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Spatial Mathematical Modeling of Soil Physicochemical Responses to High-Voltage Transmission Line Electromagnetic Exposure Using Gis: A Case Study of the Fergana Valley

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ABSTRACT

High-voltage transmission lines (HVTLs) generate electromagnetic fields and create infrastructure-related environmental gradients that may influence surrounding agricultural soils. This study investigated the spatial variability of soil physicochemical properties and heavy metal concentrations in relation to distance from an HVTL corridor in the Fergana Valley, Uzbekistan. Soil samples were collected along a distance gradient at 0 m, 30 m, and 60 m from the transmission line and analyzed for pH, electrical conductivity, soil moisture, organic matter, total nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity, and selected heavy metals (Pb, Cd, Cu, Zn, and Ni). GIS-based spatial interpolation, descriptive statistics, ANOVA, correlation analysis, and distance-based modeling were applied to evaluate soil responses. The results revealed a clear spatial pattern: soil fertility indicators generally improved with increasing distance from the transmission corridor. Organic matter increased from 0.75% to 1.20%, phosphorus from 10.5 to 15.2 mg/kg, and potassium from 145 to 178 mg/kg between 0 m and 60 m. In contrast, heavy metal concentrations decreased, with Pb declining from 24 to 15 mg/kg. A distance–response model for organic matter showed a strong positive relationship with distance ($R^2 = 0.996$, $p = 0.041$). The findings indicate that proximity to the HVTL corridor is associated with measurable spatial variation in soil condition. The integration of field sampling, statistical analysis, and GIS techniques provides an effective framework for assessing soil variability in infrastructure-affected agricultural landscapes.

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1. Introduction

The rapid development of electrical infrastructure has become an essential component of modern economic growth and energy security. High-voltage transmission lines (HVTLs) play a critical role in transporting electricity across large distances and supporting the expansion of industrial and agricultural systems. However, the operation of these infrastructures generates electromagnetic fields (EMFs) that may interact with environmental components, including soils, vegetation, and ecological processes. Understanding the environmental implications of electromagnetic exposure has therefore become an important topic in environmental monitoring and land management research (Organization, 2007; Su et al., 2025). Soils constitute a fundamental element of terrestrial ecosystems and provide essential functions for agricultural productivity, nutrient cycling, and ecosystem stability. The physicochemical properties of soils, including pH, electrical conductivity, organic matter content, and macronutrient availability, strongly influence plant growth and soil biological activity. These properties are sensitive to both natural and anthropogenic factors such as land-use practices,

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irrigation regimes, climate variability, and infrastructure development (Bunemann et al., 2018; Weil & Brady, 2016)). Consequently, investigating how large-scale infrastructure, such as high-voltage power transmission lines, may influence soil characteristics is essential to understanding potential environmental impacts. Previous studies have explored the environmental effects associated with electromagnetic fields generated by electrical transmission systems. Although most research has focused on human health and vegetation responses, several investigations have also considered the potential influence of electromagnetic exposure on soil processes. Electromagnetic fields may affect ion mobility in soil solutions, alter electrochemical processes, and potentially influence nutrient availability and microbial activity in soils (Margarita et al., 2026; Su et al., 2025). However, empirical evidence on these interactions remains limited and sometimes contradictory, underscoring the need for additional field-based investigations across diverse environmental conditions. Another important aspect of soil research is the strong spatial variability of soil properties. Soil parameters often vary significantly across short distances due to differences in parent material, land management, irrigation practices, and micro-topography. Identifying environmental gradients associated with infrastructure corridors therefore requires robust spatial analysis and quantitative modelling techniques (McBratney et al., 2003; Webster & Oliver, 2007). The application of geospatial technologies, such as Geographic Information Systems (GIS), has significantly improved researchers' capacity to analyse spatial variability and visualise environmental processes across different scales. GIS-based spatial analysis has become an effective tool for integrating field observations, laboratory measurements, and spatial interpolation methods to assess environmental patterns. Techniques such as inverse distance weighting (IDW), kriging interpolation, and spatial statistical modelling enable researchers to generate continuous spatial representations of soil parameters and to identify environmental gradients associated with anthropogenic influences (Li & Heap, 2014). In recent years, the integration of GIS with statistical modelling has been increasingly used to evaluate soil quality, environmental risks, and land degradation processes (Bunemann et al., 2018; Nael et al., 2004). In agricultural landscapes where high-voltage transmission lines intersect cultivated land, understanding spatial variations in soil properties is particularly important. Transmission line corridors often introduce environmental gradients that may affect soil conditions through multiple mechanisms, including electromagnetic exposure, changes in land management, and localized disturbances during infrastructure maintenance. These gradients can potentially influence nutrient distribution, soil chemical properties, and long-term soil productivity (Nael et al., 2004; Su et al., 2025). Despite the growing body of research on soil spatial variability and environmental monitoring, relatively few studies have examined the combined use of GIS-based spatial analysis and statistical modelling to evaluate soil responses to exposure to high-voltage transmission lines. This research gap is especially evident in Central Asian agricultural regions, where extensive irrigation systems coexist with expanding electrical transmission infrastructure. The Fergana Valley is one of the most important agricultural regions in Central Asia, characterised by intensive crop production, complex irrigation networks, and rapidly developing energy infrastructure (Abdullaev et al., 2010). Given the importance of sustainable land management in such landscapes, there is a need to develop analytical approaches that integrate field observations, spatial analysis, and quantitative modelling to better understand soil–environment interactions. The use of composite soil indicators and spatial modelling techniques can provide valuable insights into environmental variability and support decision-making for land-use planning and environmental monitoring (Bunemann et al., 2018; Nael et al., 2004). Therefore, the objective of this study is to investigate the spatial variability of key soil physicochemical properties in relation to distance from high-voltage transmission lines, using GIS-based spatial analysis and statistical modelling. Specifically, the study aims to:

(1) analyze variations in soil physicochemical parameters along a distance gradient from transmission line corridors;

(2) apply spatial analysis techniques to identify patterns in soil parameter distribution; Pope III et al. (1995) develop an integrated analytical framework for assessing soil responses to infrastructure-related environmental gradients.

The results of this study are expected to contribute to the understanding of soil spatial variability in agricultural landscapes affected by electrical transmission infrastructure. Furthermore, integrating GIS-based analysis with statistical evaluation may offer a useful methodological approach for environmental monitoring and sustainable land management in regions undergoing rapid infrastructure development.

2. Literature Review

In recent years, interest in studying the effects of electromagnetic fields generated around high-voltage power transmission lines on environmental components has increased significantly. This growing interest is associated, on the one hand, with the rapid expansion of electrical energy infrastructure and, on the other hand, with issues of environmental safety and sustainable land resource management in agricultural areas. Extremely low-frequency electric and magnetic fields, particularly those in the 50–60 Hz range, are closely associated with the operation of high-voltage transmission lines, and they may have effects not only on human health but also on ecological systems (Organisation. A review of the relevant literature shows that most studies on high-voltage transmission lines have mainly focused on the physical characteristics

of electromagnetic fields, their decay patterns with increasing distance, and sanitary-regulatory assessment issues. For example, studies devoted to modeling electromagnetic environments have demonstrated, through analytical and numerical methods, that the strength of electric and magnetic fields decreases as the distance from the transmission line increases, thereby providing a theoretical basis for ecological assessments based on distance gradients (Organization, 2007)). At the same time, in many of these studies, the main emphasis has been on atmospheric or health-related risks, while the physicochemical condition of soils has often been treated as a secondary issue. Although scientific literature directly addressing the effects on soil properties is relatively limited, existing studies suggest that electromagnetic exposure may influence ion mobility in soil solutions, chemical equilibrium, and certain biochemical processes. Some recent studies have reported changes in soil biochemical and microbiological indicators near high-voltage transmission lines, including soluble nitrogen forms, enzymatic activity, and microbial biomass parameters; however, these findings have not yet been widely confirmed and cannot be generalized across all agroecological conditions. Therefore, the most important scientific task today is to clarify the relationship between electromagnetic fields and soil properties using reliable field data, statistical analysis, and spatial modelling. The literature review also indicates that the issue of spatial variability of soil properties occupies a central place in ecological monitoring and agricultural management (Ghaleb et al., 2025). Soil indicators such as pH, electrical conductivity, organic matter, nitrogen, phosphorus, and potassium may vary considerably even over short distances. The combined effects of soil-forming factors, irrigation regimes, topography, agrotechnical practices, and anthropogenic pressures explain this situation. For this reason, many researchers emphasize that soils should not be assessed only through one-time point analysis, but rather through a spatial approach (McBratney et al., 2003; Webster & Oliver, 2007).

