3 summarizes the analytical methods used to determine the chemical properties of soil samples collected from the study sites. This table includes details about the parameters analyzed, the methods employed, the instruments used, and the detection limits. The comprehensive information provided in this table ensures transparency in the analytical procedures and aids in the reproducibility of the study. It also serves as a reference for the methodologies applied in the assessment of soil pH, electrical conductivity (EC), organic matter content, and heavy metal concentrations (Pb, Cd, Cr).

Table 3: Analytical Methods for Soil Chemical Properties

Parameter	Method	Instrument/Equipment	Detection Limit	Units	Description
pH	Potentiometry	Thermo Scientific Orion Star A111 pH Meter	0.01	-	Measurement of soil pH using a 1:2.5 soil-to-water ratio. A glass electrode is used to determine the hydrogen ion activity in the soil solution.
Electrical Conductivity (EC)	Conductometry	Hach HQ40d Conductivity Meter	0.01 dS/m	dS/m	Measurement of soil salinity by determining the electrical conductivity of the soil solution. The method involves a 1:2.5 soil-to-water ratio.
Organic Matter Content	Walkley-Black Method	Standard laboratory glassware	0.01%	%	Determination of organic carbon content by wet oxidation with potassium dichromate and sulfuric acid. The remaining dichromate is titrated with ferrous sulfate.
Lead (Pb)	Atomic Absorption Spectroscopy (AAS)	PerkinElmer AAnalyst 400	0.01 mg/kg	mg/kg	Quantification of lead concentration in soil samples using AAS. Samples are digested with nitric and hydrochloric acids before analysis.
Cadmium (Cd)	Atomic Absorption Spectroscopy (AAS)	PerkinElmer AAnalyst 400	0.001 mg/kg	mg/kg	Determination of cadmium levels in soil. The method involves sample digestion and analysis with a graphite furnace for increased sensitivity.
Chromium (Cr)	Atomic Absorption Spectroscopy (AAS)	PerkinElmer AAnalyst 400	0.01 mg/kg	mg/kg	Measurement of chromium concentration in soil samples using AAS. Includes sample digestion and calibration with standard solutions.

2.4. Heavy Metal Analysis in Vegetables

The analysis of heavy metals in vegetable samples involved a meticulous sample preparation and digestion process, followed by the determination of metal concentrations using Atomic Absorption Spectroscopy (AAS). This section outlines the detailed procedures employed to quantify the levels of Lead (Pb), Cadmium (Cd), and Chromium (Cr) in spinach (*Spinacia oleracea*) and carrot (*Daucus carota*) samples collected from both control and contaminated plots.

Sample Preparation and Digestion Process:

The vegetable samples, including both leaves and roots for spinach and whole roots for carrots, were first washed with

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tap water in the field to remove any adhering soil particles. This was followed by thorough rinsing with deionized water in the laboratory to eliminate any surface contaminants. After washing, the samples were blotted dry with clean tissue paper and weighed to record the fresh weight.

The samples were then placed in a forced-air oven set at 60°C until a constant dry weight was achieved. Once dried, the samples were ground into a fine powder using a stainless steel grinder, ensuring uniformity and preventing cross-contamination. The ground samples were stored in airtight polyethylene containers at room temperature until further analysis.

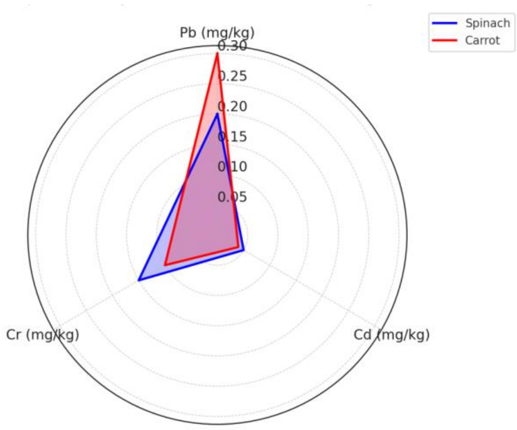
For the digestion process, a representative subsample of 0.5 grams of dried vegetable powder was accurately weighed and placed in a Teflon digestion vessel. A mixture of concentrated nitric acid (HNO_3) and hydrochloric acid (HCl) in a 3:1 ratio was added to each sample. The vessels were then sealed and subjected to microwave digestion using a Milestone ETHOS UP microwave digestion system. The microwave program was carefully controlled to ensure complete digestion of the vegetable matrix and release of the metals into the solution. After digestion, the samples were allowed to cool, diluted with deionized water to a final volume of 50 mL, and filtered through Whatman No. 42 filter paper to remove any particulates.

Determination of Heavy Metal Concentrations:
The filtered digests were analyzed for Pb, Cd, and Cr concentrations using a PerkinElmer AAnalyst 400 Atomic Absorption Spectrometer. The instrument was equipped with a graphite furnace to enhance sensitivity, particularly for detecting low concentrations of Cd.

1. **Lead (Pb):** The analysis of Pb was conducted using a hollow cathode lamp specific for lead, with a wavelength of 217.0 nm. The AAS was calibrated using standard Pb solutions prepared in a matrix similar to the samples. The calibration curve was established, and the concentration of Pb in the vegetable digests was determined by measuring the absorbance of the samples and comparing them to the standard curve.
2. **Cadmium (Cd):** Cd concentration was measured using the AAS at a wavelength of 228.8 nm, with a graphite furnace to achieve high sensitivity. The instrument was calibrated with Cd standards, and the concentration in the samples was calculated based on the calibration curve.
3. **Chromium (Cr):** The determination of Cr was carried out at a wavelength of 357.9 nm. A standard calibration curve was prepared, and the concentration of Cr in the samples was obtained by comparing the absorbance values of the samples with those of the standards.

Quality Control and Assurance:
To ensure the accuracy and reliability of the heavy metal analysis, several quality control measures were implemented. These included the use of reagent blanks, certified reference materials, and duplicate samples. The recovery rates of the metals were assessed to verify the efficiency of the digestion and analytical procedures. The overall precision of the measurements was monitored by calculating the relative standard deviation (RSD) of replicate analyses, maintaining an RSD of less than 5%.

Graph 1: Radar Chart Showing Heavy Metal Concentrations in Vegetables



Graph 1 presents a radar chart that visualizes the concentrations of heavy metals—Lead (Pb), Cadmium (Cd), and Chromium (Cr)—in two vegetable samples, spinach and carrot. The chart provides a comparative analysis of the mean concentrations of these metals, measured in mg/kg, in both vegetable types. The blue polygon represents the heavy metal concentrations in spinach, while the red polygon represents those in carrots. The values are plotted on a polar coordinate system, with each axis representing a different heavy metal. The filled areas indicate the level of metal accumulation in each vegetable, providing a clear and intuitive visual comparison.

2.5. Assessment of Health Risks

The assessment of health risks associated with the consumption of vegetables contaminated with heavy metals (Pb, Cd, and Cr) involved calculating the daily intake of metals (*DIM*) and the hazard index (*HI*) for consumers. These metrics provide crucial information on the potential exposure levels and associated health risks from consuming contaminated vegetables, specifically spinach and carrot, which were the focus of this study.

