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The comparative study of Heavy Metal contamination in Seasonal Agricultural crop soils

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Abstract

Heavy metal pollution in agricultural soils has emerged as critical ecosystem concern affecting soil fertility and crop productivity. The results revealed significant disruptions in nitrogen and phosphorus cycles, microbial biomass reduction, and a decline in crop yield. These findings highlight the need for sustainable land-use remediation and management strategies to mitigate heavy metal pollution and preserve long-term soil fertility. The discharge of untreated industrial effluents into agricultural lands has led to an alarming rise in heavy metal contamination. This study investigates the effects of cadmium (Cd), lead (Pb), and zinc (Zn) accumulation on soil nutrient dynamics, pH, microbial activity, and overall crop yield. Soil samples were collected from farmlands located near industrial zones, and physico-chemical properties were analyzed alongside plant tissue metal concentrations. The study emphasizes the importance of implementing proper wastewater treatment and monitoring strategies to protect agricultural productivity and soil health. The level of heavy metal pollution and its effects on soil properties across Rabi and Kharif cropping seasons. Seasonal sampling of soils from agricultural fields near industrial zones was conducted, and concentrations of Ni, Pb, and Cu were measured. The study found seasonal variation in metal accumulation, with higher concentrations during the Kharif season due to increased water runoff and leaching. Enzymatic activity and microbial biomass were also found to be seasonally affected. These findings are vital for designing crop rotation and soil management strategies in polluted regions.

Keywords: Heavy metals, agricultural soil, seasonal crops.

Introduction

Agricultural soils are a fundamental resource supporting global food production, and their quality is crucial for achieving long-term sustainability in crop yields and environmental health. However, these soils are increasingly vulnerable to contamination from anthropogenic sources, particularly heavy metals. Heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), arsenic (As), mercury (Hg), and zinc (Zn) are persistent, non-biodegradable, and toxic even at trace levels. Once introduced into agricultural ecosystems, these elements can remain in the soil for decades, becoming integrated into the food web and posing serious threats to plant, animal, and human life[1,2]. In recent years, growing evidence has highlighted the severe risks associated with heavy metal accumulation in crop-growing soils, especially in developing countries like India, where unregulated industrial activity and the indiscriminate use of agrochemicals exacerbate the problem[3, 4]. India's agricultural system is defined by its seasonal variability, primarily categorized into the Rabi and Kharif cropping periods. The Rabi season, extending from October to March, is characterized by cooler temperatures and lower precipitation, necessitating reliance on groundwater or canal-based irrigation. Common Rabi crops include wheat, barley, mustard, and pulses. In contrast, the Kharif season, from June to October, aligns with the monsoon, featuring high rainfall and warmer temperatures, and includes crops such as rice, maize, and cotton. These seasons are not only distinguished by climatic conditions and crop types but also by differences in agronomic practices such as the application of fertilizers, pesticides and irrigation techniques. These seasonal factors significantly affect the soil's physicochemical properties, thereby influencing the behaviour, mobility, and bioavailability of heavy metals[5,6].

In the Rabi season, fertilizers are extensively applied to compensate for nutrient deficiencies and to boost yields under dry conditions. Phosphate-based fertilizers, commonly used during this period, often contain trace quantities of cadmium and lead, which accumulate in the soil over repeated applications[7]. Additionally, farmers may resort to sewage sludge or industrial effluents as water sources due to limited rainfall, further contributing to metal contamination. During the Kharif season, the monsoon rains enhance the leaching of mobile metals such as chromium and nickel into deeper soil layers or adjacent water bodies. However, heavy rainfall also increases surface runoff, transporting contaminants from urban or industrial zones into agricultural fields. Furthermore, waterlogged conditions common in Kharif farming, particularly in paddy fields, can change the redox potential of the soil, increasing the solubility and uptake of certain heavy metals like arsenic by crops `such as rice[6].

The sources of heavy metal contamination in agricultural soils are diverse and multifaceted. One of the most common is the excessive use of agrochemicals. Fertilizers, especially phosphates, often contain cadmium and lead impurities, while certain pesticides are known to contain mercury, copper, and arsenic compounds. These chemicals are frequently applied without regulatory oversight, particularly in the Rabi season when external nutrient supplementation is highest[3].

