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RESEARCH ARTICLE

Spatial assessment of soil heavy metal pollution in Coimbatore, India

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Abstract

Heavy metal contamination of soil is a serious risk to human health, agricultural production and the environment. The purpose of this study is to evaluate the concentration and spatial distribution of important heavy metals in the soils of Coimbatore, a fast industrializing and urbanizing area in Tamil Nadu, India. These metals include Mercury (Hg), Cadmium (Cd) and Arsenic (As). Throughout the district, 145 soil samples were gathered from peri-urban, industrial, residential and agricultural locations. Atomic absorption spectrophotometry was used to evaluate the samples and Geographic Information System (GIS) mapping and geostatistical methods were used to interpret the findings. The distribution patterns were shown using spatial interpolation techniques such as Kriging and Inverse Distance Weighting (IDW). The results showed that several heavy metal concentrations were higher than allowed by national and international norms, especially in industrial and roadside areas. In addition to being a fundamental tool for sustainable land use planning, pollution mitigation and environmental monitoring in the area, this spatial evaluation offers important insights into pollution hotspots. The results of this study highlight how soil deterioration caused by industrialization has an indirect impact on agricultural production.

Keywords: heavy metals; industrial area; spatial distribution; soil health

Introduction

A major turning point in human history was the emergence of industrialization, which caused society to change from manual labour to machine-based manufacturing. This change sparked technical advancement, urbanization and economic expansion. Soil is essential to the sustainability of terrestrial ecosystems and the maintenance of biological production (1). It also controls environmental processes and ensures the well-being of both plants and animals (2). From only considering soil productivity, the idea of soil quality has expanded to include the more comprehensive connection between soil characteristics and their roles in an ecosystem (3). The ability of soil to sustain productivity and environmental quality within ecosystem and land-use limits is now referred to as soil quality (4). However, determining a universal soil quality value is difficult because of the complexity of this connection and the effect of variables including terrain, climate, parent material and hydrology (5).

Heavy metal pollution has become a serious environmental issue worldwide because of its persistent character, toxicity and biomagnification and bioaccumulation properties (6). In contrast to organic contaminants, heavy metals are not easily degradable and may last for years in the environment, with associated long-term ecological and health effects (7). Coimbatore, often referred to as the "Manchester of South India," has seen rapid industrial growth, with industries like textile manufacturing, dyeing, electroplating and foundry operations dominating the urban landscape. Unfortunately, many of these industries operate without adequate effluent treatment, discharging waste directly into nearby soils, open canals and water bodies. This has led to the accumulation of toxic metals in wetlands and other critical ecosystems across the city (8).

Coimbatore district in Tamil Nadu has witnessed rapid urbanization, resulting in environmental degradation. Agricultural soils near industrial sites demonstrate excessive deterioration in important indicators like bulk density, water holding capacity and organic carbon content (9). Surface water bodies in the area, like lakes and rivers, contain high concentrations of chemical contaminants and bacterial contamination, which go beyond tolerable levels (10). The air quality in Coimbatore is degraded, with particulate matter (PM10) and carbon monoxide being the leading pollutants. There is a high level of heavy metals, especially zinc, in the air, which is harmful to health (11). Yet, a study on Coimbatore's agricultural soils revealed that a majority of the samples were acidic in nature, but levels of heavy metals were within limits (12). The contamination not only threatens the ecological integrity of the region but also poses serious health risks to the local population through contaminated water, food and air (13). Fig. 1 represents a map which is generated based on the key words occurrence over a period.

Materials and Methods

Study area

Coimbatore is in western Tamil Nadu as shown in the Fig. 2 and has borders with sections of Kerala's Thrissur and Ernakulam districts to the south, Nilgiris District to the north, Tiruppur and Erode districts to the east and Kerala to the west (via the Palghat Gap). Situated between the Deccan Plateau and the Western Ghats, it covers an area of 4,723 km^2 and has an average elevation of 420-427 meters above sea level. Fertile plains, river basins (particularly the Noyyal River) and hilly areas in the north and west that are a part of the Anaimalai Hills and Nilgiri Biosphere Reserve make up the district's topography. It has a mostly tropical climate that is both dry and rainy. The city has comparatively milder temperatures than other regions of Tamil Nadu because to its proximity to the Western Ghats. The mild but not overly severe summer months of March through May with temperatures between 25 °C and 40 °C. While the northeast monsoon (October to December) adds more rains, the southwest monsoon (June to September) offers moderate rainfall. Temperatures typically range from 15 °C to 30 °C during the moderate and pleasant winter months of December through February. The climate in Coimbatore is generally regarded as healthy, which makes it ideal for farming, particularly for crops like cotton, coconut and other fruit crops.

Coimbatore is known as the "Manchester of South India" due to its prominence in the textile industry. Major sources of heavy metal contamination are textiles and tanneries (such as chromium from tanneries). Lead (Pb) and cadmium (Cd) are released by foundries and machining facilities in the engineering and automotive sectors. Arsenic (As) and mercury (Hg) are introduced into soils and streams by the extensive use of fertilizers and pesticides in cotton, coffee and tea plantations. Lead and chromium poisoning of soil and groundwater is associated with the Tiruppur textile belt and Coimbatore North Taluk. Research indicates that untreated wastewater from tanneries and dyeing facilities is the cause of the high heavy metal levels in the Noyyal River Basin (14).

Sources of heavy metal contamination

Coimbatore, a rapidly industrializing city in the southern Indian state of Tamil Nadu, faces increasing environmental challenges due to heavy metal contamination from various anthropogenic and natural sources. The rapid urbanization and industrial expansion in Coimbatore have led to a significant increase in the discharge of untreated or partially treated effluents into the environment, exacerbating the problem of heavy metal pollution (10). The presence of heavy metals in the environment, even at trace concentrations, poses a significant threat to human health, ecological balance and agricultural productivity (15). Continuous monitoring of this contamination is essential due to its adverse effects on human health (16). Heavy metal contamination in Coimbatore's environment stems from a complex interplay of industrial activities, agricultural practices, domestic waste disposal and natural geological processes, requiring a comprehensive understanding of these sources to develop effective mitigation strategies (17).