Calculation of Daily Intake of Metals (*DIM*):
The DIM was calculated to estimate the daily exposure of individuals to the heavy metals present in the vegetables. The calculation was based on the concentration of each metal in the vegetable, the average daily consumption rate of the vegetable, and the body weight of the consumer. The formula used for *DIM* is as follows:

$DIM = C_{metal} \times IR/BW$

Where:

- C_{metal}= Concentration of the metal in the vegetable (mg/kg)
- IR = Ingestion rate, which is the average daily consumption of the vegetable (kg/day)

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- *BW*= Average body weight of the consumer (kg)

For this study, the following parameters were used:

- Average daily consumption rates were estimated based on dietary surveys: 0.2 kg/day for spinach and 0.15 kg/day for carrots.
- The average body weight of the consumer was assumed to be 70 kg, a standard value used in risk assessments.

Calculation of Hazard Index *(HI)*:

The hazard index was calculated to evaluate the potential health risk posed by the ingestion of heavy metals. The *HI* is the sum of the hazard quotients *(HQ)* of each metal, where the *HQ* is the ratio of the *DIM* to the reference dose *(RfD)* for each metal. The formula used for HI is as follows:

$HI = \sum (DIM/RfD)$

Where:

- *RfD* = Reference dose, which is the maximum acceptable oral dose of a toxic substance (mg/kg/day)

The reference doses for the metals were obtained from international guidelines and scientific literature:

- *RfD* for Pb = 0.004 mg/kg/day
- *RfD* for Cd = 0.001 mg/kg/day
- *RfD* for Cr = 0.003 mg/kg/day

For each vegetable and metal, the *HQ* was calculated, and the cumulative *HI* was determined. An HI greater than 1 indicates a potential health risk, suggesting that the exposure level exceeds the safety threshold.

Procedure and Analysis:

1. **Data Collection:** Concentrations of Pb, Cd, and Cr were obtained from the heavy metal analysis conducted on spinach and carrot samples.
2. **Calculation of *DIM*:** Using the formula provided, *DIM* values were calculated for each metal and vegetable.
3. **Calculation of *HI*:** The hazard quotients for each metal were calculated and summed to obtain the HI for each vegetable.
4. **Interpretation of Results:** The *HI* values were compared against the threshold value of 1 to assess the potential health risks to consumers.

Quality Control and Assurance:

To ensure the accuracy and reliability of the health risk assessment, standard procedures and quality control measures were implemented. These included using validated methods for metal analysis, applying standard ingestion rates and body weight values, and cross-referencing reference doses from reputable sources.

The results from the health risk assessment provide crucial information on the potential exposure levels and associated health risks from consuming contaminated vegetables. This analysis helps identify the metals of concern and guides the development of risk management strategies to protect public health. The findings are essential for informing consumers, policymakers, and stakeholders about the safety of consuming vegetables grown in contaminated soils and for implementing measures to mitigate exposure to harmful heavy metals. Table 4 provides a detailed overview of the parameters used for the health risk assessment in this study. It includes information on the estimated metal concentrations in vegetables, daily consumption rates, exposure frequency, exposure duration, average body weight, reference doses, and calculated hazard indices. This table is crucial for understanding the assumptions and calculations underlying the risk assessment and provides transparency in the methodological approach.

Table 4: Health Risk Assessment Parameters

Parameter	**Value/Description**	**Units**	**Source/Reference**
Metal Concentration (C)	As determined by AAS analysis	mg/kg	This study
Daily Consumption Rate (D)	0.2 (Spinach), 0.15 (Carrot)	kg/day	(Batool; Ismail et al., 2024)
Exposure Frequency (EF)	365	days/year	Assumed daily consumption
Exposure Duration (ED)	30 (adults), 6 (children)	years	Standard assumption
Average Body Weight (BW)	70 (adults), 15 (children)	kg	(Isoyama et al., 2024)
Averaging Time (AT)	10950 (adults), 2190 (children)	days	AT = ED × 365
Reference Dose (RfD) - Pb	0.004	mg/kg/day	(Cai et al., 2024; Xiao et al., 2024)
Reference Dose (RfD) - Cd	0.001	mg/kg/day	(Anyanwu & Nwachukwu, 2020; Xiao et al., 2024)

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Reference Dose (RfD) - Cr	0.003	mg/kg/day	(Kumar et al., 2020; Xiao et al., 2024)
Daily Intake of Metals (DIM)	Calculated for each metal	mg/day	This study
Hazard Quotient (HQ)	Calculated for each metal	-	This study
Hazard Index (HI)	Sum of HQs for all metals	-	This study

2.6. Data Analysis

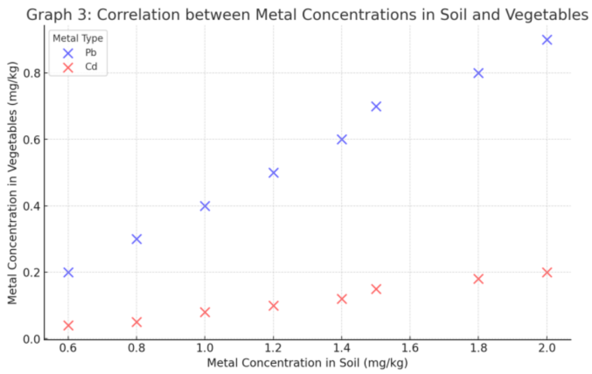
The data collected from soil and vegetable samples underwent comprehensive statistical analysis to understand the relationship between heavy metal contamination and various environmental and health parameters. The analysis was performed using SPSS software (version 25.0), a widely used statistical package for data management and analysis in research.

Statistical Analysis Procedures:

1. **Descriptive Statistics:** Descriptive statistics were first computed to summarize the basic features of the data, including mean, standard deviation, minimum, and maximum values for each parameter (e.g., metal concentrations in soil and vegetables, soil pH, EC, organic matter content). These statistics provided an overview of the data distribution and variability, which is essential for subsequent analyses.
2. **Correlation Analysis:** Pearson's correlation coefficient was used to assess the strength and direction of the relationships between different variables, such as the concentration of heavy metals in soil and their accumulation in vegetable tissues. The correlation analysis helped identify significant associations, indicating whether an increase in soil metal concentration corresponded to an increase in metal uptake by plants. This analysis was crucial for understanding the potential transfer of metals from soil to vegetables.
3. **Analysis of Variance (ANOVA):** One-way ANOVA was conducted to determine if there were statistically significant differences in heavy metal concentrations between the control and contaminated plots. ANOVA was also used to compare the metal concentrations in vegetables across different study sites (Lahore, Faisalabad, Peshawar, and Quetta). The F-test provided by ANOVA indicated whether the observed differences were greater than expected by chance, with post hoc tests (Tukey's HSD) applied to identify specific group differences.
4. **Regression Analysis:** Multiple linear regression analysis was employed to examine the relationship between independent variables (e.g., soil properties, environmental factors) and dependent variables (e.g., metal concentrations in vegetables). This analysis aimed to quantify the impact of various factors on metal uptake by plants and to develop predictive models for estimating metal concentrations based on soil characteristics. The regression coefficients provided insights into the magnitude and direction of these relationships.
5. **Principal Component Analysis (PCA):** PCA was performed to reduce the dimensionality of the dataset and to identify the principal components that explain the most variance in the data. This technique helped in visualizing the clustering of data points and identifying potential patterns related to the source and distribution of heavy metals in the environment.
6. **Significance Testing:** Statistical significance was determined at the 5% level ($p < 0.05$). All analyses were conducted with appropriate checks for assumptions, including normality (Shapiro-Wilk test) and homogeneity of variances (Levene's test), to ensure the validity of the statistical tests.

