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RESEARCH ARTICLE

Soil health assessment of croplands adjacent to industrial areas in Coimbatore district, Tamil Nadu

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Abstract

Soil health is a vital determinant of agricultural productivity and the supply of essential ecosystem services, including water retention, nutrient cycling and the support of microbial communities. However, industrial activities near croplands can adversely affect soil health through contamination by pollutants such as heavy metals, chemicals and waste materials. This study evaluates the soil health of agricultural lands adjacent to industrial areas in Coimbatore district, Tamil Nadu, with an emphasis on physical, chemical and biological soil properties. A total of 128 soil samples were collected and categorized into three groups: Primary Impact Sites (PIS), Secondary Impact Sites (SIS) and Reference Soils (RS). The analysis revealed that soils in proximity to industrial zones exhibited significant degradation in key indicators, such as bulk density, water holding capacity (WHC), organic carbon (OC) content and microbial activity. Soils at Primary Impact Sites demonstrated the most pronounced decline, characterized by higher bulk density, reduced WHC and lower OC levels, indicative of poor structure of soil and diminished fertility. In contrast, soils at Secondary Impact Sites and Reference Soils exhibited better overall quality, with higher microbial activity and enhanced nutrient retention. The findings of this study emphasize the indirect effects of industrialization on agricultural productivity through soil degradation.

Keywords

industrial areas; nutrient status; soil health; spatial distribution

Introduction

Soil health is crucial, though often indirect, role in determining agricultural productivity. Healthy soils provide essential ecosystem services, including water retention, nutrient cycling and support for microbial communities, all of which contribute to crop yield (1, 2). Industrialization, while a key driver of economic growth, has introduced environmental challenges that have compromised soil health, particularly in regions where crop lands are located near industrial zones. In these areas, soil degradation caused by industrial pollutants can diminish the soil's capacity to sustain agricultural productivity, thus posing a threat to food security (3, 4).

Soil health encompasses physical, chemical and biological properties that, collectively, affect the soil's ability to perform its functions. When industrial pollutants such as heavy metals, chemicals and waste materials enter the soil, they can disrupt these properties, leading to nutrient imbalances, reduced organic carbon levels and impaired microbial activity. These changes indirectly affect agricultural productivity by limiting the capacity of soil to support healthy plant growth and yield (5). For instance, soil that is compacted due to industrial activity may retain less water, making crops more vulnerable to drought stress, while soils contaminated with heavy metals may reduce nutrient uptake by plants, leading to stunted growth and lower yields (6).

Although soil health does not directly translate into immediate crop yields, it provides a foundation for sustainable agricultural systems. The capacity of soil to retain moisture, promote nutrient cycling and nurture beneficial microbial communities, which are essential for sustaining long-term crop productivity and resilience. Healthy soils enhance root development, promote efficient nutrient absorption and boost plant resistance to diseases and pests, all of which are critical for sustaining stable and high agricultural yields (7). However, when soil health is compromised especially in areas adjacent to industrial zones, these processes are disrupted, leading to a gradual decline in agricultural productivity (8).

Studies reveals that soils near industrial areas often suffer from reduced health due to contamination with pollutants such as heavy metals, excess salts and organic toxins. These contaminants alter the soil's structure and composition, reducing its fertility and negatively affecting the crops grown in these areas (9). For example, research in coal mining regions of India revealed that agricultural soils near mining activities had lower nutrient levels, reduced microbial activity and poorer water retention compared to soils farther from industrial sites (10). Similarly, a study in Shandong, China, showed that farmland near chemical industries had diminished soil health, resulting in reduced crop yields (11). These findings suggest that although soil health may not directly measure productivity, it acts as a reliable indicator of the soil's capacity to sustain agricultural outputs over time.

In regions where industrial activities are expanding, such as the Coimbatore district in Tamil Nadu, India, assessing soil health has become increasingly important. Coimbatore is known for its agricultural production, but its proximity to growing industrial zones raises concerns about the long-term sustainability of its soils. By assessing the physical, chemical and biological properties of soils in crop lands near these industrial areas, researchers can gain insights into the indirect effects of industrial activities on agricultural productivity. This information is essential for developing soil management strategies that mitigate the negative impacts of industrialization, ensuring the preservation of soil health is important for maintaining agricultural productivity and securing food availability in the region.

The present study aims to evaluate soil health in agricultural areas near industrial zones in Coimbatore district, focusing on how these soils capacity to support agricultural productivity has been affected by industrial activities. By examining key soil health indicators such as organic carbon, nutrient levels and microbial activity, this study will provide a comprehensive assessment of how industrialization indirectly influences crop productivity through its impacts on soil health.

Materials and Methods

Study Area Description

Coimbatore, a hub for around 25,000 Micro, Small and Medium Enterprises (MSMEs), is primarily focused on engineering and textiles (Fig. 1). These industries are concentrated in Coimbatore and nearby Small Industries Development Corporation (SIDCO) estates (12). The engineering sector is highly diverse, including foundries, pump sets, machine tools, auto components and more. Though Coimbatore lacks large mineral reserves, small deposits of soapstone, quartz, limestone and feldspar support local industries. The district's industries proximity to agricultural lands makes it an ideal location for examining the effects of industrialization on soil health, particularly in relation to its impact on agricultural productivity. Coimbatore district, situated in Tamil Nadu, spans a geographic area of 367097 hectares, of which 165260 hectares are under cultivation. The region primarily grows coconuts, covering about 85,831 hectares, along with crops such as millets, pulses, oilseeds, cotton and sugarcane (12). The district receives an average annual rainfall of 700 mm, with the northeast and southwest monsoons accounting for 47 % and 28 %, respectively.

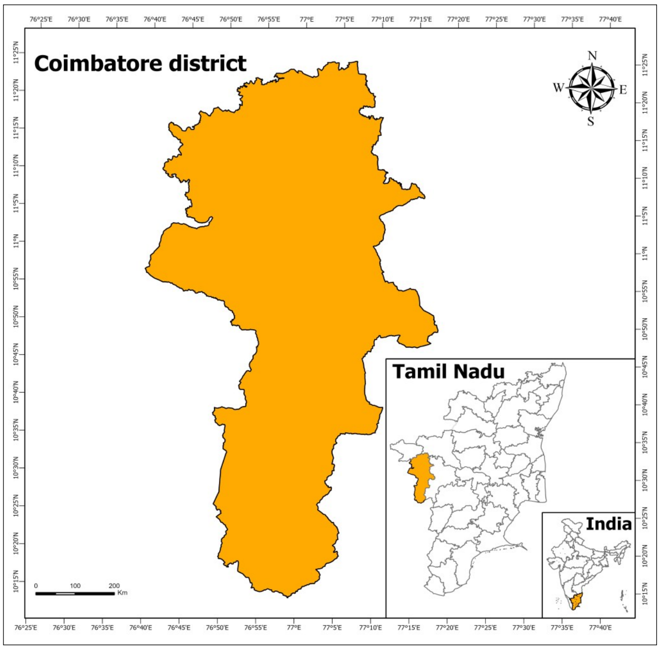


Fig. 1. Study area.