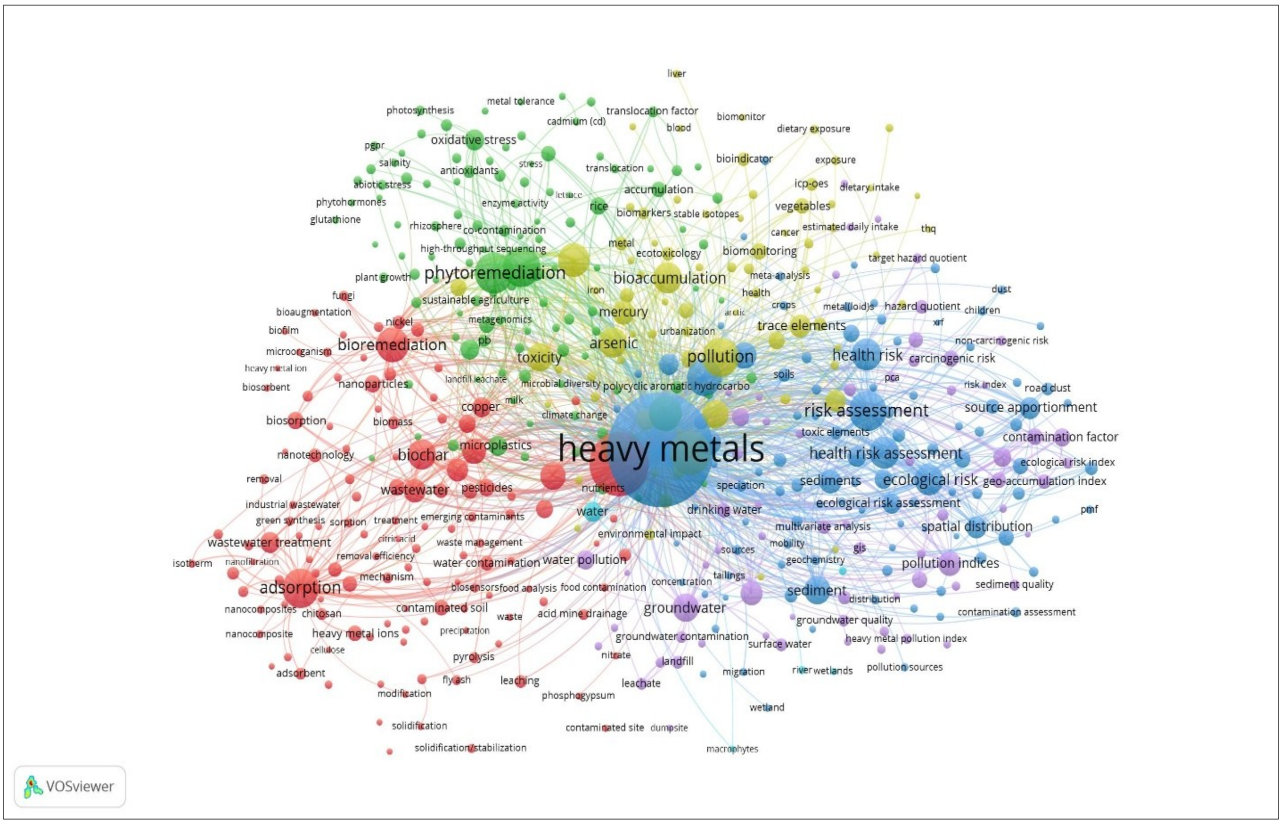

Fig. 1. Map generated based on key words co-occurrence.