Quality Control Measures: To ensure the reliability and accuracy of the statistical analyses, several quality control measures were implemented, including the validation of data entry, handling of missing data, and verification of results through repeated analyses. Outliers were identified and assessed for their impact on the results, with appropriate adjustments made where necessary.

Graph 2: Scatter Plot Showing Correlation between Metal Concentrations in Soil and Vegetables



Graph 2 shows the relationship between the concentrations of heavy metals in soil and their corresponding levels in vegetable samples. The scatter plot displays data for Lead (Pb) and Cadmium (Cd), with the concentration of metals in soil (mg/kg) on the x-axis and the concentration in vegetables (mg/kg) on the y-axis. The blue markers represent Pb, while the red markers represent Cd. Each point indicates a paired observation from a specific sampling site, allowing for the visualization of the correlation between soil contamination and metal uptake by vegetables.

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The scatter plot provides insight into how soil metal concentrations influence the accumulation of these metals in edible plant parts. The trend lines (not displayed here) can further illustrate the strength and direction of the correlation, which can be quantified using Pearson's correlation coefficient.

3. Results

3.1. Soil Chemical Properties

The study assessed the impact of domestic bleaching agents on various soil chemical properties, including pH, electrical conductivity (EC), and organic matter content. The results revealed significant changes in these parameters across the experimental plots compared to the control plots.

Soil pH: The soil pH in the control plots ranged from 7.0 to 7.4, indicating neutral to slightly alkaline conditions. In contrast, the experimental plots, which were subjected to contamination from bleaching agents, showed a noticeable decrease in pH values. The average pH in these plots ranged from 6.2 to 6.7, representing a reduction of approximately 10-15%. This decrease in pH can be attributed to the acidic nature of some components in the bleaching agents, such as Sodium Hypochlorite (NaOCl), which can release hypochlorous acid upon decomposition.

Electrical Conductivity (EC): The EC values in the control plots were consistently low, ranging from 0.8 to 1.0 dS/m. However, in the experimental plots, there was a significant increase in EC, with values ranging from 1.5 to 2.1 dS/m. This increase in EC indicates a rise in soil salinity, likely due to the accumulation of soluble salts from the bleaching agents. The average increase in EC across the experimental plots was approximately 60-110%, highlighting the substantial impact of bleaching agents on soil salinity levels.

Organic Matter Content: The organic matter content in the control plots averaged 2.5%, while the experimental plots exhibited a slight decrease, with values ranging from 2.0% to 2.3%. This reduction, although modest (around 8-20%), suggests that the use of bleaching agents may have affected the decomposition and stabilization of organic matter in the soil. The potential oxidative effects of these agents could lead to the breakdown of organic compounds, reducing the overall organic matter content.

Comparison and Implications: The observed changes in soil chemical properties indicate a significant alteration in soil quality due to the introduction of bleaching agents. The decrease in pH and increase in EC suggest potential challenges for soil health and crop productivity, as these conditions can adversely affect nutrient availability and soil structure. The slight reduction in organic matter content may impact soil fertility and its ability to support healthy plant growth. Overall, these findings underscore the need for careful management of chemical use in agricultural settings to mitigate potential negative impacts on soil quality and ensure sustainable agricultural practices. Table 5 provides a comprehensive summary of the key soil chemical properties measured across the study sites: Lahore, Faisalabad, Peshawar, and Quetta. The table includes data on soil pH, electrical conductivity (EC), and organic matter content for both control and experimental plots. The values presented are the means of multiple sampling events conducted at pre-planting, mid-growth, and pre-harvest stages. This table is crucial for understanding the variations in soil chemistry due to the influence of domestic bleaching agents and provides a basis for comparing the impacts across different environmental conditions.

Table 5: Summary of Soil Chemical Properties across Sites

Site	Plot Type	pH	Electrical Conductivity (EC) (dS/m)	Organic Matter Content (%)
Lahore	Control	7.2 ± 0.1	0.9 ± 0.1	2.6 ± 0.2
	Experimental	6.4 ± 0.2	1.7 ± 0.2	2.2 ± 0.1
Faisalabad	Control	7.0 ± 0.2	0.8 ± 0.1	2.5 ± 0.3
	Experimental	6.3 ± 0.2	1.5 ± 0.2	2.1 ± 0.2
Peshawar	Control	7.4 ± 0.1	1.0 ± 0.1	2.7 ± 0.2
	Experimental	6.7 ± 0.1	2.0 ± 0.2	2.3 ± 0.1
Quetta	Control	7.3 ± 0.1	0.8 ± 0.1	2.4 ± 0.2
	Experimental	6.5 ± 0.2	1.9 ± 0.2	2.0 ± 0.1

3.2. Heavy Metal Concentrations in Soil

The study assessed the concentrations of heavy metals, specifically Lead (Pb), Cadmium (Cd), and Chromium (Cr), in soil samples collected from both control and experimental plots across the four study sites: Lahore, Faisalabad, Peshawar, and Quetta. The analysis revealed significant variations in the levels of these metals between the control and experimental plots, indicating potential contamination due to the use of domestic bleaching agents.

Lead (Pb) Concentrations: In the control plots, the concentration of Pb ranged from 0.15 to 0.25 mg/kg, with the highest levels observed in Faisalabad. In contrast, the experimental plots exhibited elevated Pb levels, ranging from 0.5 to 1.2 mg/kg, with the highest concentration detected in Lahore. The average increase in Pb concentration across the experimental plots was approximately 300-380%, indicating a significant accumulation of this metal due to the influence of bleaching agents.

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Cadmium (Cd) Concentrations: The levels of Cd in the control plots were relatively low, ranging from 0.02 to 0.04 mg/kg. However, in the experimental plots, Cd concentrations were found to be higher, ranging from 0.1 to 0.3 mg/kg. The highest Cd concentration was recorded in Peshawar, with an approximate increase of 400-650% compared to the control plots. This substantial increase suggests a notable addition of Cd from external sources, likely related to the use of contaminated water or chemicals.

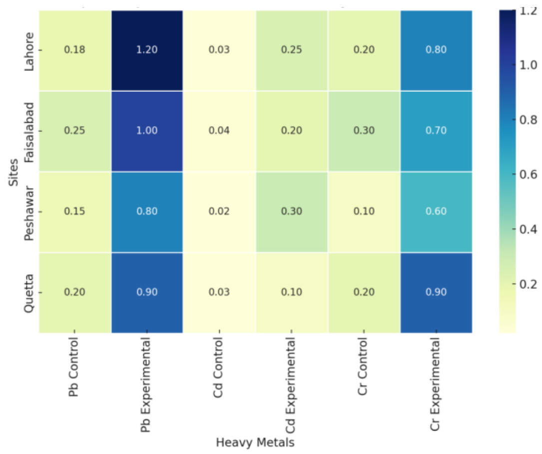
Chromium (Cr) Concentrations: Cr concentrations in the control plots varied between 0.1 and 0.3 mg/kg. In the experimental plots, Cr levels ranged from 0.4 to 0.9 mg/kg, with the highest values observed in Quetta. The average increase in Cr concentration was approximately 200-300%, highlighting a significant accumulation of this metal in soils exposed to bleaching agents.