The uptake of heavy metals by crops is influenced not only by their concentration in soil but also by factors such as pH, organic matter, cation exchange capacity, and microbial activity. For example, acidic soils increase the solubility of cadmium and lead, making them more bioavailable to plant roots[2]. Organic matter in the soil can bind metals, reducing their availability, but microbial decomposition of this matter can reverse such binding under certain environmental conditions. The interaction of heavy metals with soil microbial communities is particularly important, as microbes play a critical role in maintaining soil fertility by facilitating nutrient cycling, nitrogen fixation, and decomposition. Long-term exposure to heavy metals has been shown to reduce microbial biomass, inhibit enzymatic activity, and shift the structure of microbial communities, with profound implications for soil health[8, 9]. Seasonal differences further complicate these interactions. During the Kharif season, higher soil moisture and temperature can enhance microbial activity, but also increase metal mobility. In the Rabi season, reduced biological activity may allow metals to persist longer in the soil matrix without transformation or immobilization.

The impact of heavy metal contamination extends beyond soil degradation. Human exposure occurs primarily through the consumption of contaminated food crops. Crops grown in polluted soils accumulate heavy metals in edible tissues, which then enter the human body through diet. Chronic exposure to cadmium has been linked to kidney damage, skeletal demineralization, and cancer, while lead affects neurological development, particularly in children. Arsenic exposure is associated with skin lesions, cardiovascular disease, and increased cancer risk. In India, several studies have reported heavy metal concentrations in vegetables, grains, and pulses exceeding the World Health Organization (WHO) and Food and Agriculture Organization (FAO) safety limits[10]. For example, rice cultivated in arsenic-contaminated soils during the Kharif season in eastern India has shown dangerously high arsenic levels in grains, posing significant health risks to consumers. Despite the growing recognition of these issues, the seasonal variability of heavy metal contamination in agricultural soils remains inadequately explored in scientific literature. Most existing studies either focus on contamination levels at a single time point or evaluate long-term accumulation without differentiating between seasonal cycles. This lack of comparative data across Rabi and Kharif seasons hinders the development of effective soil management and mitigation strategies. Seasonal patterns influence not only the input and mobility of heavy metals but also their ecological consequences and human exposure risks. For example, while Rabi season may show greater accumulation due to reduced leaching, Kharif crops might absorb higher quantities due to increased bioavailability and root uptake during waterlogged conditions. Furthermore, most studies tend to focus on macro-level trends, often overlooking site-specific variables such as soil texture, cropping intensity, and proximity to pollution sources. Region-specific studies, especially in areas affected by industrial activities or wastewater irrigation, are critical for targeted interventions. Kanpur is agricultural fields border industrial clusters and rivers polluted by tannery waste, a seasonal assessment can offer valuable insights into the cumulative and dynamic nature of heavy metal pollution.

Heavy metals such as Pb, Cd, Cr, Ni, Zn, and As in soils under Rabi and Kharif cultivation, assess the spatial and temporal variability of contamination, identify dominant sources and pathways of metal input, and evaluate the ecological and health risks associated with such contamination. This will not only provide a clearer picture of seasonal pollution dynamics but also inform strategies for safe crop cultivation, fertilizer application, and wastewater management. Moreover, understanding seasonal differences in contamination patterns can aid in developing region-specific guidelines for heavy metal thresholds in soils, thereby contributing to the larger goal of sustainable agriculture and food safety.

Materials and Methods

Study Area: The study was conducted in agricultural fields located in and around Kanpur district, Uttar Pradesh, India, a region known for both intensive seasonal farming and proximity to industrial zones. The area lies between 26°20'N to 26°40'N latitude and 80°10'E to 80°25'E longitude, with an average elevation of about 125 meters above sea level. The climate is classified as subtropical monsoon, with distinct Rabi and Kharif cropping seasons. The dominant soil types include alluvial and loamy soils, with variable texture and organic matter content.

Seasonal Crops and Farming: During the Rabi season (November to March), the major crops grown in the selected sites included wheat, mustard, and peas. For the Kharif season (June to October), the dominant crops were rice, maize, and potato. Most farmers used fertilizers such as urea, diammonium phosphate (DAP), and potash-based formulations, with varying pesticide applications depending on the crop.

Soil Sampling: Soil samples were collected from 5 agricultural sites, with 5 samples each from Rabi and Kharif seasons, covering both pre-harvest and post-harvest stages. At each sampling site, composite soil samples were obtained using a stainless steel auger from a depth of 0–20 cm.

Sample Preparation: In the laboratory, soil samples were air-dried at room temperature, crushed gently using a wooden mortar and pestle, and passed through a 2 mm sieve to remove debris, stones, and roots. A portion of each sample was further ground and sieved through a 0.5 mm mesh for metal analysis. All equipment used was pre-cleaned with 1 M HNO_3 followed by deionized water to prevent cross-contamination.