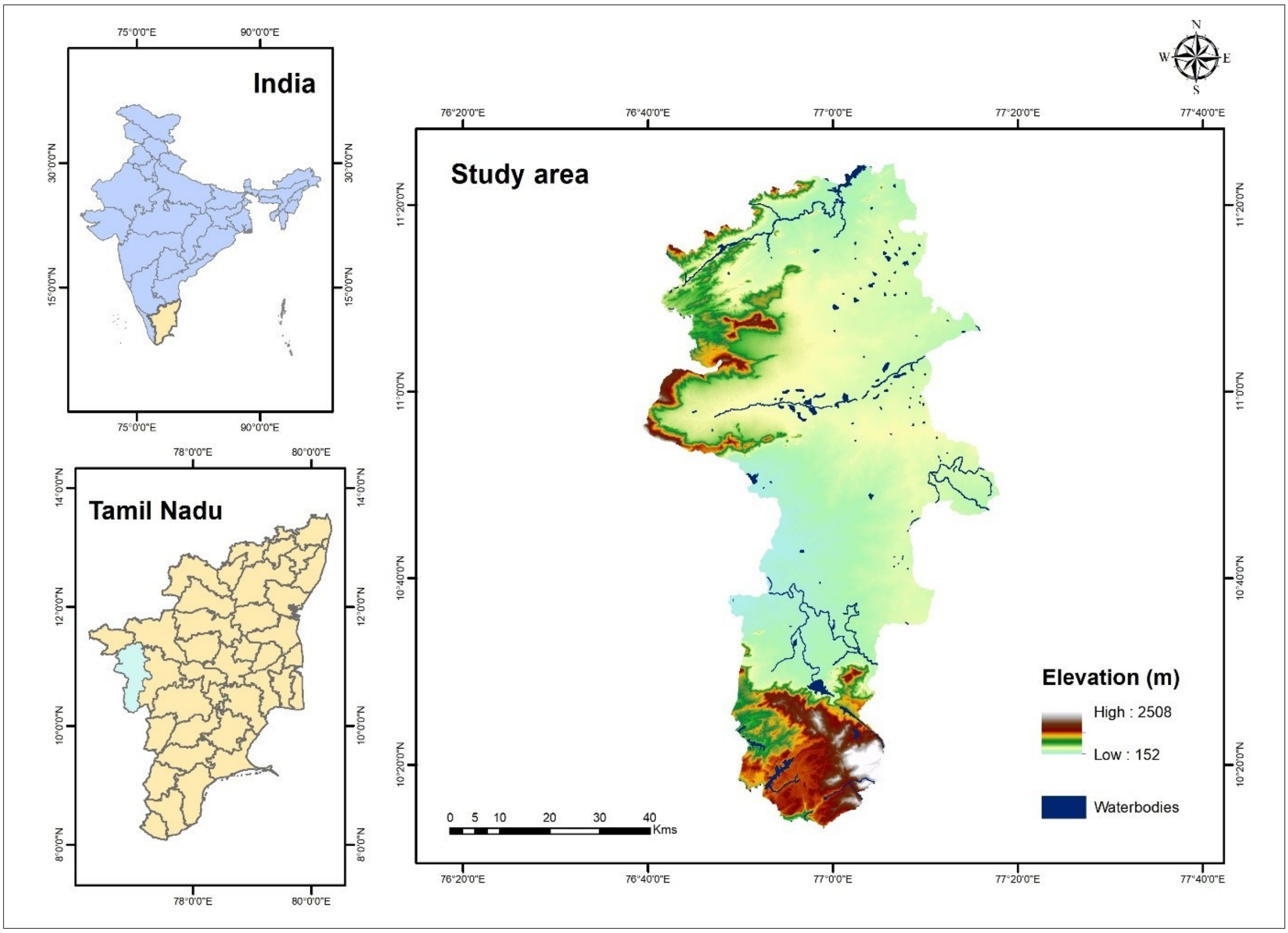

Fig. 2. Location information of the study area.

Industrial activities represent a major source of heavy metal contamination in Coimbatore, with textile industries, electroplating facilities, foundries and tanneries being prominent contributors. Textile industries, known for their extensive use of dyes and chemicals, release heavy metals such as chromium, copper and zinc into wastewater streams (18). Electroplating facilities, which employ heavy metals like cadmium, chromium, lead and nickel in their processes, often discharge these metals into the environment through wastewater and sludge (19, 20). Foundries, involved in metal casting and processing, can release heavy metals such as lead, cadmium and arsenic into the air and water through emissions and waste disposal (21). Tanneries, which use chromium salts in the tanning process, are a significant source of chromium contamination in the environment (22). Industrial wastewater, often discharged without adequate treatment, carries a cocktail of heavy metals that can contaminate surface water, groundwater and soil, posing risks to aquatic ecosystems, agricultural lands and human populations. The non-degradable nature of heavy metals leads to their persistence in the environment, accumulating in sediments, soils and biota, further amplifying their harmful effects (23). Heavy metals discharged from industries can contaminate water resources, rendering them unsuitable for drinking, irrigation and industrial purposes (24). The accumulation of heavy metals in agricultural soils can lead to reduced crop yields, contamination of food crops and potential health risks to consumers (25).

Agricultural practices, while essential for food production, can also contribute to heavy metal contamination in Coimbatore through the use of fertilizers, pesticides and irrigation water. Fertilizers, particularly phosphate fertilizers, may contain trace amounts of heavy metals such as cadmium, arsenic and lead as impurities (26). Pesticides, including insecticides, herbicides and fungicides, can contain heavy metals like arsenic, copper and mercury as active ingredients or contaminants. Irrigation water, especially when sourced from contaminated rivers or groundwater, can introduce heavy metals into agricultural soils (27). The continuous application of fertilizers and pesticides over time can lead to the accumulation of heavy metals in the soil, affecting soil health, microbial activity and crop quality. Heavy metals in agricultural soils can be taken up by plants, accumulating in edible tissues and posing risks to human health through the consumption of contaminated food crops (28). Moreover, the application of sewage sludge as a soil amendment, while beneficial for nutrient enrichment, can also introduce heavy metals into agricultural soils if the sludge is not properly treated and monitored (29). The environmental effects of heavy metals in agriculture are very negative and include agrochemicals, sludge application and wastewater (30). The heavy metals present in sludge may decrease the number of spores and the diversity of AMF (31).

Domestic waste disposal practices in Coimbatore also contribute to heavy metal contamination, particularly through the improper disposal of electronic waste (e-waste) and household waste. Electronic waste, containing a variety of heavy metals such as lead, mercury, cadmium and chromium, poses a significant environmental threat when improperly discarded or recycled (32). Household waste, including batteries, paints and cleaning products, can also contain heavy metals that leach into the environment when disposed of in landfills or open dumps (33).

Industry selection

Industries were divided into groups according to how they affected the health of the soil: Primary impact industries: quarries, foundries and electroplating plants all have immediate and direct effects on soil, including the loss of topsoil and the discharge of heavy metals, which leads to soil erosion and deterioration. Secondary effect industries: Paper, cement and textile mills all have an indirect influence on soil through dust, water pollution and chemical runoff, which reduces fertility over time. In order to concentrate on areas with a greater potential for soil deterioration, other low-impact industries were not included in this study. The purpose of this classification is to pinpoint the important industries which causes loss to soil health which are influenced by Coimbatore's industrial operations.

Sample collection

A 500 m^2 grid sampling approach was used to collect soil samples from agricultural fields close to several industrial locations in the Coimbatore district. A total of 145 samples were taken from major impact industries such electroplating, foundries, quarries, paper and textile mills. To ensure that there was no overlap with other industrial operations, a purposive sample technique was employed to concentrate on regions that were most likely impacted by the industries. To prevent metal contamination, soil was removed using plastic tools from a depth of 10 to 15 cm. It was then wrapped in polythene bags and labelled with GPS coordinates.

Interpolation method

In geo-statistics and geographic information systems (GIS), the Inverse Distance Weighted (IDW) methodology is a popular spatial interpolation method that uses nearby known data points to predict values at unsampled places. IDW uses a distance-based weighting technique to give nearby points more weight, based on the idea that proximity corresponds with similarity. A weighted average of nearby locations, whose weights are inversely proportional to the distance raised to a user-defined power. When sampling is dense enough in relation to the local variation you are trying to imitate, IDW produces its best results. The outputs could not accurately depict the intended surface if the input point sample is uneven or sparse. IDW is widely used for applications such as resource management, elevation modelling and environmental monitoring (such as mapping temperature or rainfall) since it is simple to implement and computationally efficient.