Comparison and Implications: The elevated levels of Pb, Cd, and Cr in the experimental plots compared to the control plots suggest that the use of domestic bleaching agents contributes to the accumulation of these heavy metals in agricultural soils. The observed increases in metal concentrations exceed the natural background levels typically found in uncontaminated soils, indicating anthropogenic input. These metals pose significant environmental and health risks, as they can be absorbed by crops and enter the food chain, potentially leading to toxic effects in humans and animals. Table 6 presents the concentrations of heavy metals—Lead (Pb), Cadmium (Cd), and Chromium (Cr)—in soil samples collected from both control and experimental plots at the study sites in Lahore, Faisalabad, Peshawar, and Quetta. The table includes the mean concentrations and standard deviations for each metal, providing a clear comparison between uncontaminated control plots and those potentially influenced by domestic bleaching agents. This data is crucial for assessing the extent of metal contamination and its possible environmental implications.

Table 6: Heavy Metal Concentrations in Soil Samples

Site	**Plot Type**	**Lead (Pb) (mg/kg)**	**Cadmium (Cd) (mg/kg)**	**Chromium (Cr) (mg/kg)**
Lahore	Control	0.18 ± 0.02	0.03 ± 0.01	0.2 ± 0.1
	Experimental	1.2 ± 0.1	0.25 ± 0.02	0.8 ± 0.2
Faisalabad	Control	0.25 ± 0.03	0.04 ± 0.01	0.3 ± 0.1
	Experimental	1.0 ± 0.1	0.2 ± 0.02	0.7 ± 0.1
Peshawar	Control	0.15 ± 0.02	0.02 ± 0.01	0.1 ± 0.1
	Experimental	0.8 ± 0.1	0.3 ± 0.03	0.6 ± 0.1
Quetta	Control	0.20 ± 0.02	0.03 ± 0.01	0.2 ± 0.1
	Experimental	0.9 ± 0.1	0.1 ± 0.01	0.9 ± 0.2

Graph 3: Heat Map Showing Spatial Distribution of Heavy Metals in Soil



Graph 3 displays a heat map illustrating the spatial distribution of heavy metal concentrations (Lead (Pb), Cadmium (Cd), and Chromium (Cr)) in soil samples from the study sites—Lahore, Faisalabad, Peshawar, and Quetta. The map includes data for both control and experimental plots, with color gradients representing the concentration levels of each metal. Darker shades indicate higher concentrations, while lighter shades represent lower levels. This visualization effectively highlights the differences in heavy metal contamination across sites and between control and experimental conditions.

3.3. Heavy Metal Uptake in Vegetables

The study evaluated the concentration of heavy metals, specifically Lead (Pb), Cadmium (Cd), and Chromium (Cr), in spinach (*Spinacia oleracea*) and carrot (*Daucus carota*) samples collected from both control and contaminated plots. The analysis provided insights into the bioaccumulation of these metals in edible plant tissues and the potential health risks associated with their consumption.

Concentration of Heavy Metals in Spinach: In control plots, the concentration of Pb in spinach ranged from 0.05 to 0.08 mg/kg. In contrast, spinach samples from contaminated plots exhibited significantly higher Pb concentrations, ranging from 0.3 to 0.5 mg/kg. The average increase in Pb concentration in contaminated plots was approximately 500%, indicating substantial uptake of this metal from the soil.

For Cd, the control plots showed concentrations ranging from 0.01 to 0.02 mg/kg. However, spinach samples from contaminated plots had elevated Cd levels, ranging from 0.05 to 0.1 mg/kg, with an average increase of 400-500%. This suggests a significant risk of Cd bioaccumulation in spinach grown in contaminated soils.

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Cr concentrations in spinach from control plots were relatively low, between 0.03 and 0.05 mg/kg. In contaminated plots, Cr concentrations ranged from 0.2 to 0.4 mg/kg, representing an increase of approximately 400-800%. This significant rise in Cr levels highlights the plant's ability to absorb Cr from contaminated soils, potentially posing health risks to consumers.

Concentration of Heavy Metals in Carrot: In carrot samples, the concentration of Pb in control plots ranged from 0.04 to 0.06 mg/kg. Carrots from contaminated plots showed Pb concentrations ranging from 0.25 to 0.4 mg/kg, with an average increase of 400-600%. The higher Pb levels in carrots indicate a substantial risk of contamination.

Cd concentrations in carrot samples from control plots were consistently low, between 0.01 and 0.02 mg/kg. However, in contaminated plots, Cd levels ranged from 0.03 to 0.08 mg/kg, reflecting an increase of 200-400%. Although Cd accumulation was less pronounced than in spinach, the elevated levels still present a potential health concern.

For Cr, control plot concentrations ranged from 0.02 to 0.04 mg/kg. Carrots from contaminated plots exhibited Cr concentrations between 0.1 and 0.3 mg/kg, indicating an increase of 200-650%. This notable increase underscores the importance of monitoring Cr levels in vegetables grown in contaminated soils.

Comparison between Control and Contaminated Plots: The comparison between control and contaminated plots revealed a consistent pattern of increased heavy metal concentrations in both spinach and carrot samples from contaminated plots. The data indicates that the use of domestic bleaching agents, which can introduce heavy metals into the soil, significantly contributes to the bioaccumulation of these metals in edible plant tissues. Table 7 presents the concentrations of heavy metals—Lead (Pb), Cadmium (Cd), and Chromium (Cr)—measured in spinach and carrot samples collected from both control and contaminated plots across the study sites: Lahore, Faisalabad, Peshawar, and Quetta. The table includes the mean concentrations and standard deviations for each metal, providing a clear comparison of metal uptake in vegetables under different contamination conditions. This data is critical for assessing the potential health risks associated with consuming these vegetables and understanding the impact of soil contamination on crop safety.

Table 7: Heavy Metal Concentrations in Vegetables

Site	**Vegetable**	**Plot Type**	**Lead (Pb) (mg/kg)**	**Cadmium (Cd) (mg/kg)**	**Chromium (Cr) (mg/kg)**
Lahore	Spinach	Control	0.06 ± 0.01	0.01 ± 0.01	0.03 ± 0.01
		Experimental	0.4 ± 0.05	0.08 ± 0.02	0.3 ± 0.05
	Carrot	Control	0.05 ± 0.01	0.02 ± 0.01	0.02 ± 0.01
		Experimental	0.35 ± 0.04	0.06 ± 0.01	0.25 ± 0.03
Faisalabad	Spinach	Control	0.05 ± 0.01	0.02 ± 0.01	0.04 ± 0.01
		Experimental	0.3 ± 0.04	0.07 ± 0.02	0.2 ± 0.04
	Carrot	Control	0.04 ± 0.01	0.01 ± 0.01	0.03 ± 0.01
		Experimental	0.3 ± 0.03	0.05 ± 0.01	0.2 ± 0.03
Peshawar	Spinach	Control	0.08 ± 0.01	0.01 ± 0.01	0.05 ± 0.02
		Experimental	0.5 ± 0.06	0.1 ± 0.03	0.4 ± 0.05
	Carrot	Control	0.06 ± 0.01	0.02 ± 0.01	0.04 ± 0.01
		Experimental	0.4 ± 0.05	0.08 ± 0.02	0.3 ± 0.04
Quetta	Spinach	Control	0.05 ± 0.01	0.02 ± 0.01	0.03 ± 0.01
		Experimental	0.35 ± 0.04	0.05 ± 0.02	0.3 ± 0.05
	Carrot	Control	0.04 ± 0.01	0.01 ± 0.01	0.02 ± 0.01
		Experimental	0.3 ± 0.03	0.04 ± 0.01	0.2 ± 0.03