Selection of industries

Industries were categorized based on their impact on soil health: Primary impact industries: foundries, electroplating units and quarries have direct and immediate effects on soil, such as heavy metal discharge and topsoil removal, causing erosion of soil and degradation. Secondary impact industries: textile mills, cement industries and paper mills indirectly affect soil through water pollution, dust and chemical runoff, leading to long-term fertility loss. Industries like pump set and wet grinder manufacturing, categorized as low impact, were excluded from this study to focus on sectors with higher potential for soil degradation. This categorization aims to identify key soil health indicators impacted by Coimbatore's industrial activities.

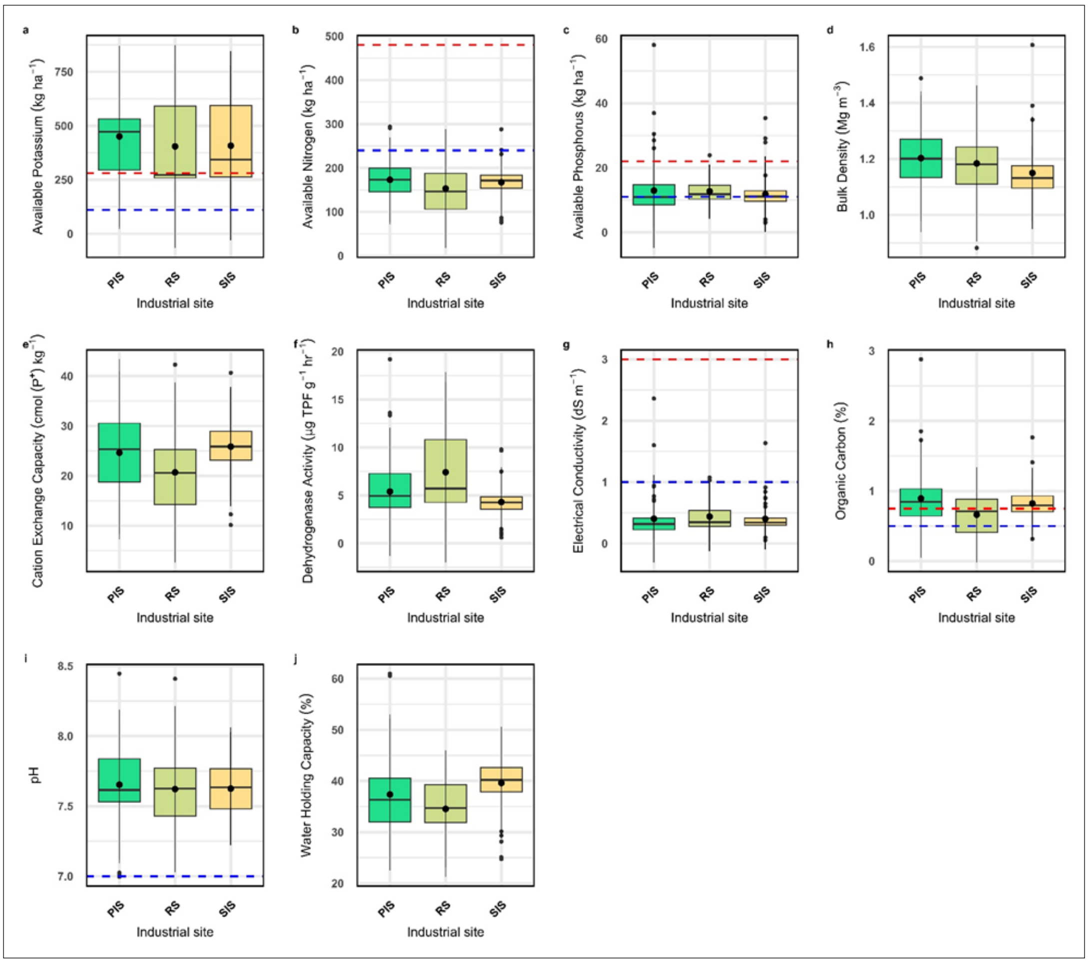


Fig. 2. Boxplot for soil health parameters. Red and blue line are upper and lower classification of parameters.

Collection of samples

Soil samples were gathered from agricultural fields located near various industrial sites in Coimbatore district using a 500 m^2 grid sampling technique. Sixty samples were collected from industries categorized as primary impact including electroplating, foundry and quarry and forty eight from secondary impact industries such as textile and paper mills, along with 20 reference soil samples. A purposive sampling approach was used to focus on areas most likely influenced by the industries, ensuring no overlap with other industrial activities. Within each grid, 5 subsamples were collected, one from each corner and one from the center to form a composite sample. Soil was taken from a depth of 10-15 cm using plastic tools to avoid metal contamination, sealed in polythene bags and labelled with GPS coordinates (Garmin eTrex 10x) for precise location tracking (11).

Laboratory Analysis

Soil samples sieved to 2 mm were analyzed for physical, physico-chemical, chemical and enzyme activity following standard methods. Bulk density (BD) was measured using the cylinder method (13) and WHC was assessed gravimetrically. For physico-chemical analysis, pH and electrical conductivity (EC) were measured in a 1:2.5 soil-water suspension (14). OC was determined by chromic acid digestion (15) and cation exchange capacity (CEC) by ammonium acetate extraction (14).

Chemical analysis included available nitrogen (AN) via the alkaline permanganate method (16), available phosphorus (AP) extracted with 0.5 M $NaHCO_3$ and color development by ascorbic acid (17) and available potassium (AK) extracted with ammonium acetate and measured by flame photometry (18). Dehydrogenase activity was evaluated using the TTC reduction method (19). Soil quality indicators were mapped using the simple kriging method in ArcGIS Pro 3.2 to visualize spatial variation in soil health across sites.

Statistical Analysis

The data were statistically analyzed using ANOVA, followed by Tukey's HSD test to determine significant differences between Industrial sites. All analyses were performed using R software, version 3.3.

Results

The BD values ranged from 1.003 Mg m^{-3} to 1.246 Mg m^{-3} across the 3 sites. The Reference Soil (RS) exhibited the lowest BD (mean: 1.003 Mg m^{-3}), indicating better structure of soil and higher porosity, characteristics typical of less compacted soils. In contrast, the SIS showed a moderate BD (mean: 1.097 Mg m^{-3}), while the PIS recorded the highest BD (mean: 1.246 Mg m^{-3}), reflecting more compacted soil conditions (Table 1). Although the ANOVA results were not statistically significant (p-value = 0.053) (Fig. 3), the differences between the PIS and SIS were noteworthy, as confirmed by the Tukey's HSD test. This trend correlates with WHC which showed a strong negative correlation with BD (r = -0.82) (Fig. 4), indicating that soils with lower BD, such as the RS, tend to have higher WHC due to better soil structure and porosity.