Results and Discussion

Table 1. Descriptive statistics of basic parameters accessed in industrial areas of Coimbatore, India

Parameters	RMS	RANGE
pH	0.24	1.52
EC	0.317	2.363
N	21.40	196.59
P	3.06	26.9
K	82.24	652.42
CEC	3.81	29.16

The experimental findings for the soil parameters (pH, EC, N, P, K and CEC) as summarized in Table 1, are consistent with the industrial and agricultural setting of Coimbatore. Localized alkalinity variations are indicated by the pH range (1.52) and RMS deviation (0.24), which are probably caused by industrial effluents or the use of lime in farmlands. Because of the large salt loads from effluents, Coimbatore's soils frequently show alkaline shifts, which are impacted by the textile dying industry and untreated sewage discharge. Moderate salinity is indicated by EC values (RMS = 0.317, range = 2.363), which are in line with research that links irrigation with tainted Noyyal River water to higher EC in semi-urban soils. Variability in nutrients reflects the regions heavy fertilizer usage and unequal application of organic waste. For example, regular potash fertilization causes Coimbatore’s agricultural soils to frequently exhibit high potassium levels, but irregular sewage sludge application corresponds with phosphorus variability. The red soils of Coimbatore, which are susceptible to compaction from industrial pollution, are characterized by mixed clay and organic content, as shown by CEC values in Table 1.

pH exhibited the lowest RMS deviation (0.24) among all parameters, suggesting relatively stable measurements with minimal average variability shown in Fig. 3. However, the observed range of 1.52 units indicates that localized fluctuations in acidity/alkalinity occurred, potentially reflecting spatial or temporal heterogeneity in soil conditions. EC showed moderate variability, with an RMS of 0.317 and a range of 2.363 shown in Fig. 4. This implies that while average deviations were modest, extreme values (e.g., in saline or nutrient-depleted zones) contributed to a broader spread in the data. Cation Exchange Capacity (CEC), a critical indicator of soil fertility, demonstrated moderate variability with an RMS of 3.81 and a range of 29.16. These values align with expectations for soils with diverse clay and organic matter content, which directly influence CEC as shown in Fig. 5.

Nutrient concentrations displayed markedly higher variability. Nitrogen (N) had the largest absolute RMS (21.40) and range (196.59), underscoring substantial heterogeneity in nitrogen distribution across samples as shown in Fig. 6. This could reflect uneven organic matter decomposition, fertilizer application, or leaching effects. Phosphorus (P) shown in Fig. 7 followed a similar trend but with lower magnitudes (RMS = 3.06, range = 26.9), suggesting less extreme variability compared to nitrogen. Potassium (K), however, showed the widest relative range (652.42) and the highest RMS (82.24) shown in Fig. 8, indicating pronounced fluctuations, likely influenced by differences in soil mineralogy, crop uptake, or fertilization practices.

With an RMS of 2.50 and the widest range (9.86), Mercury (Hg) shown in Fig. 9 has the most variability of all the heavy metals. This noticeable expansion most likely results from sporadic contamination events, including incorrectly disposed of electronic debris, leftovers from burning coal, or past usage of fungicides containing mercury. The risk of mercury bioaccumulation in ecosystems is highlighted by the high range, especially in samples that are getting close to the top limit of the observed values.

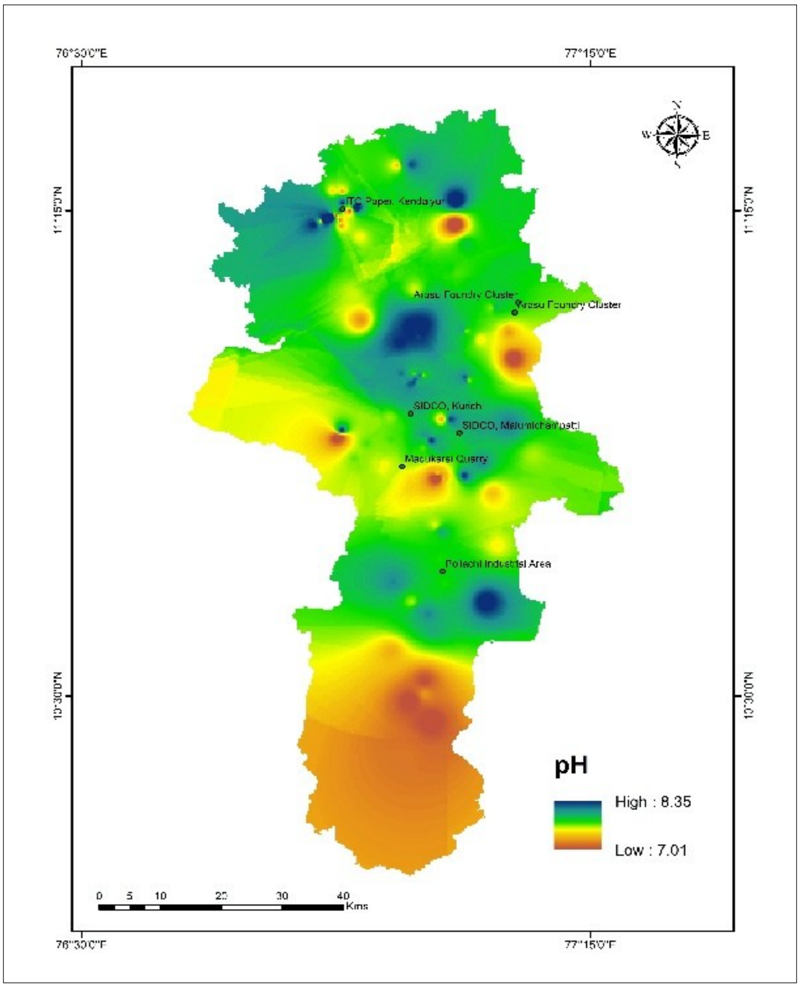

Fig. 3. Spatial distribution of pH of Coimbatore district.