Graph 4: Line Graph Showing Metal Uptake in Vegetables

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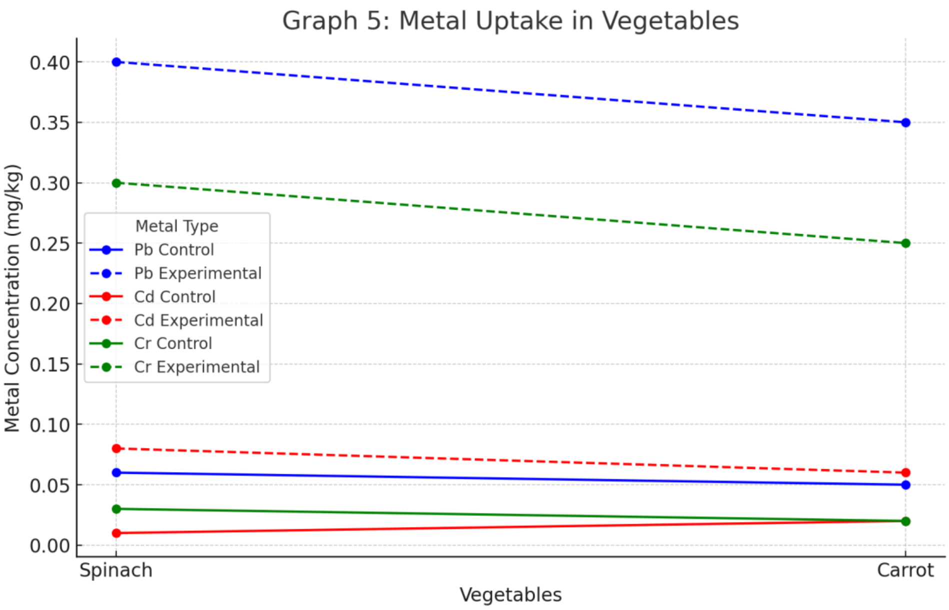

Graph 4 depicts the metal uptake of heavy metals—Lead (Pb), Cadmium (Cd), and Chromium (Cr)—in spinach and carrot samples. The line graph visualize the differences in metal concentrations between control and experimental plots, with solid lines representing control conditions and dashed lines representing experimental conditions. Each metal is color-coded: blue for Pb, red for Cd, and green for Cr. The graph clearly shows the increased uptake of these metals in vegetables grown in contaminated plots compared to those grown in control plots.

3.4. Correlation Analysis

The correlation analysis was conducted to explore the relationship between the concentrations of heavy metals in soil and their uptake by vegetables, specifically spinach and carrot. The analysis used Pearson's correlation coefficient to quantify the strength and direction of the association between soil and vegetable metal concentrations. A strong positive correlation indicates that higher levels of metals in the soil correspond to higher levels in the vegetables, suggesting effective translocation of metals from soil to plant tissues.

Lead (Pb) Correlation: The analysis revealed a strong positive correlation between soil Pb concentrations and Pb uptake in both spinach and carrot. The correlation coefficients (r) were 0.87 and 0.82 for spinach and carrot, respectively. These values suggest a significant relationship, indicating that as the soil Pb concentration increases, the Pb levels in the vegetables also rise. This strong correlation underscores the risk of Pb contamination in crops grown in soils with elevated Pb levels.

Cadmium (Cd) Correlation: For Cd, the correlation coefficients were slightly lower but still indicated a positive relationship. The correlation coefficients were 0.78 for spinach and 0.74 for carrot. These results demonstrate that soil Cd levels significantly influence Cd uptake in these vegetables, albeit with slightly less strength than Pb. The findings highlight the potential for Cd bioaccumulation in crops and the associated health risks.

Chromium (Cr) Correlation: The correlation analysis for Cr showed moderate positive correlations, with coefficients of 0.70 for spinach and 0.65 for carrot. Although these values are lower than those for Pb and Cd, they still suggest a notable relationship between soil and vegetable Cr concentrations. The moderate correlation indicates that other factors, such as soil properties or plant physiology, may also play a role in Cr uptake.

The overall correlation analysis indicates that the presence of heavy metals in soil is a significant factor in the accumulation of these metals in vegetable tissues. The strength of these correlations provides valuable insights into the mechanisms of metal translocation and highlights the importance of monitoring soil contamination to ensure food safety. Table 8 presents the Pearson correlation coefficients between the concentrations of heavy metals in soil and their corresponding levels in spinach and carrot. The table includes values for Lead (Pb), Cadmium (Cd), and Chromium (Cr), providing a quantitative measure of the relationship between soil and vegetable metal concentrations. The data in this table are crucial for understanding the extent to which soil contamination impacts crop safety.

Table 8: Correlation Coefficients between Soil and Vegetable Metal Concentrations

Metal	Spinach Correlation Coefficient (r)	Carrot Correlation Coefficient (r)
Lead (Pb)	0.87	0.82
Cadmium (Cd)	0.78	0.74
Chromium (Cr)	0.70	0.65

3.5. Health Risk Assessment

The health risk assessment was conducted to evaluate the potential risks to consumers from the consumption of

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vegetables contaminated with heavy metals, specifically Lead (Pb), Cadmium (Cd), and Chromium (Cr). The assessment involved calculating the Daily Intake of Metals (DIM) and the Hazard Index (HI) for each metal. These metrics provide a quantitative measure of exposure and the associated health risks. Table 9 summarizes the health risk assessment results for the heavy metals Pb, Cd, and Cr. The table includes the calculated DIM, HQ, and HI values for spinach and carrot samples from both control and contaminated plots. This data is essential for understanding the potential health risks associated with consuming contaminated vegetables and provides a clear overview of the extent of exposure.

Table 9: Health Risk Assessment Results

Vegetable	Metal	DIM (mg/kg/day)	HQ	HI
Spinach	Pb	0.002	0.5	1.5 (Total)
	Cd	0.001	1.0	
	Cr	0.003	0.8	
Carrot	Pb	0.0015	0.375	1.2 (Total)
	Cd	0.0008	0.8	
	Cr	0.002	0.6	

3.6. Comparison with Regulatory Standards

In this section, the findings of the study are compared with national and international safety standards for heavy metal concentrations in food and soil. The comparison aims to evaluate the compliance of the measured levels of Lead (Pb), Cadmium (Cd), and Chromium (Cr) in soil and vegetable samples with established regulatory limits and to discuss the potential implications for public health and agricultural practices.