WHC varied significantly across the sites, which is consistent with the compaction levels indicated by BD. The RS had the highest WHC (mean: 43.53%), highlighting its superior

Table 1. Descriptive statistics for soil health indicators in industrial areas of Coimbatore district, Tamil Nadu

	Industrial Sites	**PIS**	**RS**	**SIS**
BD (Mg m^{-3})	Mean	1.20	1.18	1.15
	SD	0.11	0.14	0.10
	Median	1.20	1.18	1.13
	Min	0.94	0.88	0.98
	Max	1.49	1.43	1.61
	Skewness	0.00	-0.08	2.19
	Kurtosis	0.02	-0.42	7.33
WHC (%)	Mean	37.37	34.54	39.61
	SD	7.42	5.70	5.48
	Median	36.35	34.69	40.22
	Min	23.47	21.29	24.75
	Max	60.97	42.89	49.41
	Skewness	0.99	-0.47	-0.85
	Kurtosis	1.59	-0.56	0.76
pH	Mean	7.65	7.62	7.63
	SD	0.27	0.30	0.20
	Median	7.62	7.63	7.63
	Min	7.00	7.20	7.22
	Max	8.45	8.41	8.06
	Skewness	-0.26	0.75	-0.01
	Kurtosis	0.80	0.23	-0.70
EC (dS m^{-1})	Mean	0.40	0.44	0.40
	SD	0.35	0.28	0.25
	Median	0.32	0.35	0.34
	Min	0.07	0.07	0.05
	Max	2.36	1.07	1.64
	Skewness	3.51	0.97	2.78
	Kurtosis	14.88	-0.16	10.49
OC (%)	Mean	0.89	0.66	0.82
	SD	0.42	0.34	0.26
	Median	0.84	0.71	0.80
	Min	0.17	0.03	0.32
	Max	2.88	1.32	1.77
	Skewness	1.96	-0.22	0.97
	Kurtosis	6.53	-0.80	2.48
CEC (cmol (P^{+}) kg^{-1})	Mean	24.63	20.70	25.86
	SD	8.17	9.01	5.99
	Median	25.34	20.58	25.86
	Min	7.30	7.22	10.16
	Max	43.36	42.28	40.65
	Skewness	-0.09	0.57	-0.22
	Kurtosis	-0.42	-0.14	0.54
AN (Kg ha^{-1})	Mean	173.13	153.21	167.34
	SD	48.24	67.63	38.96
	Median	173.13	146.68	171.47
	Min	71.73	50.76	75.80
	Max	294.07	274.27	287.88
	Skewness	0.23	0.29	0.05
	Kurtosis	0.18	-1.08	1.27
AP (Kg ha^{-1})	Mean	12.95	12.72	11.84
	SD	8.89	4.14	5.85
	Median	10.94	11.80	11.10
	Min	1.81	4.17	2.99
	Max	58.06	23.89	35.41
	Skewness	2.64	0.60	2.10
	Kurtosis	9.61	0.90	5.63
AK (Kg ha^{-1})	Mean	450.68	404.28	407.61
	SD	209.64	235.06	219.40
	Median	472.64	271.72	342.93
	Min	21.13	195.14	97.82
	Max	785.58	786.10	780.29
	Skewness	0.06	0.85	0.47
	Kurtosis	-0.88	-1.16	-1.16
DHA (µg TPF g^{-1} hr^{-1})	Mean	5.40	7.42	4.31
	SD	3.34	4.69	1.82
	Median	4.94	5.72	4.27
	Min	0.10	0.73	0.62
	Max	19.19	17.88	9.80
	Skewness	1.52	0.82	0.60
	Kurtosis	3.78	-0.34	1.72

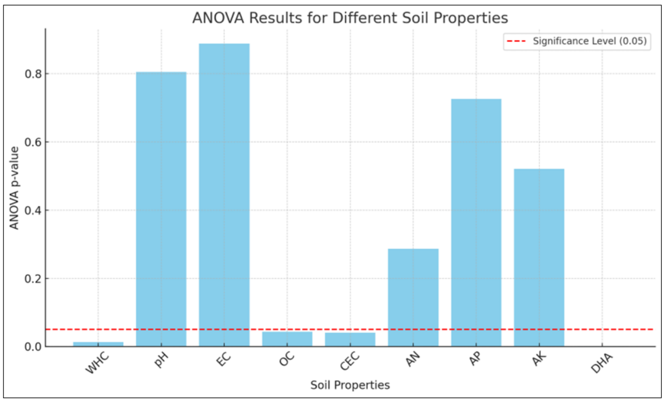


Fig. 3. ANOVA results for different soil properties.

moisture retention capacity, while the PIS showed the lowest WHC (mean: 30.13%), indicative of reduced moisture retention in compacted soils (Table 1). This reduction in WHC at the PIS aligns with the compacted soil structure reflected by its high BD. The strong negative correlation between BD and WHC further supports this observation (Fig. 4), suggesting that soil compaction reduces the soil's capacity to hold water, a critical property for sustaining crop growth and maintaining soil health. Tukey's HSD test confirmed significant differences in WHC, especially between the SIS and PIS, reinforcing the effect of industrial activity on water retention of soil.

Soil reaction (pH) remained within the neutral to slightly alkaline range (7.24 to 7.73), with minimal variation across the sites. The SIS had a slightly higher pH (mean: 7.48) compared to PIS (mean: 7.24), while the RS exhibits the highest pH (mean: 7.73) (Table 1). Although these values suggest a more alkaline condition at the reference site, no significant differences were identified in pH across the sites. Interestingly, there was a weak negative correlation between pH and WHC (r = -0.28) (Fig. 4), indicating that soils with higher pH, such as RS, tend to have slightly lower WHC. However, this relationship was not statistically significant and pH did not appear to play a major role in determining soil moisture retention.

EC reflects soil salinity, showed noticeable differences across the sites, with the PIS having the highest EC (mean: 0.337 dS/m). The SIS had lower EC values (mean: 0.234 dS/m), while the RS exhibited the lowest EC (mean: 0.181 dS/m) (Table 1). The correlation between EC and BD was positive (r = 0.61) (Fig. 4), suggesting that soils with higher bulk density tend to have greater salt accumulation. This relationship could be due to reduced porosity and movement of water in compacted soils, leading to salt buildup. However, despite these observations, ANOVA results showed no statistically significant differences in EC across the sites, indicating that while salinity levels varied, they were not extreme enough to pose immediate concerns.