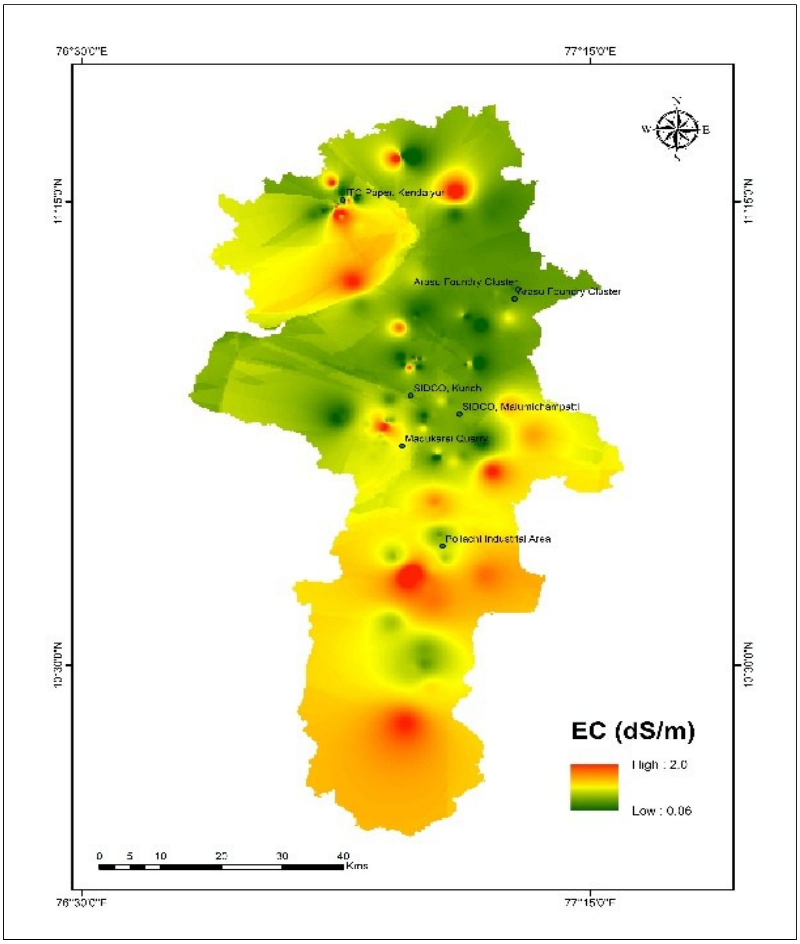

Fig. 4. Spatial distribution of electrical conductivity of Coimbatore district.

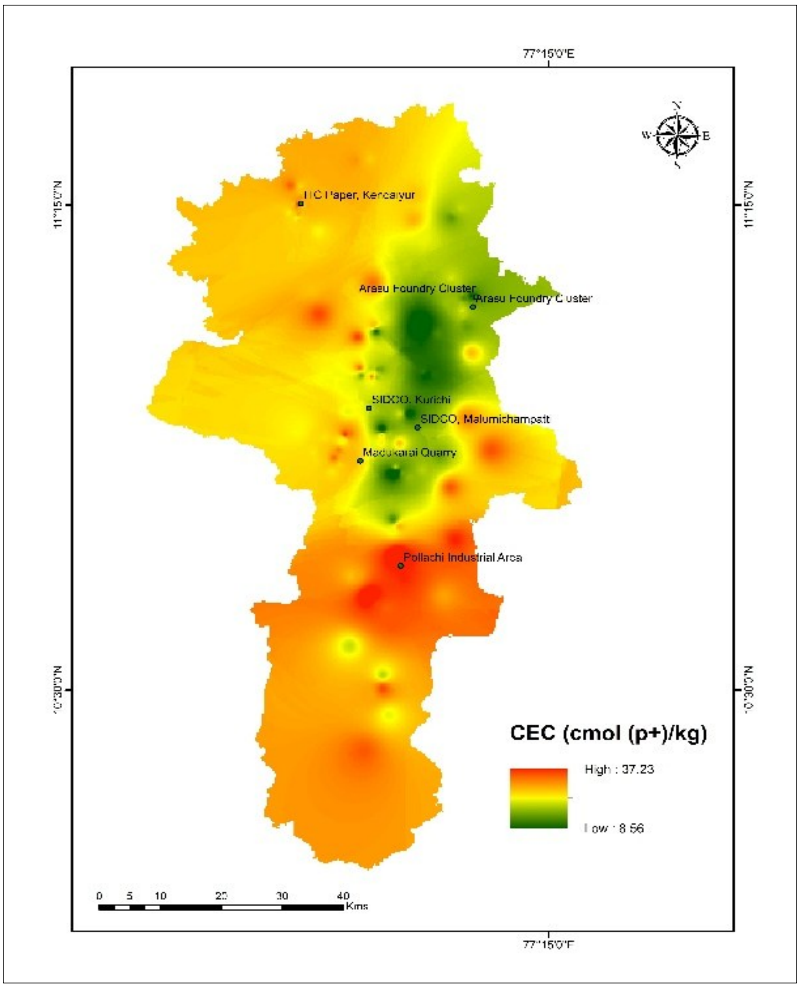

Fig. 5. Spatial distribution of cation exchange capacity of Coimbatore district.