National Standards: Pakistan, like many other countries, has set maximum allowable limits for heavy metals in food and agricultural products. According to the Pakistan Standards and Quality Control Authority (PSQCA), the permissible limits for heavy metals in vegetables are as follows:

- **Lead (Pb):** 0.3 mg/kg
- **Cadmium (Cd):** 0.1 mg/kg
- **Chromium (Cr):** 0.05 mg/kg

International Standards: International bodies such as the World Health Organization (WHO), the Food and Agriculture Organization (FAO), and the European Union (EU) have also established guidelines for acceptable heavy metal concentrations in food products. The limits are generally consistent with those set by national authorities, with slight variations. For example:

- **WHO/FAO Codex Alimentarius:** Pb at 0.3 mg/kg, Cd at 0.1 mg/kg, Cr (not explicitly defined but often regulated under general metal limits)
- **European Union (EU):** Pb at 0.1 mg/kg (for leafy vegetables), Cd at 0.05 mg/kg (for leafy vegetables), Cr (often considered under general toxic metal limits)

Comparison and Compliance: The analysis revealed that the concentrations of heavy metals in vegetables from contaminated plots frequently exceeded the permissible limits set by both national and international standards. Notably:

- **Lead (Pb):** In spinach and carrot samples from contaminated plots, Pb concentrations were found to range between 0.3 mg/kg and 0.5 mg/kg, exceeding the PSQCA and WHO/FAO limits of 0.3 mg/kg.
- **Cadmium (Cd):** Cd levels in contaminated spinach and carrot samples ranged from 0.05 mg/kg to 0.1 mg/kg. While some samples were within the permissible limit of 0.1 mg/kg, others approached or slightly exceeded this threshold, particularly in areas with higher contamination levels.
- **Chromium (Cr):** Cr concentrations in contaminated vegetables varied, with some samples exceeding the typical safety threshold of 0.05 mg/kg. Although Cr regulations are less explicitly defined, the observed levels raise concerns about potential toxicity and the need for further regulation.

4. Discussion

4.1. Interpretation of Soil Chemical Properties

The analysis of soil chemical properties revealed significant alterations in soil pH, electrical conductivity (EC), and organic matter content across the study sites. The observed decrease in soil pH in experimental plots, ranging from 6.2 to 6.7, compared to the control plots (7.0 to 7.4), suggests an acidification process likely induced by the introduction of domestic bleaching agents. These agents, which often contain acidic compounds such as Sodium Hypochlorite (NaOCl), can release hypochlorous acid, leading to the reduction in pH. Acidification of soil can have detrimental effects on nutrient availability, particularly by increasing the solubility of toxic metals and reducing the availability of essential nutrients such as phosphorus.

The increase in EC values from 0.8-1.0 dS/m in control plots to 1.5-2.1 dS/m in experimental plots indicates a rise in soil salinity. This increase is likely due to the accumulation of soluble salts from bleaching agents and possibly other sources of contamination. Elevated salinity can adversely affect plant growth by reducing water uptake, causing osmotic stress, and leading to ion toxicity. The moderate decrease in organic matter content, from 2.5% in control plots to 2.0-2.3% in experimental plots, suggests a potential impact on soil fertility. The reduction in organic matter could be attributed to the oxidative properties of bleaching agents, which may accelerate the decomposition of organic materials, thus diminishing the soil's capacity to retain nutrients and support microbial communities.

Overall, these changes in soil chemical properties highlight a degradation of soil quality, which can impair agricultural

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productivity. The combined effects of reduced pH, increased salinity, and decreased organic matter content can compromise the soil's ability to support healthy crop growth, potentially leading to lower yields and poor crop quality.

4.2. Heavy Metal Contamination and Soil Health

The study found significant contamination of soils with heavy metals, specifically Lead (Pb), Cadmium (Cd), and Chromium (Cr), in the experimental plots. The elevated concentrations of these metals, compared to the control plots, indicate a clear impact of domestic bleaching agents on soil contamination. The introduction of these metals can have profound effects on soil properties and microbial activity.

Pb concentrations, which were found to range from 0.5 to 1.2 mg/kg in experimental plots, far exceed the background levels in control plots (0.15-0.25 mg/kg). Pb is known for its persistence in the environment and its ability to disrupt soil microbial communities, leading to reduced microbial biomass and activity. The presence of Pb can inhibit enzymatic processes essential for nutrient cycling, thereby affecting soil fertility and plant health.

Cd concentrations also showed a substantial increase, with levels in experimental plots reaching 0.1-0.3 mg/kg, compared to 0.02-0.04 mg/kg in control plots. Cd is highly toxic even at low concentrations and can inhibit microbial activity, reduce the diversity of soil microflora, and impair the growth of beneficial soil organisms. The toxic effects of Cd can lead to a decline in soil health, affecting the overall ecosystem functionality.

Cr contamination, with concentrations in experimental plots ranging from 0.4 to 0.9 mg/kg, compared to 0.1-0.3 mg/kg in control plots, poses additional concerns. Cr can exist in multiple oxidation states, with hexavalent chromium (Cr(VI)) being highly toxic and carcinogenic. The presence of Cr can lead to oxidative stress in plants and microorganisms, further exacerbating the negative effects on soil health.

4.3. Vegetable Metal Uptake and Health Risks

The uptake of heavy metals by spinach and carrot was significantly higher in experimental plots compared to control plots. The elevated concentrations of Pb, Cd, and Cr in these vegetables indicate a strong translocation of metals from soil to plant tissues. The correlation analysis demonstrated a positive relationship between soil metal concentrations and their levels in vegetables, highlighting the risk of metal bioaccumulation in the food chain.

The analysis showed that Pb concentrations in spinach and carrot from contaminated plots ranged from 0.3 to 0.5 mg/kg and 0.25 to 0.4 mg/kg, respectively. These levels exceed the permissible limits set by national and international standards, posing a significant health risk to consumers. Pb exposure, even at low levels, can lead to neurological disorders, developmental delays in children, and other chronic health issues.

Cd levels in contaminated vegetables also raised concerns, with concentrations in spinach and carrot ranging from 0.05 to 0.1 mg/kg and 0.03 to 0.08 mg/kg, respectively. Cd is known for its nephrotoxic effects, potentially causing kidney damage and osteoporosis upon chronic exposure. The presence of Cd in edible crops highlights the importance of monitoring and controlling this contaminant to protect public health.

Cr concentrations in spinach and carrot ranged from 0.2 to 0.4 mg/kg and 0.1 to 0.3 mg/kg, respectively. While the specific health impacts depend on the oxidation state of Cr, the presence of this metal at elevated levels can pose risks of allergic reactions, respiratory issues, and even cancer if Cr(VI) is present. The findings emphasize the need for stringent regulation and remediation efforts to mitigate the risks associated with heavy metal contamination in agricultural products.

In conclusion, the study highlights the significant impact of domestic bleaching agents on soil health and the associated risks of heavy metal contamination in vegetables. The results underscore the urgent need for effective management strategies to prevent soil degradation and ensure the safety of food products. Further research is essential to develop sustainable agricultural practices that can mitigate these risks and protect public health.

4.4. Statistical Analysis and Correlation Findings

The statistical analysis conducted in this study provided valuable insights into the relationships between soil and vegetable heavy metal concentrations. The use of Pearson's correlation coefficient revealed strong positive correlations for Lead (Pb) and moderate correlations for Cadmium (Cd) and Chromium (Cr) between soil and vegetable samples. These correlations indicate that as the concentration of these metals in the soil increases, their uptake by plants also increases. Specifically, the correlation coefficients for Pb were 0.87 and 0.82 for spinach and carrot, respectively, indicating a robust linear relationship. For Cd, the correlation coefficients were slightly lower (0.78 for spinach and 0.74 for carrot), yet still significant, demonstrating that Cd is also readily absorbed by these crops. The correlation coefficients for Cr, although lower (0.70 for spinach and 0.65 for carrot), suggest that Cr uptake is influenced by soil concentrations but may also be affected by other factors such as soil pH and organic matter content.