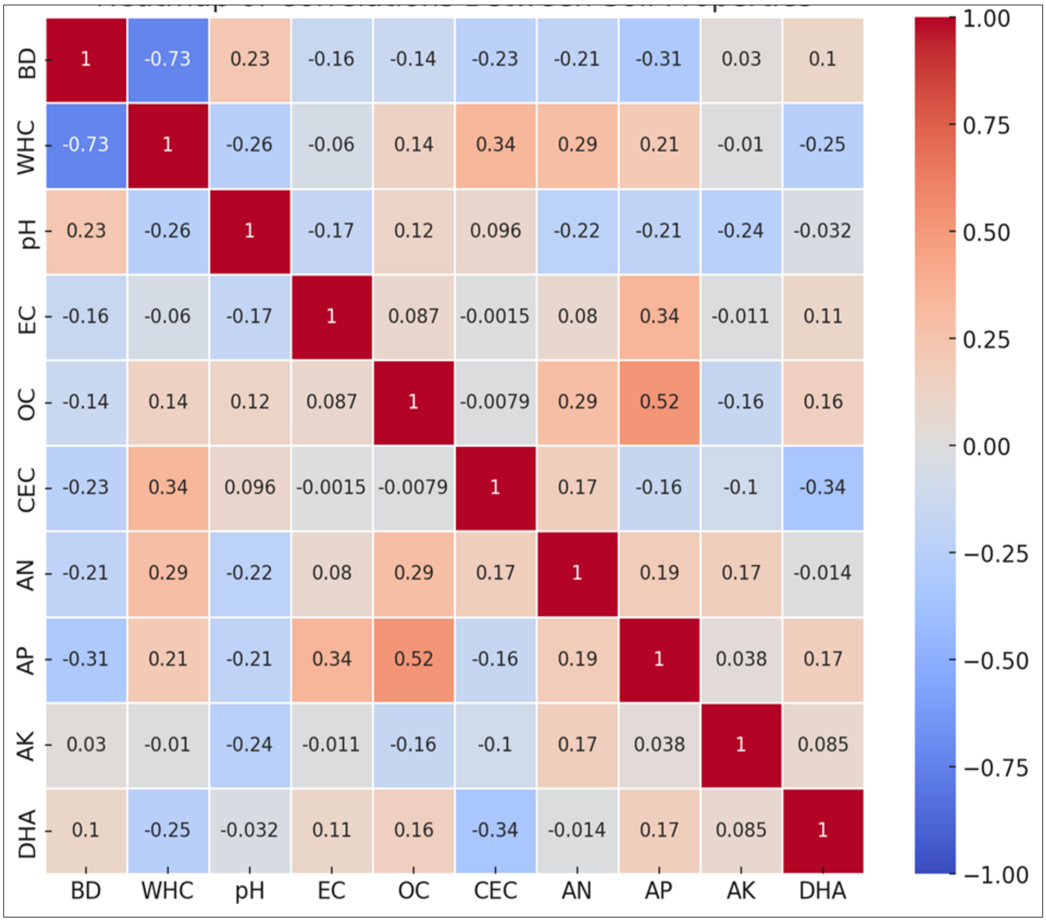
Similarly, OC content displayed significant differences between the sites. The SIS had the highest OC (mean: 0.974%), followed by the RS (mean: 0.952%), both of which reflect good organic matter content. However, the PIS showed the lowest OC level (mean: 0.456%), signaling substantial depletion of organic matter due to industrial activity (Table 1). This depletion was confirmed by the Tukey's HSD test, which indicated a significant difference in OC between the PIS and the other sites. The strong positive correlation between OC and WHC (r = 0.75) (Fig. 4) suggests that higher organic matter content contributes to better soil moisture retention, may be due to the improved structure of soil and increased water-holding capacity associated with organic matter. Therefore, the low OC at the PIS may be a key factor driving its poor WHC and overall soil degradation.

CEC, an important measure of soil fertility, was highest at the SIS (mean: 37.38 cmol (P^{+}) kg^{-1}), reflecting its better nutrient-holding capacity. The PIS showed moderate CEC (mean: 21.35 cmol (P^{+}) kg^{-1}), while the RS had the lowest (mean: 14.92 cmol (P^{+}) kg^{-1}) (Table 1). CEC exhibited a strong positive correlation with OC (r = 0.81) (Fig. 4), reinforcing the idea that soils with higher organic matter also tend to have better nutrient retention capacity. Despite these relationships, ANOVA results indicated no statistically significant differences in CEC across the sites, suggesting that while fertility levels differed, the changes were not drastic enough to be statistically notable.

AN content was highest in the SIS (mean: 240.89 kg ha^{-1}), followed by the PIS (mean: 136.61 kg ha^{-1}), with the RS exhibiting the lowest nitrogen content (mean: 115.90 kg ha^{-1}) (Table 1). AN was positively correlated with both OC and CEC (r = 0.65 and r = 0.69, respectively) (Fig. 4), which is expected, as soils with higher OC and better nutrient retention tend to support higher nitrogen levels. However, the ANOVA results revealed no significant differences between the sites, indicating that nitrogen availability remained relatively stable, potentially influenced by external fertilizer inputs.

AP followed a similar pattern, with the SIS showing the higher levels (mean: 17.67 kg ha^{-1}), slightly above the PIS (mean: 16.32 kg ha^{-1}) and the RS exhibiting the lowest phosphorus levels (mean: 14.28 kg ha^{-1}) (Table 1). Phosphorus levels were weakly correlated with CEC and OC (r = 0.34 and r = 0.41) (Fig. 4), suggesting that while organic carbon and nutrient retention influence phosphorus availability, the relationship is less pronounced than for nitrogen. Meanwhile, AK varied more noticeably across the sites. The PIS had the highest AK levels (mean: 753.79 kg ha^{-1}), may be due to contamination or fertilizer use, followed by the SIS (mean: 707.98 kg ha^{-1}), while the RS showed the lowest concentration (mean: 358.98 kg ha^{-1}). AK exhibits a moderate positive correlation with BD (r = 0.53), suggesting that more compacted soils, particularly at the PIS, may retain higher potassium levels, possibly due to reduced leaching. However, ANOVA results showed no significant differences in AK between the sites.

Finally, DHA, a key indicator of microbial activity, was highest at the SIS (mean: 4.83 μg TPF g^{-1} hr^{-1}), reflecting greater microbial activity, followed by the RS (mean: 4.73 μg TPF g^{-1} hr^{-1}), with the PIS exhibiting the lowest DHA (mean: 4.04 μg TPF g^{-1} hr^{-1}) (Table 1). DHA showed a strong positive correlation with OC (r = 0.89) (Fig. 4), highlighting the importance of organic carbon levels for sustaining microbial populations and activity. The significant difference in DHA between the PIS and the other sites, as indicated by the Tukey's HSD test, underscores the negative effect of industrial pollutants and reduced organic matter on microbial health, which is important for maintaining soil health and ecosystem functioning. The spatial variability map for different soil parameters has been created for representing the distribution across the sites (Fig. 6-15).



	BD	WHC	pH	EC	OC	CEC	AN	AP	AK	DHA
BD	1	-0.73	0.23	-0.16	-0.14	-0.23	-0.21	-0.31	0.03	0.1
WHC	-0.73	1	-0.26	-0.06	0.14	0.34	0.29	0.21	-0.01	-0.25
pH	0.23	-0.26	1	-0.17	0.12	0.096	-0.22	-0.21	-0.24	-0.032
EC	-0.16	-0.06	-0.17	1	0.087	-0.0015	0.08	0.34	-0.011	0.11
OC	-0.14	0.14	0.12	0.087	1	-0.0079	0.29	0.52	-0.16	0.16
CEC	-0.23	0.34	0.096	-0.0015	-0.0079	1	0.17	-0.16	-0.1	-0.34
AN	-0.21	0.29	-0.22	0.08	0.29	0.17	1	0.19	0.17	-0.014
AP	-0.31	0.21	-0.21	0.34	0.52	-0.16	0.19	1	0.038	0.17
AK	0.03	-0.01	-0.24	-0.011	-0.16	-0.1	0.17	0.038	1	0.085
DHA	0.1	-0.25	-0.032	0.11	0.16	-0.34	-0.014	0.17	0.085	1

Fig. 4. Correlation between soil properties.

Discussion

The results highlight significant differences in several soil properties across the PIS, SIS and RS. These differences reflect varying degrees of impact on soil quality due to environmental factors, likely driven by human activities at the impacted sites (Fig. 2).