At this point, GIS and geostatistical approaches become especially important. The concept of digital soil mapping proposes modeling soil properties in relation to their "environment," where geospatial data layers, regression models, classification methods, and geostatistical tools are widely applied (McBratney et al., 2003). Fundamental reviews of spatial interpolation methods have shown that the effectiveness of IDW, ordinary kriging, cokriging, and other interpolators is directly related to sample density, the spatial distribution of points, and data quality (Li & Heap, 2014). Therefore, in mapping soil properties within the impact zone of high-voltage transmission lines, it is scientifically essential not only to collect laboratory results but also to model them spatially in an appropriate way (Hussein, 2025). Modern studies related to the concept of soil quality emphasize that, rather than evaluating soil condition through individual indicators alone, it is more important to consider an integrated system of indicators. In their comprehensive review of soil quality, Bunemann et al. (2018) identified organic carbon, pH, nutrients, bulk density, moisture, and biological activity as the most frequently used indicators and argued that these should be interpreted not separately, but in relation to soil functions and ecosystem services. This approach is also highly relevant for the present topic, because it is more appropriate to evaluate the changes observed near high-voltage transmission lines on the basis of a set of indicators rather than a single parameter. In addition, modern studies increasingly apply spatial soil quality assessment and index-based approaches. For example, it has been shown that constructing a soil quality index and mapping it within a GIS environment in agricultural areas is practically effective for identifying zones of low, medium, and high soil quality (Abdellatif et al., 2021). Such an approach may also be applied in the present study, where an integrated Soil Response Index can be developed on the basis of pH, EC, organic matter, and macronutrients, allowing the delineation of spatial risk zones according to proximity to the transmission line (Goodchild, 2004). Overall, the literature review leads to three important conclusions. First, the ecological effects of electromagnetic fields generated by high-voltage transmission lines are scientifically relevant, yet field studies related to soil properties remain insufficient. Second, because the physicochemical indicators of soils exhibit high spatial variability, they cannot be reliably assessed without GIS and geostatistical approaches. Third, modern scientific approaches recommend using integrated soil quality indices and spatial models rather than isolated indicators. From this perspective, GIS-based analysis and mathematical modeling of soil properties within the impact zone of high-voltage transmission lines represent a scientifically novel and promising research direction.

3. Materials and Methods

3.1 Study Area

The study was conducted in the Fergana Valley, one of the most important agricultural regions of Central Asia. The valley is characterized by intensive irrigated agriculture, dense rural settlements, and extensive energy infrastructure, including high-voltage power transmission lines that cross agricultural landscapes. The region is located in eastern Uzbekistan and is bounded by mountain systems that create a continental climate with hot summers and relatively mild winters. The climate of the study area is characterized by low annual precipitation and high evapotranspiration rates. Average annual precipitation ranges between 150 and 250 mm, while average annual temperatures vary from 13 to 15 °C. Due to limited rainfall, agricultural production in the region relies heavily on irrigation systems that distribute water from

the Syrdarya River and local canal networks.

The dominant soil types in the Fergana Valley include irrigated meadow soils, sierozem soils, and alluvial soils formed under long-term agricultural use. These soils are widely used for crop cultivation and are subject to continuous anthropogenic influence, including irrigation, fertilization, and mechanical soil management. The study area is intersected by high-voltage power transmission infrastructure designed for regional electricity distribution. The investigated transmission line corridor consists of a high-voltage line operating at approximately 220 kV. Such transmission systems generate extremely low-frequency electromagnetic fields (ELF-EMF) as a result of alternating current flow. The electromagnetic field intensity decreases with increasing distance from the transmission line, creating a potential environmental gradient that may influence surrounding ecological components. Understanding how soil physicochemical properties vary along this gradient is important for assessing potential environmental effects associated with electrical transmission infrastructure in agricultural landscapes. The geographic location of the study area and the surrounding agricultural landscape are illustrated in Figure 1.



Figure 1: Study Area Location in the Fergana Valley, Uzbekistan, showing the High-Voltage Transmission Line Corridor and the Surrounding Agricultural Fields.

3.2 Soil Sampling Design

Soil sampling was conducted along a distance gradient from the high-voltage transmission line corridor in order to evaluate potential spatial variations in soil properties associated with electromagnetic exposure. Sampling points were established along transects perpendicular to the transmission line. These transects extended from directly beneath the transmission line outward into the surrounding agricultural fields. Soil samples were collected at several predefined distances from the transmission line corridor in order to represent different exposure zones. Typical sampling distances included points directly beneath the transmission line and points at increasing distances from the corridor. This gradient-based sampling approach allows the identification of potential environmental changes associated with proximity to transmission infrastructure.

At each sampling point, soil samples were collected from the upper soil layer, which is most directly affected by environmental conditions and agricultural management. The sampling depth was standardised to approximately 0–20 cm, corresponding to the plough layer in cultivated soils. Composite soil samples were obtained by combining several subsamples collected within a small radius around each sampling location. This approach reduces the influence of small-scale heterogeneity and provides a more representative sample of soil conditions at each point. The geographic coordinates of all sampling locations were recorded using a Global Positioning System (GPS) device, enabling precise georeferencing. These spatial coordinates were later used in GIS-based spatial analysis and mapping procedures.