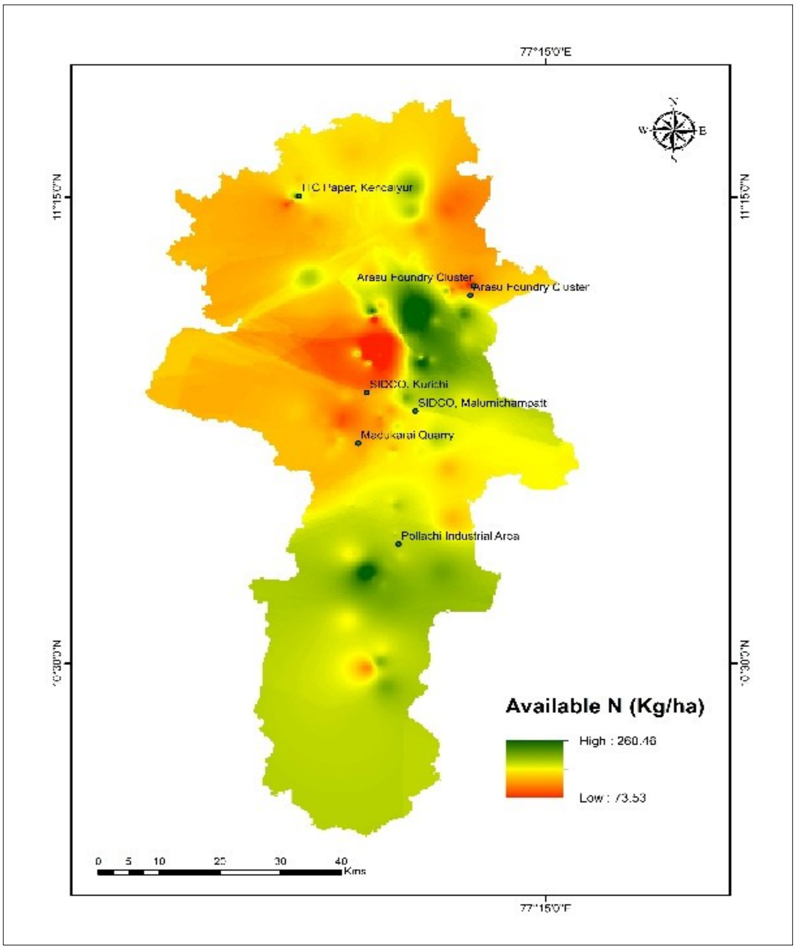

Fig. 6. Spatial distribution of available nitrogen of Coimbatore district.

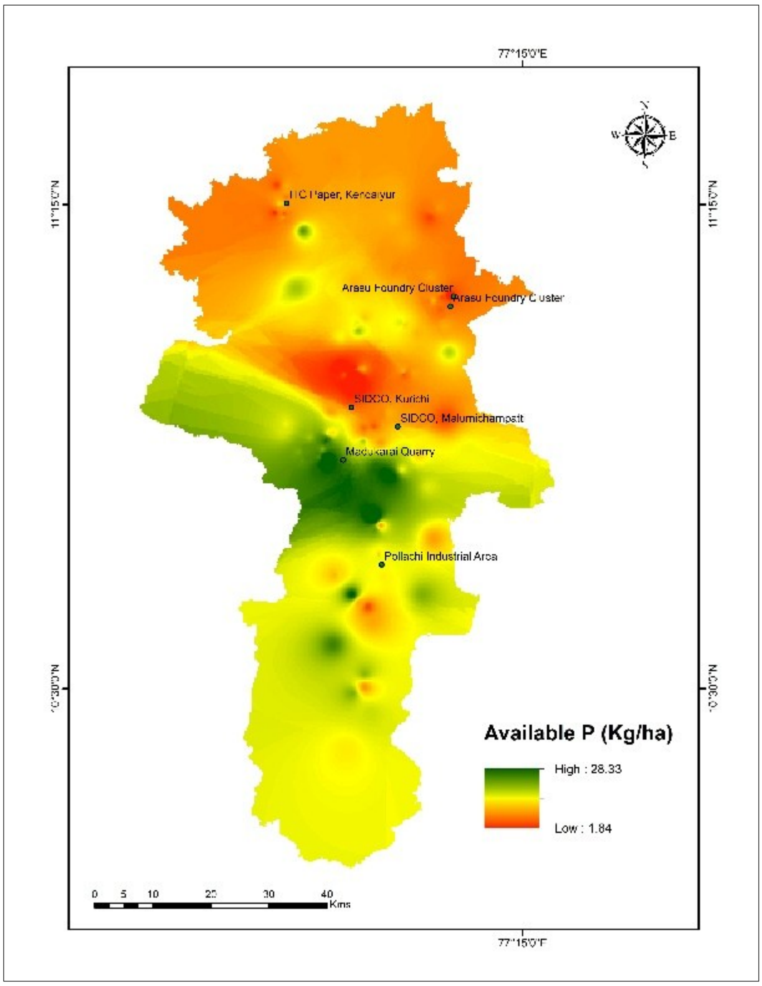

Fig. 7. Spatial distribution of available phosphorus of Coimbatore district.

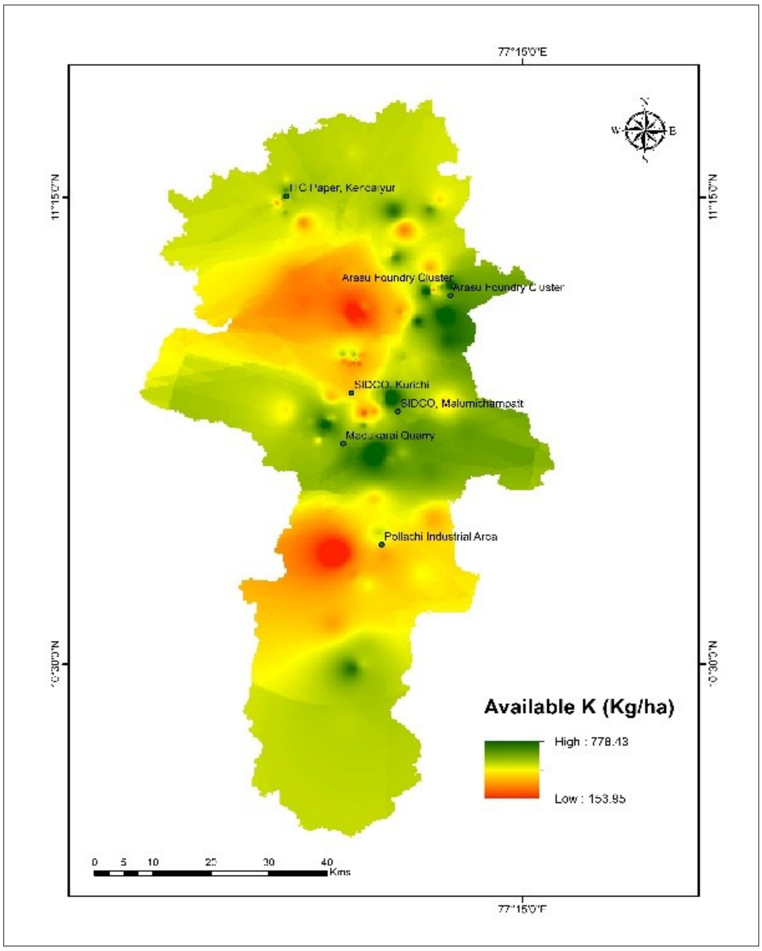

Fig. 8. Spatial distribution of available potassium of Coimbatore district.