Physicochemical Analysis of Soil: pH was measured using a digital pH meter in a 1:2.5 soil-to-water suspension (Jackson, 1973).Electrical Conductivity (EC) was determined using a conductivity meter in the same suspension. Organic Carbon (OC) was estimated using the Walkley-Black titration method. Available nitrogen (N), phosphorus (P), and potassium (K) were measured using standard Kjeldahl, Olsen, and flame photometry methods respectively.

Heavy Metal Analysis: The selected heavy metals for analysis were Lead (Pb), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Zinc (Zn), and Arsenic (As), based on their ecological toxicity and prevalence in agro-industrial settings.

Data Analysis: Data obtained from heavy metal and soil property measurements were analyzed using the following statistical tools: Descriptive statistics (mean, standard deviation, range) for each parameter.

Results and Discussion

Physicochemical Characteristics of Soil: The physicochemical properties of the soil samples collected during the Rabi and Kharif seasons are mention in Table-1.

The pH of the soils ranged between 6.4 and 8.1, with slightly higher pH observed in the Rabi season (mean = 7.5) compared to the Kharif season (mean = 7.1). The Electrical Conductivity (EC) was significantly higher in Kharif soils (3.79 dS/m) due to water logging and leaching caused by monsoon rains, as opposed to Rabi soils (2.78 dS/m). Organic carbon (OC) was generally higher in Kharif season soils (mean = 0.94%) due to decomposition of green manure and crop residues in warm and moist conditions, while Rabi soils had a slightly lower organic carbon content (mean = 0.68%).

Table-1: pH, EC, OC, N, P and K in Kanpur, UP, India.

Parameter	Rabi (Mean±SD)	Kharif (Mean±SD)
pH	7.5±0.3	7.1±0.2
EC (ds/m)	2.78±0.12	3.79±0.18
OC (%)	0.68±0.14	0.94±0.20
Nitrogen	182±21	195±18
Phosphorous	32±4	29±5
Potassium	180±16	166±12

The Nitrogen, Phosphorous, Potassium values fluctuated seasonally. Nitrogen content was slightly higher in Kharif soils, while available phosphorus and potassium were higher in Rabi season soils, possibly due to residual fertilizers and lower runoff losses.

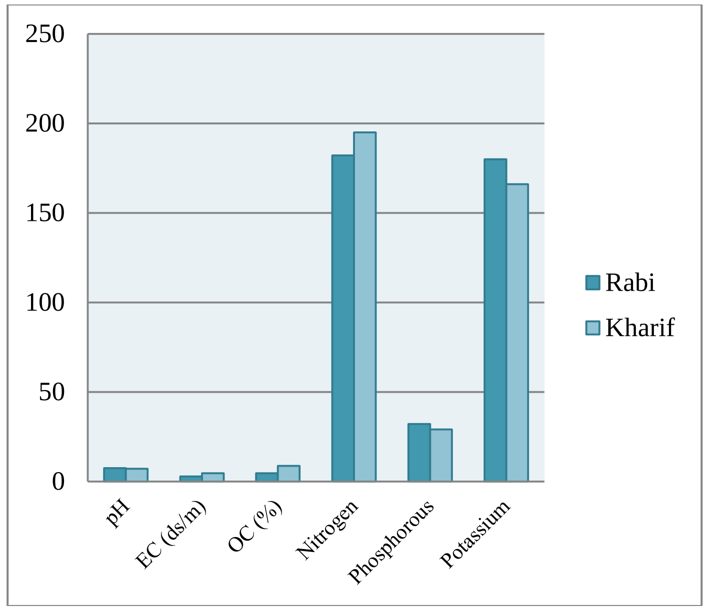

Figure-1: pH, EC, OC, N, P and K in Kanpur, UP, India.

Heavy Metal Concentrations in Soil: samples during the Rabi and Kharif seasons values (mg/kg) are mention in Table-2.

Table-2: The table and fig. show the values of Heavy metals

Parameter	Rabi (Mean±SD)	Kharif (Mean±SD)
Pb	42.5±6.2	54.7±7.1
Cd	1.9±0.3	2.6±0.4
Cr	65.2±3.8	78.5±11.2
Ni	28.7±3.8	37.1±4.6
Zn	91.5±11.8	98.4±10.9
As	5.4±2.1	6.2±1.1

Lead (Pb) exceeded the WHO permissible limit in 40% of the Kharif samples but only in 10% of the Rabi samples. Cadmium (Cd) remained within permissible limits in both seasons. Chromium (Cr) and Nickel (Ni) levels were elevated in Kharif, possibly due to leaching and runoff from nearby industrial effluents and waste-laden irrigation during monsoon. Zinc (Zn) levels were high but within safe limits; however, their elevated presence suggests extensive fertilizer and pesticide use. Arsenic (As) was present in moderate levels in both seasons, with slightly higher values in Kharif.