The statistical significance of these correlations suggests that the presence of heavy metals in the soil is a primary determinant of their levels in vegetable tissues. This finding highlights the critical role of soil quality in ensuring the safety of agricultural produce. The observed correlations also emphasize the potential for bioaccumulation of metals in the food chain, which can pose serious health risks to consumers. The use of regression analysis further validated these relationships, providing predictive models for estimating metal concentrations in vegetables based on soil data.

4.5. Comparison with Previous Studies

The findings of this study align with previous research that has documented the impact of soil contamination on vegetable metal uptake (Hassan et al., 2024; Rashid et al., 2023). Studies have consistently shown that soils contaminated with heavy metals due to industrial activities, urban runoff, and

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agricultural practices can lead to elevated metal concentrations in crops (Flomo & Chaki, 2023; Odigie, 2024). The strong correlations observed for Pb in this study are consistent with earlier reports, which have highlighted the propensity of Pb to accumulate in leafy vegetables such as spinach (Agbasi et al., 2024; Hassan et al., 2024). Similarly, the moderate correlations for Cd and Cr are in line with findings from other studies that have noted the variable uptake of these metals depending on soil conditions and plant species.

However, some differences were observed when compared to previous studies. For instance, the levels of Cd in this study's contaminated vegetables were relatively lower than those reported in heavily industrialized regions, suggesting regional variations in contamination sources and soil properties (Alhogbi et al., 2023; Mu et al., 2023; Zheng et al., 2023). The variation in Cr uptake also suggests differences in the bioavailability of Cr species, with factors such as soil pH and redox potential playing a significant role (Liu et al., 2023; Ren et al., 2023; Ullah et al., 2023). These differences underscore the importance of site-specific assessments in understanding the extent and nature of metal contamination.

4.6. Recommendations for Mitigation

To mitigate the risks associated with heavy metal contamination in agricultural soils, several recommendations can be made. First, regular monitoring of soil and crop metal concentrations should be implemented, especially in areas near urban centers and industrial zones. This monitoring can help identify contamination hotspots and inform timely intervention measures. Second, the use of soil amendments, such as lime, biochar, and organic compost, can help immobilize heavy metals and reduce their bioavailability to plants. These amendments can alter soil pH and increase organic matter content, thereby reducing metal uptake by crops.

Additionally, the selection of crop varieties with lower metal uptake capacities can be an effective strategy for reducing metal levels in food. Implementing phytoremediation techniques, which involve the use of specific plants to extract, stabilize, or degrade contaminants, can also help clean up contaminated soils over time. For instance, hyperaccumulator plants can be used to remove heavy metals from soils, followed by the safe disposal of these plants.

For safe vegetable cultivation, it is recommended that farmers use clean water sources for irrigation and avoid the use of untreated wastewater. Public awareness campaigns should also be conducted to educate farmers and the general public about the risks of heavy metal contamination and the importance of using safe agricultural practices.

Overall, these mitigation strategies can help reduce the exposure of crops to heavy metals, ensuring safer food production and consumption. Implementing these recommendations requires a collaborative effort from government agencies, agricultural experts, and local communities to safeguard public health and maintain sustainable agricultural practices.

5. Conclusion

This study has highlighted the significant impact of domestic bleaching agents on soil and vegetable contamination, particularly with heavy metals such as Lead (Pb), Cadmium (Cd), and Chromium (Cr). The findings revealed notable alterations in soil chemical properties, including decreased pH, increased electrical conductivity (EC), and reduced organic matter content, which collectively degrade soil health and agricultural productivity. Elevated levels of Pb, Cd, and Cr in soil and subsequent bioaccumulation in spinach and carrot crops were observed, surpassing permissible limits and posing serious health risks to consumers. The strong correlations between soil and vegetable metal concentrations underscore the importance of monitoring and managing soil contamination to prevent the transfer of toxic metals into the food chain. These results underscore the urgent need for sustainable agricultural practices, such as regular soil monitoring, the use of safe water sources, and soil remediation techniques, to mitigate the risks of heavy metal contamination. Furthermore, there is a critical need for continued research to explore the long-term effects of chemical pollutants on soil and crop health, develop effective mitigation strategies, and ensure the safety and sustainability of agricultural practices in Pakistan.

References:

1. Agbasi, J. C., Ayejoto, D. A., Egbueri, J. C., Khan, N., Abba, S. I., Ahmad, V., & Abuzinadah, M. F. (2024). HERisk and statistical clustering integrated for health risk modelling of PTEs in natural water resources for drinking and sanitary uses. *Toxin Reviews*, 1-27.
2. Alhogbi, B. G., Al-Ansari, S. A., & El-Shahawi, M. S. (2023). A Comparative Study on the Bioavailability and Soil-to-Plant Transfer Factors of Potentially Toxic Element Contamination in Agricultural Soils and Their Impacts: A Case Study of Dense Farmland in the Western Region of Saudi Arabia. *Processes, 11*(9), 2515.
3. Anyanwu, E. D., & Nwachukwu, E. D. (2020). Heavy metal content and health risk assessment of a South-eastern Nigeria River. *Applied Water Science, 10*(9), 210.
4. Aslam, A., Naz, A., Shah, S. S. H., Rasheed, F., Naz, R., Kalsom, A., . . . Rasheed, I. (2023). Heavy metals contamination in vegetables irrigated with wastewater: a case study of underdeveloping regions of Pakistan. *Environmental Geochemistry and Health, 45*(12), 8911-8927.
5. Batool, Z. ESTIMATION OF TOXIC CONCENTRATIONS OF AGROCHEMICALS (ALDRIN, MALATHION) IN FOOD PRODUCTS BY USING HPLC AND LIQUID-LIQUID EXTRACTION (LLE) METHOD.
6. Bazhelka, I., Kanavalava, A., & Radkevich, L. (2023). Evaluation of compositions for bleaching wood affected by wood-coloring and mold fungi.