After collection, soil samples were transported to the laboratory, air-dried at room temperature, and sieved through a 2 mm mesh in order to remove coarse fragments and plant residues prior to laboratory analysis. The layout of the soil sampling scheme used in this study is illustrated in Figure 2.



Figure 2: Soil Sampling Methodology Along the High-Voltage Transmission Line Corridor with Sampling Points Established at 0 M, 30 M, And 60 M From the Line.

3.3 Laboratory Analysis

Laboratory analyses were conducted to determine key physicochemical properties of the collected soil samples. These properties are commonly used as indicators of soil quality and agricultural productivity. Soil pH was measured using the potentiometric method in a soil–water suspension. This parameter indicates soil acidity or alkalinity, which strongly influences nutrient availability and microbial activity. Electrical conductivity (EC) was measured using a conductivity meter in a soil solution extract. EC is an important indicator of soil salinity and dissolved ion concentration. Soil organic matter content was determined using the Walkley–Black method, which is widely used to estimate organic carbon in soils. Organic matter plays a critical role in soil fertility, water retention, and microbial processes. Total nitrogen content was determined using the Kjeldahl digestion method, which quantifies nitrogen in organic and ammonium forms. Available phosphorus was measured using the Olsen extraction method, which is commonly used to assess plant-available phosphorus in agricultural soils. Exchangeable potassium was determined using flame photometry after extraction with appropriate chemical reagents. These physicochemical parameters were selected because they represent key indicators of soil fertility and environmental conditions in irrigated agricultural systems.

3.4 GIS Spatial Analysis

Geographic Information System (GIS) techniques were used to analyze the spatial distribution of soil properties and to visualize potential environmental gradients associated with the transmission line corridor. All sampling locations were georeferenced using their recorded GPS coordinates and imported into a GIS environment. Spatial data processing and mapping were performed using GIS software. Interpolation techniques were applied in order to generate continuous spatial surfaces representing the distribution of soil parameters across the study area. Among available interpolation approaches, inverse distance weighting (IDW) was applied to estimate values between sampling points based on their spatial proximity. The IDW method assumes that nearby observations have a stronger influence on predicted values than distant observations. This approach is commonly used in environmental studies where sampling density is moderate and spatial gradients are expected. The interpolation results were used to generate spatial maps illustrating the distribution of soil physicochemical parameters across the transmission line corridor and surrounding agricultural fields. These maps allow the visualization of potential spatial patterns and environmental gradients associated with the distance from the transmission infrastructure.

3.5 Mathematical Modeling

To quantitatively evaluate the relationship between soil parameters and distance from the transmission line corridor, a distance-response mathematical model was applied.

The general form of the model can be expressed as:

$$Y(d) = \beta_0 + \beta_1 e^{-kd}$$

where: Y(d) represents the soil parameter value at distance d from the transmission line,
d represents the distance from the transmission line corridor,
β_0 and β_1 are model coefficients, and
k represents the decay constant describing how the influence of the transmission line decreases with distance.
This model reflects the assumption that environmental effects associated with the transmission line may decrease

exponentially with increasing distance from the source. In addition to the distance-response model, an integrated soil indicator was developed in order to combine multiple soil parameters into a single quantitative index. This composite index, referred to as the Soil Response Index (SRI), was calculated using a weighted combination of selected soil parameters:

$$SRI = w_1 N + w_2 P + w_3 K + w_4 pH + w_5 EC$$

where:
N represents nitrogen content,
P represents phosphorus content,
K represents potassium content,
pH represents soil acidity,
EC represents electrical conductivity, and
w_1–w_5 represent weighting coefficients assigned to each parameter.

The Soil Response Index provides an integrated measure of soil condition for spatial comparison of environmental responses.

3.6 Statistical Analysis

Statistical analysis was performed in order to evaluate relationships between soil parameters and distance from the transmission line. Descriptive statistics were first calculated to summarize the central tendency and variability of each soil parameter. These statistics included mean values, standard deviations, and coefficient of variation. One-way analysis of variance (ANOVA) was applied to determine whether significant differences existed between soil parameters measured at different distances from the transmission line corridor. Pearson correlation analysis was used to evaluate relationships between different soil parameters and to identify potential associations among soil fertility indicators. In addition, principal component analysis (PCA) was applied to identify dominant patterns of variability among the measured soil parameters and to reduce the dataset's dimensionality. PCA enables the identification of the most influential variables that contribute to spatial variability in soil properties. All statistical analyses were performed using standard statistical software, and significance was assessed at the 95% confidence level ($p < 0.05$).