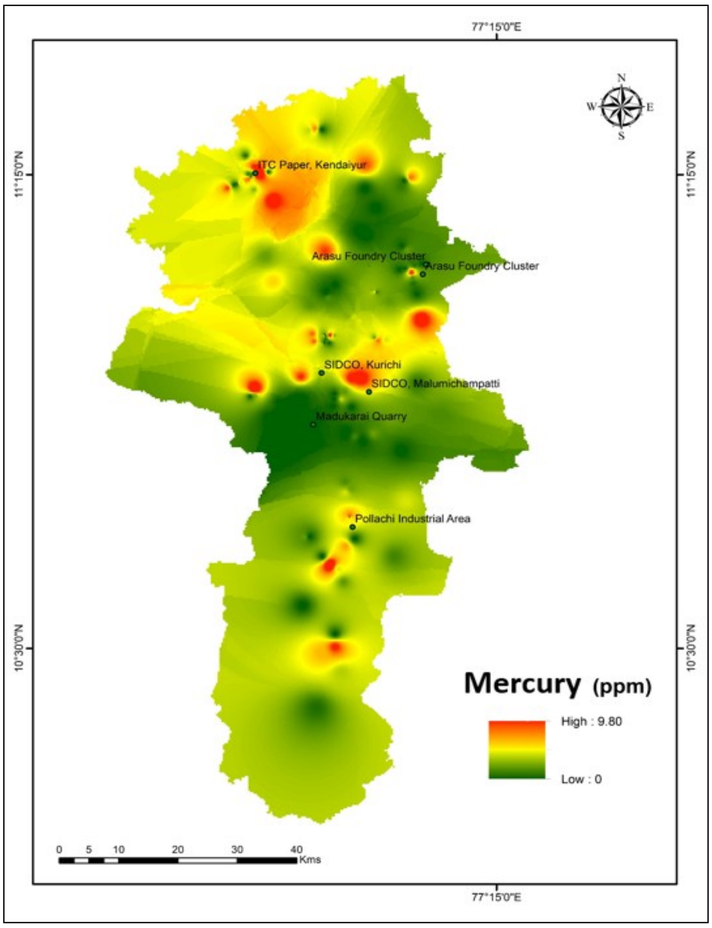

Fig. 9. Spatial distribution of mercury of Coimbatore district.

In this group, Cadmium (Cd) exhibited the least variability, with a limited range of 2.03 and an RMS of 0.371. Even though this suggests rather constant cadmium levels in the majority of samples, considering cadmium's high toxicity and environmental durability, even little variations are noteworthy. The narrow range may be the result of consistently dispersed, homogenous sources throughout the research region as shown in Fig. 10, including the application of phosphate fertilizer or air deposition from smelting operations.

Different patterns of contamination throughout the studied locations are revealed by the variation in heavy metal concentrations, as displayed in Table 2. Observed ranges and root mean square (RMS) variations offer important information about the distribution and possible environmental hazards of these hazardous components. Arsenic (As) had a range of 7.93 and an RMS of 2.21, indicating significant variability. These results point to localized hotspots of arsenic pollution as shown in Fig. 11, which may result from man-made activities like application of pesticides or industrial discharges, or from natural geological sources like bedrock which is high in arsenic. The range of almost 8 units highlights the existence of zones that are both barely and severely polluted, requiring focused treatment in impacted regions.

Future thrusts

The study offers important new information on the general health of the soil and its geographical distribution. However, it has some limitations, such as limits in geographic resolution, a lack of long-term and seasonal data and the omission of microbial effect. Since, this is a pilot project only a very few basic parameters and a limited heavy metal were analysed at first.

Table 2. Descriptive statistics of heavy metals accessed in industrial areas of Coimbatore, India

Parameters	RMS	RANGE
Arsenic (As)	2.21	7.93
Mercury (Hg)	2.50	9.86
Cadmium (Cd)	0.371	2.03

Discussion

In summary, nutrient-related parameters (N, P, K) exhibited the most pronounced variability, as evidenced by their high RMS and range values, while pH and EC showed comparatively lower deviations. These findings emphasize the importance of site-specific management strategies in agricultural or environmental applications, particularly for nutrients prone to large spatial or temporal fluctuations. Combine phytoremediation with soil amendments (biochar) to immobilize metals in wetlands can be a remediation measure for the heavy metals in the city. Establish decentralized effluent treatment plants (DETPs) in textile clusters like Tiruppur to curb Cr and Cd inflows.

Reversing the negative impacts of industrial operations on soil health requires restoration initiatives that concentrate on increasing soil organic carbon and reducing soil compaction. Soil quality may be greatly enhanced by techniques like introducing organic amendments (such as compost or cover crops) and reducing soil disturbance through decreased tillage. These activities have a direct impact on improved water retention, microbial activity and soil fertility all of which are closely related to long-term agricultural output. Long-term food security and environmental sustainability are ensured by improving soil health through these sustainable methods, which also increase crop yields and strengthen agricultural systems resilience. In