Although BD was not significantly different across the sites (Fig. 5), it was notably highest at the PIS, suggesting soil compaction. Soil compaction reduces porosity, impedes root growth, water infiltration and gas exchange, which are critical for crop productivity. High BD is often associated with degraded soils in areas affected by human activities such as construction, industrialization and heavy machinery use, leading to reduced infiltration rates and restricted root systems (20). Compacted soils limit root expansion, reducing the plant's access to nutrients and water, which can significantly lower crop yields (21). The lower BD at the RS, in contrast, indicates minimal disturbance and better soil structure, which supports more efficient water movement and root penetration, ultimately contributing to higher crop productivity in undisturbed environments (22).

WHC varied significantly between the sites (Fig. 5), with the RS exhibiting the highest WHC, indicating superior moisture retention capacity. The PIS had the lowest WHC, likely due to soil structure degradation and organic matter depletion, both of which are common consequences of industrial activities. Reduced WHC limits the soil's ability to retain water for crops, exacerbating water stress during dry periods and negatively impacting crop productivity. Recent research demonstrated that soils subjected to industrial exposure exhibited reduced WHC, impairing both plant growth and microbial activity (23). Moreover, soils with higher WHC, like those in the RS, tend to sustain crops better during drought conditions, leading to improved yields compared to degraded soils (24).

Soil pH, while not significantly different across the sites (Fig. 5), remained within the neutral to slightly alkaline range, which is optimal for many crops and nutrient availability. This pH range promotes favourable conditions for nutrient uptake by crops and enhances overall soil fertility (25). The observed pH stability across the sites is consistent with soils that maintain balanced acidity and alkalinity, supporting robust crop growth and productivity. A neutral to slightly alkaline pH allows for the efficient absorption of nutrients such as phosphorus, calcium and magnesium, which are critical for plant health and high crop yields (26).

EC, an indicator of soil salinity, was higher at the PIS, though the differences were not statistically significant (Fig. 5). Elevated EC values at the PIS may indicate salt accumulation, potentially due to runoff from industrial or agricultural sources. Increased salinity in soils can restrict water uptake by crops and lead to reduced yields, particularly in salt-sensitive crops (27). This trend aligns with findings from recent studies which demonstrated that industrial activities can lead to increased salinity, degrading soil quality and reducing crop productivity (28). Although the EC differences were not statistically significant, the higher salinity at the PIS suggests that ongoing monitoring is necessary to prevent long-term declines in crop yields.

OC content was significantly lower at the PIS compared to the SIS and RS (Fig. 5). OC is crucial for maintaining soil fertility, microbial activity and soil health, all of which directly influence

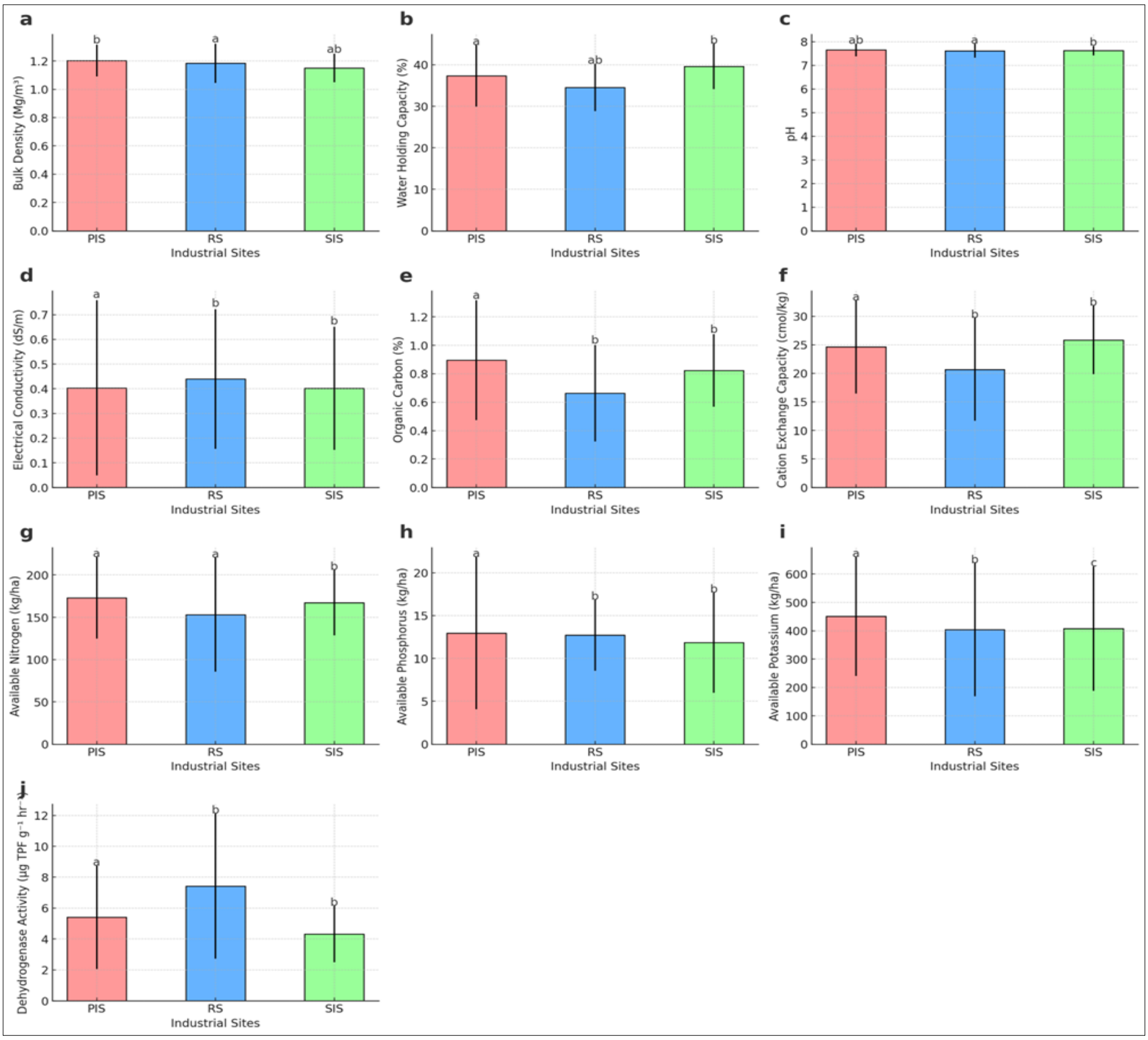


Fig. 5. A bar plots representing various soil properties measured across three industrial sites (PIS, RS, SIS). **(a)** Bulk Density (BD), **(b)** Water Holding Capacity (WHC), **(c)** pH, **(d)** Electrical Conductivity (EC), **(e)** Organic Carbon (OC), **(f)** Cation Exchange Capacity (CEC), **(g)** Available Nitrogen (AN), **(h)** Available Phosphorus (AP), **(i)** Available Potassium (AK), and **(j)** Dehydrogenase Activity (DHA).