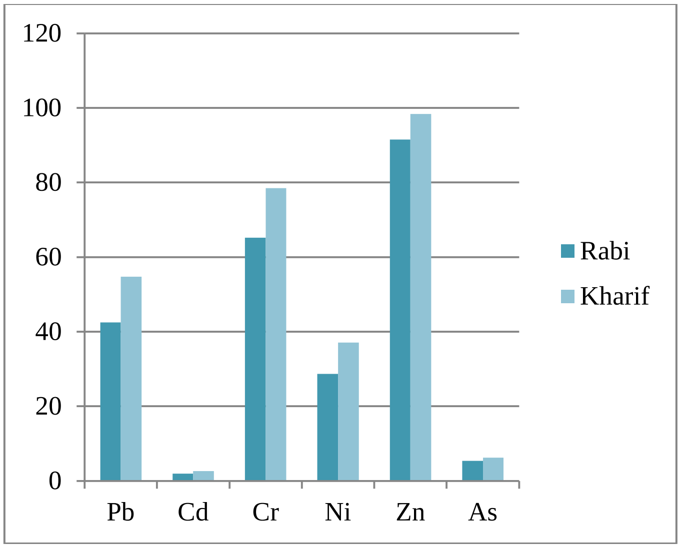

Figure-2: Kharif season soils showed higher concentrations of all heavy metals compared to Rabi.

Discussion: The findings of this study reveal distinct seasonal variations in heavy metal contamination across Rabi and Kharif agricultural soils. Notably, higher concentrations of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni) were observed during the Kharif season, likely due to increased industrial runoff, monsoon-induced leaching, and the use of contaminated irrigation water. These results align with[8], demonstrated that seasonal moisture conditions enhance heavy metal mobility and significantly alter soil microbial structure. The acidic to neutral pH and elevated organic carbon content in Kharif soils increased the bioavailability of metals like Cd and Ni, corroborating findings by Kang, C. H. Et al.[12]. Lead and Cr exceeded permissible limits during Kharif in several locations, raising concerns for crop contamination and human health risk. These contaminants may originate from industrial effluents, atmospheric deposition, and agrochemical inputs, as previously reported[4,11].

While Rabi soils generally showed lower contamination levels, persistent use of fertilizers and residual pollutants still contributed to trace metal accumulation. Zinc (Zn), though essential, was found in elevated quantities in both seasons, likely due to over application of Zn-fortified fertilizers, consistent with observation[13].

Conclusion

This study provides critical insights into the seasonal dynamics of heavy metal contamination in agricultural soils, with a comparative focus on Rabi and Kharif cropping periods in the industrially influenced region of Kanpur. The analysis revealed that Kharif season soils exhibited significantly higher concentrations of heavy metals—particularly lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni)—as compared to Rabi soils. These seasonal discrepancies are influenced by factors such as monsoonal runoff, flood irrigation, soil pH shifts, and anthropogenic activities like industrial discharge and excessive use of chemical fertilizers and pesticides. The implications of this research extend beyond the academic sphere. Policymakers can use such data to establish seasonal guidelines for fertilizer and pesticide use, regulate wastewater irrigation, and promote safer cropping patterns in contaminated regions. Farmers can be educated about the seasonal risks of heavy metal uptake by crops and encouraged to adopt practices such as crop rotation, organic amendments, and phytoremediation. The comparative analysis of heavy metal contamination across seasonal agricultural soils reveals a pressing need for multidimensional interventions to mitigate environmental, agronomic, and health risks. Future prospects lie in integrating scientific innovation, sustainable agricultural practices, and robust policy frameworks to address the growing challenge of heavy metal pollution in both Rabi and Kharif cropping systems. Conventional methods such as soil excavation or washing are often expensive and environmentally disruptive. Phytoremediation, in particular, involves the use of hyper accumulator plants capable of absorbing and storing heavy metals. Selecting species based on the seasonal growth cycle cool-season plants for Rabi and monsoon-adapted species for Kharif—could optimize remediation effectiveness. Research into genetically engineered plants with enhanced metal uptake potential also holds significant promise.

The results emphasize the urgent need for season-specific soil monitoring, pollution control policies, and sustainable agricultural practices. Adoption of phyto remediation techniques, organic amendments, and responsible agrochemical usage must be prioritized. Additionally, raising awareness among farmers regarding the risks of heavy metal contamination and promoting integrated soil fertility management are essential steps toward long-term agricultural sustainability and environmental protection.

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