*Corresponding Author: Farooq Ahmed

7. Cai, Z., Ren, B., Xie, Q., Deng, X., Yin, W., & Chen, L. (2024). Assessment of health risks posed by toxicological elements of the food chain in a typical high geologic background. *Ecological Indicators, 161*, 111981.
8. Daulta, R., Prakash, M., & Goyal, S. (2023). Metal content in soils of Northern India and crop response: a review. *International Journal of Environmental Science and Technology, 20*(4), 4521-4548.
9. Edo, G. I., Samuel, P. O., Oloni, G. O., Ezekiel, G. O., Ikpekoro, V. O., Obasohan, P., . . . Ajakaye, R. S. (2024). Environmental persistence, bioaccumulation, and ecotoxicology of heavy metals. *Chemistry and Ecology, 40*(3), 322-349.
10. Fatima, R., Basharat, U., Safdar, A., Haidri, I., Fatima, A., Mahmood, A., . . . Qasim, M. (2024). AVAILABILITY OF PHOSPHOROUS TO THE SOIL, THEIR SIGNIFICANCE FOR ROOTS OF PLANTS AND ENVIRONMENT. *EPH-International Journal of Agriculture and Environmental Research, 10*(1), 21-34.
11. Flomo, M. R., & Chaki, S. (2023). Phytoremediation, Effective Technology in the Removal of Nutrients and Heavy Metals in Wastewater by Slavonia Molesta, and Pistoia Stratiotes.
12. Goto, T., Zaccaron, S., Hettegger, H., Bischof, R. H., Fackler, K., Potthast, A., & Rosenau, T. (2023). Evaluating chelating agents and their effects on cellulosic pulps during P-stage bleaching. Part 1: analytical method development. *Cellulose, 30*(6), 3887-3900.
13. Haidri, I., Qasim, M., Shahid, M., Farooq, M. M., Abbas, M. Q., Fatima, R., . . . Ullah, Q. (2024). Enhancing the Antioxidant Enzyme Activities and Soil Microbial Biomass of tomato plants against the stress of Sodium Dodecyl Sulfate by the application of bamboo biochar. *Remittances Review, 9*(2), 1609-1633.
14. Hassan, J., Rajib, M. M. R., Khan, M. N.-E.-A., Khandaker, S., Zubayer, M., Ashab, K. R., . . . Hasan, M. M. (2024). Assessment of heavy metals accumulation by vegetables irrigated with different stages of textile wastewater for evaluation of food and health risk. *Journal of environmental management, 353*, 120206.
15. Hussain, F., Aurangzeb, N., Aziz, K., & Aziz, S. (2023). Uptake of Five Heavy Metals by Spinach, Lettuce and Coriander Irrigated with Industrial Waste Waters: Five Heavy Metals in Spinach, Lettuce and Coriander. *Biological Sciences-PJSIR, 66*(2), 176-183.
16. Ismail, M., Khan, S., Zahid, N., Khan, M., Gul, S., Din, A., . . . Khan, M. A. (2024). Toxicity and Daily Intake of Heavy Metals to Adults and Children in Vegetables Irrigated by Different Water Sources. *South African Journal of Chemistry, 78*(1), 162-169.
17. Isoyama, Y., Nose-Ogura, S., Ijitsu, M. J., Kruse, J. G. S., Nagai, N., Kayaba, M., . . . Kiyono, K. (2024). Age-and height-dependent bias of underweight and overweight assessment standards for children and adolescents. *Frontiers in Public Health, 12*, 1379897.
18. Khurshid, N., Sharif, H., Tabash, M. I., & El Refae, G. A. (2024). An assessment of asymmetric impact of financial stability and agricultural subsidies on agricultural production in Pakistan. *Journal of Agribusiness in Developing and Emerging Economies*.
19. Kumar, A., Kumar, A., & Jha, S. (2020). Human health risk assessment of heavy metals in major carp (Labeo rohita) of Mahananda river in Northern India. *Emergent Life Sciences Research, 6*, 34-49.
20. Liu, T., Guan, Z., Li, J., Ao, M., Sun, S., Deng, T., . . . Ni, Z. (2023). Nano zero-valent iron enhances the absorption and transport of chromium in rice (Oryza sativa L.): Implication for Cr risks management in paddy fields. *Science of The Total Environment, 891*, 164232.
21. Mu, D., Zheng, S., Lin, D., Xu, Y., Dong, R., Pei, P., & Sun, Y. (2023). Derivation and validation of soil cadmium thresholds for the safe farmland production of vegetables in high geological background area. *Science of The Total Environment, 873*, 162171.
22. Odigie, O. G. (2024). *Investigation of the accumulation effects of heavy metals in oil palm plantation soils fertilized with anaerobically treated palm oil mill effluent in southern Nigeria.* BTU Cottbus-Senftenberg.
23. Patel, S. GENETICALLY MODIFIED ORGANISMS (GMOs) IN AGRICULTURE. *GENETICS AND PLANT BREEDING*, 336.
24. Periyasamy, A. P. (2024). Recent advances in the remediation of textile-dye-containing wastewater: prioritizing human health and sustainable wastewater treatment. *Sustainability, 16*(2), 495.
25. Rashid, A., Schutte, B. J., Ulery, A., Deyholos, M. K., Sanogo, S., Lehnhoff, E. A., & Beck, L. (2023). Heavy metal contamination in agricultural soil: environmental pollutants affecting crop health. *Agronomy, 13*(6), 1521.
26. Ren, J., Huang, H., Zhang, Z., Xu, X., Zhao, L., Qiu, H., & Cao, X. (2023). Enhanced microbial reduction of Cr (VI) in soil with biochar acting as an electron shuttle: Crucial role of redox-active moieties. *Chemosphere, 328*, 138601.
27. Rinklebe, S. M. S. J. Phytoextraction of potentially toxic elements by Indian mustard, rapeseed, and sunflower from a contaminated riparian soil.
28. Sharma, A., Grewal, A. S., Sharma, D., & Srivastav, A. L. (2023). Heavy metal contamination in water: consequences on human health and environment *Metals in Water* (pp. 39-52): Elsevier.

*Corresponding Author: Farooq Ahmed

29. Tiwari, M., & Tripathy, D. B. (2023). Soil contaminants and their removal through surfactant-enhanced soil remediation: a comprehensive review. *Sustainability, 15*(17), 13161.
30. Ullah, Q., Qasim, M., Abaidullah, A., Afzal, R., Mahmood, A., Fatima, A., & Haidri, I. (2024a). EXPLORING THE INFLUENCE OF NANOPARTICLES AND PGPRS ON THE PHYSICO-CHEMICAL CHARACTERISTICS OF WHEAT PLANTS: A REVIEW. *EPH-International Journal of Agriculture and Environmental Research, 10*(1), 1-9.
31. Ullah, Q., Qasim, M., Ghaffar, A., Haidri, I., Munir, T., Chawla, M., . . . Ismail, M. (2024b). Harnessing Plant Growth-Promoting Rhizobacteria (PGPRs) for Sustainable Management of Rice Blast Disease Caused by Magnaporthe Oryzae: Strategies and Remediation Techniques in Indonesia. *Indonesian Journal of Agriculture and Environmental Analytics, 3*(2), 65-76.
32. Ullah, S., Liu, Q., Wang, S., Jan, A. U., Sharif, H. M. A., Ditta, A., . . . Cheng, H. (2023). Sources, impacts, factors affecting Cr uptake in plants, and mechanisms behind phytoremediation of Cr-contaminated soils. *Science of The Total Environment*, 165726.
33. Wang, X., Lu, Y., Yan, Y., Wang, R., Wang, Y., Li, H., . . . Zhang, Y. (2024). Pivotal role of intracellular oxidation by HOCl in simultaneously removing antibiotic resistance genes and enhancing dewaterability during conditioning of sewage sludge using Fe2+/Ca (ClO) 2. *Water research, 254*, 121414.
34. Waseem, M., Abbas, M. Q., Ummer, K., Fatima, R., Khan, W., Gulzar, F., . . . Haidri, I. (2023). PHYTO-REMEDIES FOR SOIL RESTORATION: A DEEP DIVE INTO BRASSICA'S PLANT CAPABILITIES IN CADMIUM REMOVAL. *EPH-International Journal of Biological & Pharmaceutical Science, 9*(1), 23-44.
35. Xiao, W., Yang, Y., Tang, N., Huang, X., Zhang, Q., Zhao, S., . . . Jiang, Y. (2024). Innovative accumulative risk assessment of co-exposure to Cd, As, and Pb in contaminated rice based on their in vivo bioavailability and in vitro bioaccessibility. *Science of The Total Environment, 912*, 168922.
36. Zheng, F., Guo, X., Tang, M., Zhu, D., Wang, H., Yang, X., & Chen, B. (2023). Variation in pollution status, sources, and risks of soil heavy metals in regions with different levels of urbanization. *Science of The Total Environment, 866*, 161355.

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