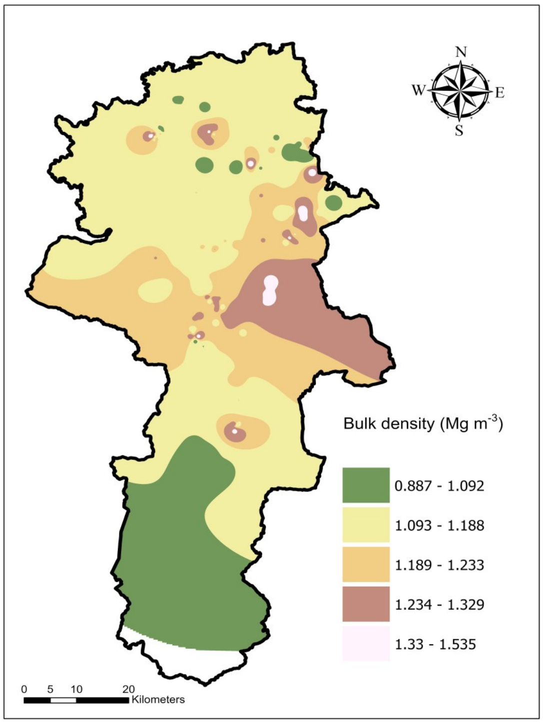


Fig. 6. Spatial distribution of Bulk density.

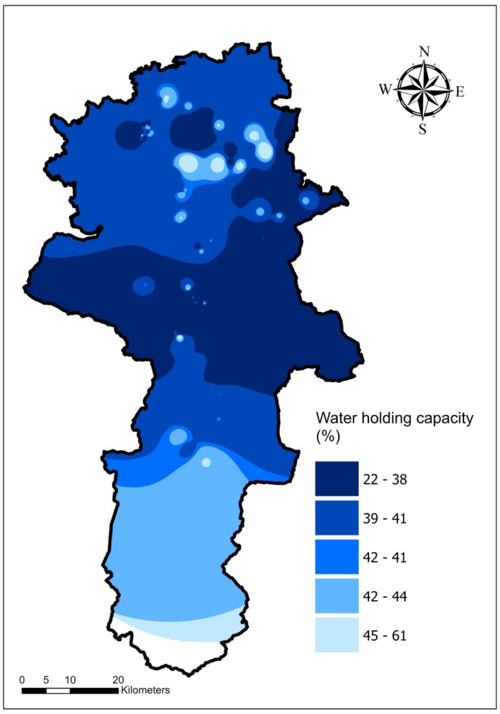


Fig. 7. Spatial distribution of Water holding capacity.

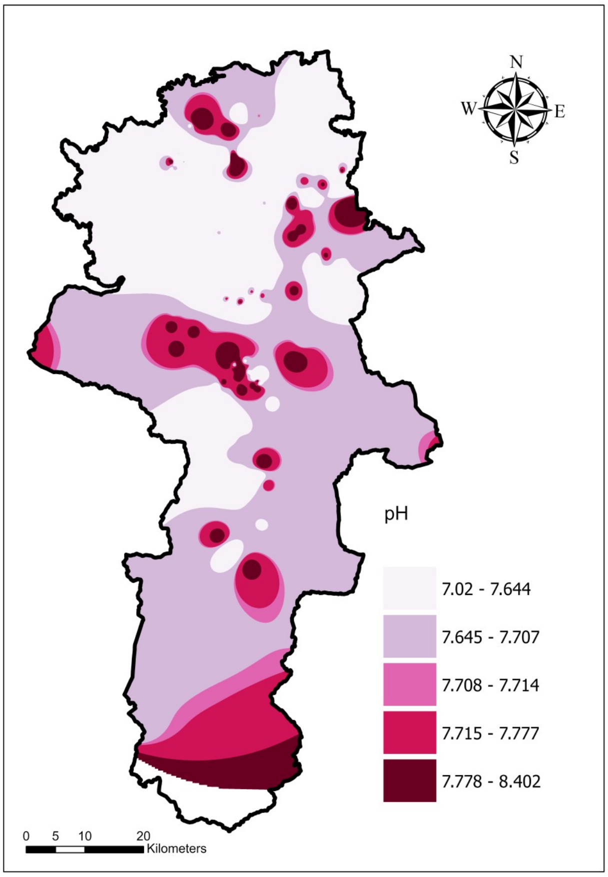


Fig. 8. Spatial distribution of pH.

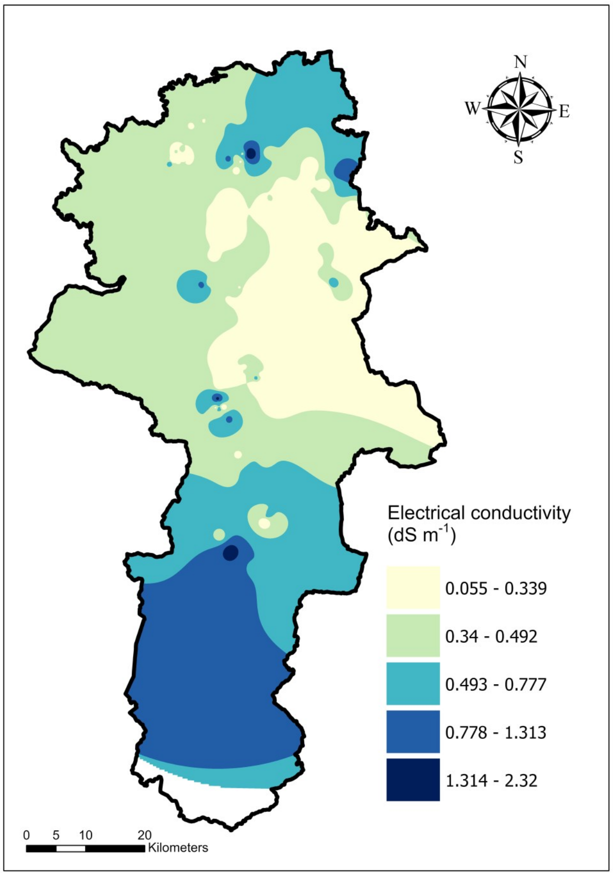


Fig. 9. Spatial distribution of Electrical conductivity.

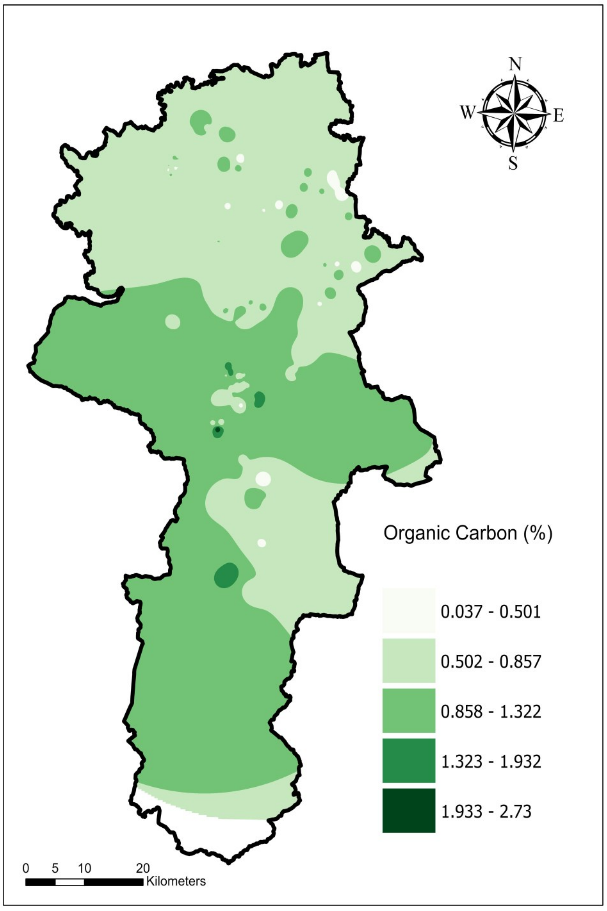


Fig. 10. Spatial distribution of Organic carbon.