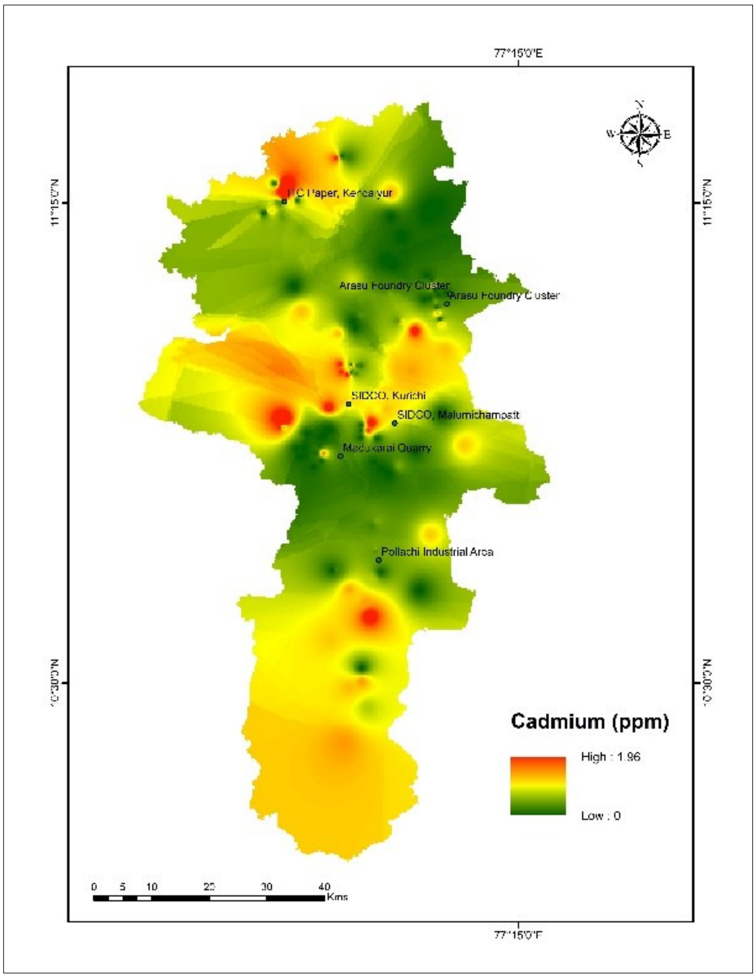

Fig. 10. Spatial distribution of Cadmium of Coimbatore district.

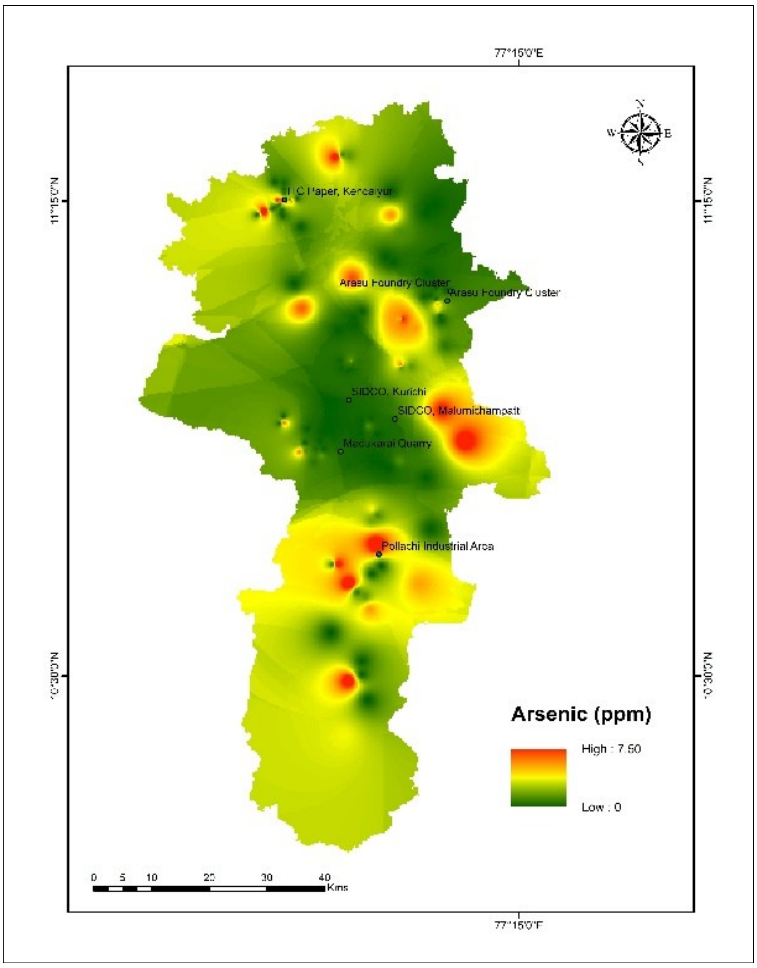

Fig. 11. Spatial distribution of Arsenic of Coimbatore district.

order to preserve agricultural lands potential for production and promote more sustainable farming practices, it is essential that soil deterioration in industrial regions be addressed.

Conclusion

The evaluation of the soil quality close to many industrial locations in the research region showed how much industrial activity affects the characteristics of the soil. Particularly, it has been shown that the regions main causes of soil degradation are foundries, paper mills, textile mills, electroplating facilities, quarry and cement industries. However, it is difficult to isolate the effects of specific sectors due to the unequal distribution of enterprises and the inherent variety of soil throughout the research region. This study emphasizes the necessity of thorough, site-specific investigation to precisely evaluate the effects of industrial operations on soil quality. Site-specific studies are crucial since the impacts of industry on soil might differ greatly based on the kind of industry, operating procedures and local environmental factors.

Initiatives to restore soil health by increasing organic carbon content and mitigating compaction are critical for counteracting the damaging effects of industrial practices. Strategies like incorporating organic materials (e.g., compost or cover crops like green manure) and adopting low-tillage methods to reduce soil disruption can markedly enhance soil conditions. These measures increase the fertility, increases water-holding capacity and heightened microbial diversity which are the key factors that reinforce sustainable agricultural yields over time.

This study's findings also highlight the importance of stringent environmental regulations concerning wastewater discharge and industrial waste management. Policymakers could leverage these insights to enforce stricter pollution control measures, establish buffer zones around industrial sites, or require soil remediation as part of the permitting process for industrial operations. To minimize ecological harm and align with sustainability targets, businesses should prioritize advanced waste treatment systems, strengthen emission controls and perform regular soil quality assessments. Implementing a holistic strategy for soil monitoring and management guided by these findings would enhance agricultural productivity, protect biodiversity and preserve environmental health, ensuring soils remain fertile and resilient for future generations.

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Authors' contributions

TKT and KPR conceptualized the study. TKT carried out survey, sample collection. TK and PS developed the methodology and carried out the formal analysis. The original draft was written by TKT, KPR, KP and TVR. TKT, TVR, SP, SK and PPC contributed to writing the review and editing of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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