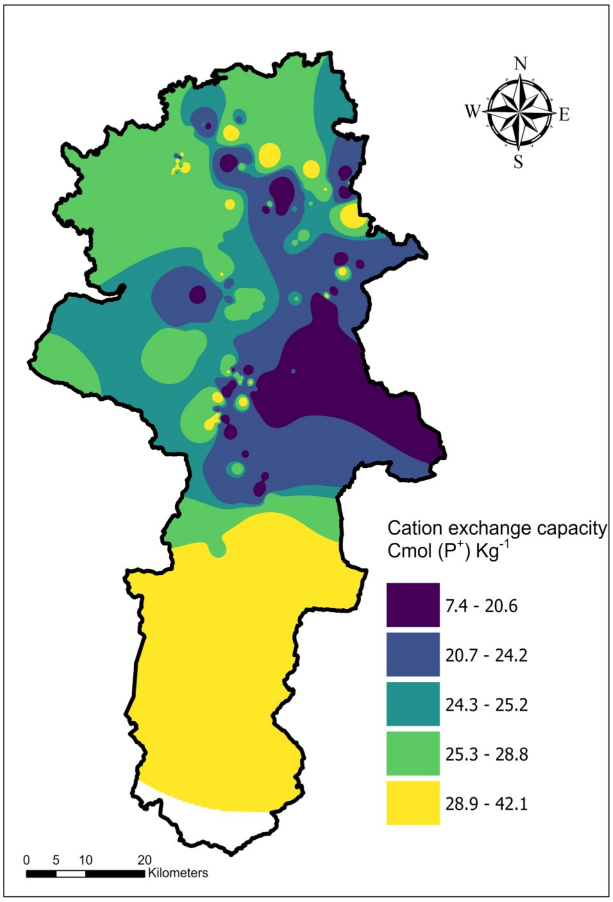


Fig. 11. Spatial distribution of Cation exchange capacity.

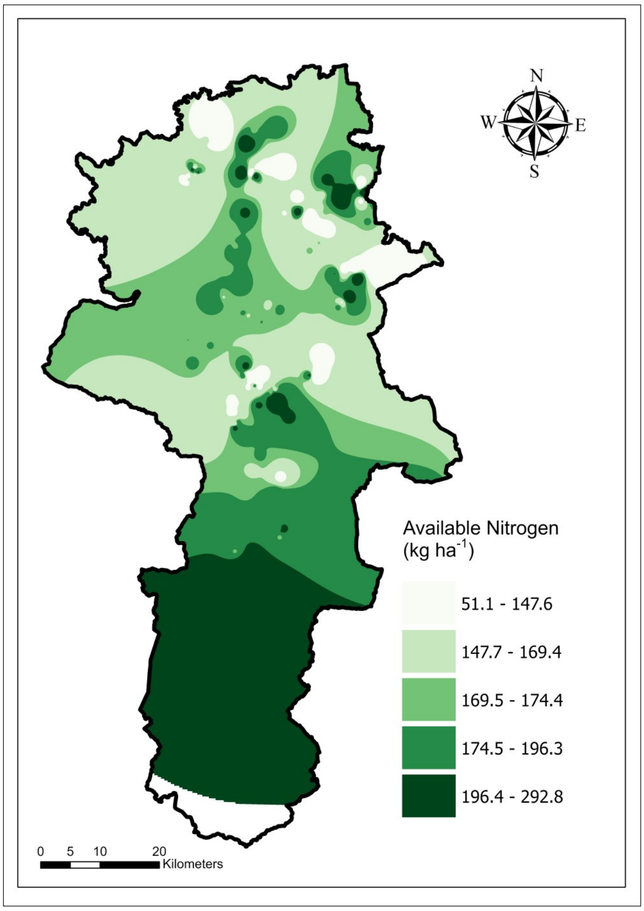


Fig. 12. Spatial distribution of Available Nitrogen.

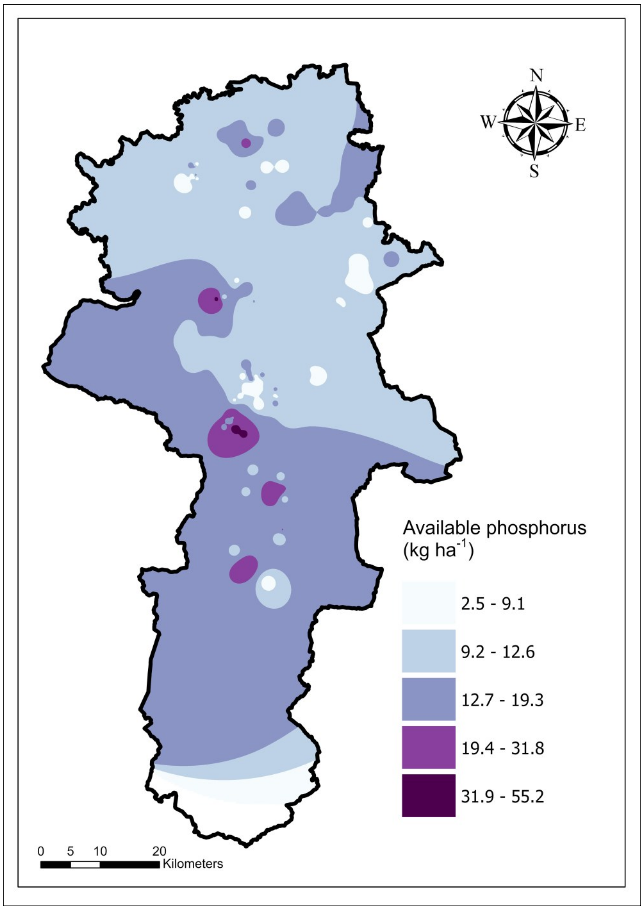


Fig. 13. Spatial distribution of Available Phosphorus.

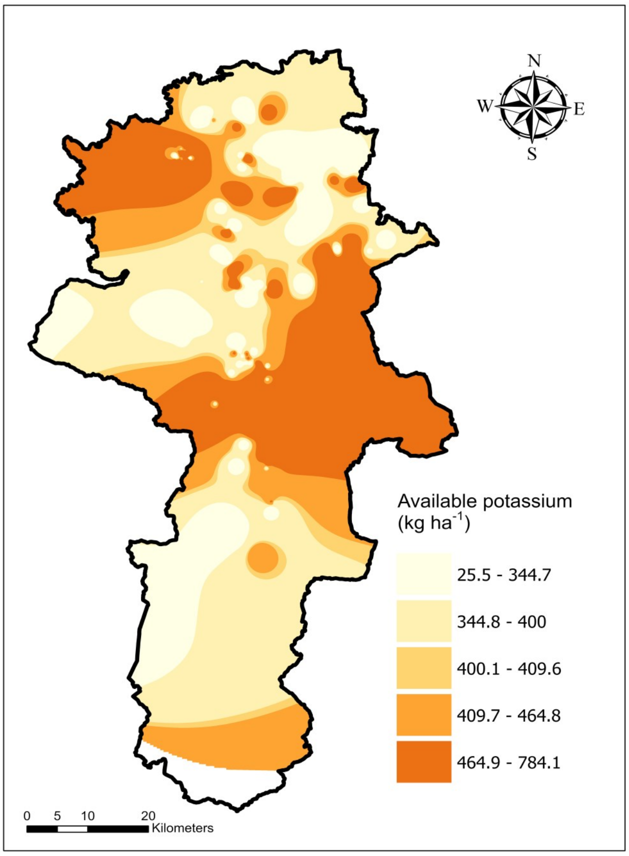


Fig. 14. Spatial distribution of Available potassium.

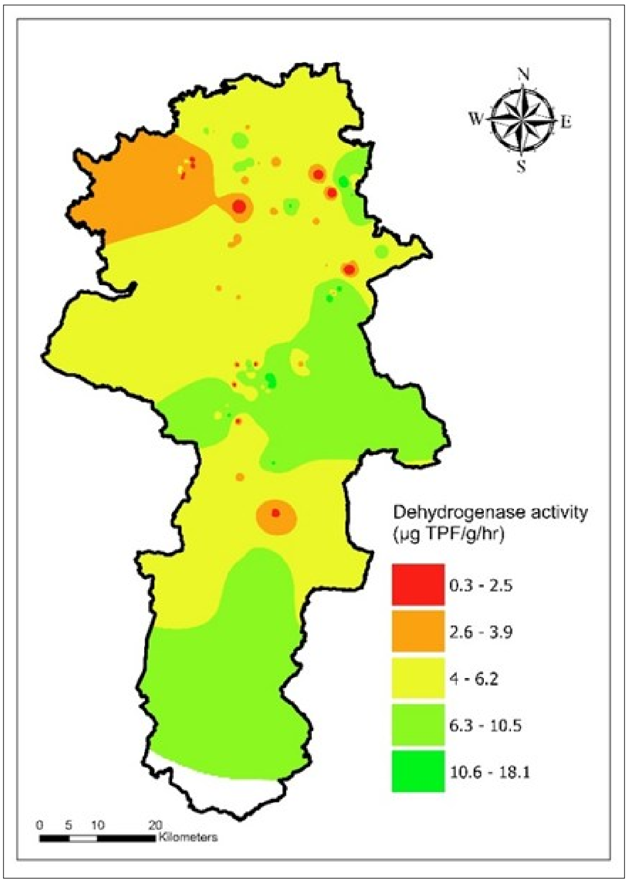


Fig. 15. Spatial distribution of Dehydrogenase activity.

crop productivity. The reduction in OC at the PIS is likely due to industrial activities that deplete organic matter, disrupting the nutrient cycles essential for sustainable crop production (29). Soils with lower organic carbon have diminished fertility, leading to poor crop growth and lower yields (30). Maintaining organic matter is essential for ensuring long-term soil health and sustainable agriculture (31).

CEC, although not significantly different between the sites (Fig. 5), was highest at the SIS, suggesting better retention of nutrient and fertility. Higher CEC values are associated with nutrient availability for crops (32). Soils with high CEC can retain more nutrients, providing a more consistent supply of essential elements such as calcium, magnesium and potassium to crops, which supports higher yields (33). Although the PIS exhibited lower CEC, the lack of significant differences suggests that nutrient retention is still relatively stable across the sites. However, further degradation at the PIS could eventually reduce its capacity to support productive agriculture.

The levels of AN, AP and AK were not significantly different across the sites, though some variations were observed (Fig. 5). The SIS generally had higher nutrient levels, which could support better crop productivity compared to the more impacted PIS. Elevated potassium levels at the PIS could result from fertilizer application or contamination, which has been observed in soils impacted by human activities (34). Despite these variations, nutrient availability remains relatively stable, which is crucial for maintaining crop yields. However, continuous industrial exposure could lead to imbalances in nutrient availability, affecting crop productivity over time (35).

DHA, a key indicator of microbial activity was significantly lower at the PIS compared to the other sites (Fig. 5). Reduced DHA reflects poor microbial health, likely caused by soil compaction, organic matter depletion and potential contamination at the PIS. Microbial activity plays a crucial role in nutrient cycling and organic matter decomposition, both of which are essential for maintaining soil quality and supporting crop productivity (36). Higher DHA values at the SIS and RS suggest better soil health, which is directly linked to higher crop productivity. Soils with robust microbial activity tend to exhibit better availability of nutrient and organic matter content, supporting higher yields (37).

This study underscores the significant impacts of human activity on soil properties and their direct influence on crop productivity. At the PIS, soil compaction, reduced organic matter and lower microbial activity suggest clear signs of degradation, which could lead to declining crop yields if left unaddressed. The findings align with existing literature, supporting the need for sustainable management practices to avoid further soil deterioration and ensure long-term agricultural productivity in impacted areas.

Conclusion

The study's findings demonstrate that soil health degradation at the PIS has direct and critical implications for agricultural productivity. Key factors such as organic carbon depletion, reduced WHC and diminished DHA are essential components of soil health that collectively influence crop growth and yield potential. The degradation observed in these areas at the PIS leads to lower soil fertility, which restricts nutrient availability to plants, weakens root development and impairs the soil's capacity to retain water, ultimately reducing crop yields. Poor structure of soil and reduced resilience to environmental stressors, such as drought or nutrient deficiencies, further exacerbate these negative effects.

In contrast, the SIS and RS maintained better soil health, characterized by higher organic carbon levels, improved nutrient retention and more active microbial communities. These healthier soils supported enhanced soil structure, improved retention of water and more efficient nutrient cycling, which are all critical factors for sustained agricultural productivity. Soils rich in organic matter and with strong microbial activity support improved root development, enhance nutrient absorption and offer greater resilience to environmental stresses, leading to more consistent and increased crop yields. The differences between these sites emphasize the importance of maintaining soil health for long-term agricultural productivity.

Restoration efforts that focus on enhancing soil organic carbon and alleviating soil compaction are vital to reversing the negative impacts of industrial activities on soil health. Practices such as applying organic amendments (e.g., compost or cover crops) and minimizing soil disturbance through reduced tillage can significantly improve soil quality. These actions directly contribute to increased soil fertility, better water retention and enhanced microbial activity, all of which are strongly linked to long-term agricultural productivity. Enhancing soil health through these sustainable practices not only boosts crop yields but also enhances the resilience of agricultural systems, ensuring both long-term food security and environmental sustainability. Therefore, addressing soil degradation in industrial areas is crucial for maintaining the productive capacity of agricultural land and fostering more sustainable farming systems

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Authors' contributions

AK carried out the survey, sample collection, laboratory analysis and participated in the sequence alignment and drafted the manuscript. KSB supervised and corrected manuscript. ST, RK, SP, AB and PCP participated in the design of the study and supported the work. 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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