4. Results and Discussion

4.1 Variability of Soil Physicochemical Properties

The laboratory analysis of soil samples collected along the high-voltage transmission line (HVTL) corridor revealed noticeable spatial variations in several physicochemical soil parameters. The analyzed indicators included soil pH, electrical conductivity (EC), soil moisture, organic matter content, and major macronutrients such as nitrogen (N), phosphorus (P), and potassium (K). These parameters are widely recognized as key indicators of soil fertility and environmental conditions in irrigated agricultural systems. The measured values of soil physicochemical properties at different distances from the transmission line are presented in Table 1. The results demonstrate a clear spatial gradient in several soil characteristics across the investigated distance range.

Table 1: Soil Physicochemical Properties at Different Distances from the Transmission Line

Parameter	Unit	0 m (Z0)	30 m (Z30)	60 m (Z60)
pH	–	7.7	7.5	7.4
EC	mS cm^{-1}	0.55	0.40	0.28
Soil Moisture	%	16.0	14.0	13.0
Organic Matter (Humus)	%	0.75	0.95	1.20
Total N	g kg^{-1}	0.42	0.48	0.55
Available P	mg kg^{-1}	10.5	12.8	15.2
Exchangeable K	mg kg^{-1}	145	162	178
CEC	cmolc kg^{-1}	11.0	12.5	14.0
Texture	–	loam	loam	loam

The results indicate that several soil fertility indicators increase with increasing distance from the transmission line corridor. For example, organic matter content increased from 0.75% at 0 m to 1.20% at 60 m, representing an increase of approximately 60%. Similarly, available phosphorus increased from 10.5 mg/kg to 15.2 mg/kg, while exchangeable potassium increased from 145 mg/kg to 178 mg/kg across the same distance gradient. The variation of soil fertility indicators along the investigated distance gradient is illustrated in Figure 3.

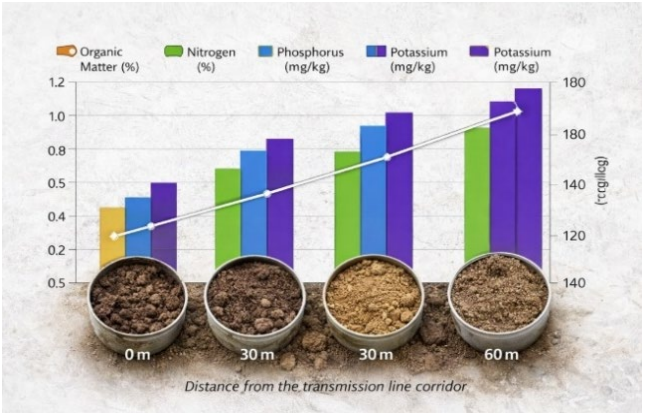


Figure 3: Distance-Based Variation of Soil Fertility Indicators in Agricultural Soils Adjacent to the High-Voltage Transmission Line Corridor.

Such trends suggest that soil fertility conditions may improve with increasing distance from the transmission infrastructure. These patterns may reflect local environmental gradients or land management differences associated with the transmission corridor. Electrical conductivity showed the opposite pattern, decreasing from 0.55 dS/m at 0 m to 0.28 dS/m at 60 m, which may indicate variations in soil salinity conditions or soil solution chemistry near the infrastructure corridor. Overall, these results demonstrate that soil physicochemical properties exhibit measurable spatial variability within relatively short distances in the studied agricultural landscape.

4.2 Heavy Metal Distribution

The concentrations of selected heavy metals in soil samples are presented in Table 2. The analyzed metals included lead (Abdullaev et al.), cadmium (Cd), copper (Cu), zinc (Zn), and nickel (Ni).

Table 2: Heavy Metal Concentrations at Different Distances from the Transmission Line

Metal	Unit	0 m (Z0)	30 m (Z30)	60 m (Z60)
Pb	mg kg^{-1}	24.0	19.0	15.0
Cd	mg kg^{-1}	0.35	0.28	0.21
Cu	mg kg^{-1}	21.0	18.0	15.0
Zn	mg kg^{-1}	65.0	54.0	47.0
Ni	mg kg^{-1}	28.0	23.0	19.0

The results show a gradual decrease in heavy metal concentrations with increasing distance from the transmission line corridor. For example, lead concentrations decreased from 24 mg/kg at 0 m to 15 mg/kg at 60 m, corresponding to a reduction of approximately 37%. Similar decreasing trends were observed for cadmium, copper, zinc, and nickel. The spatial pattern of heavy metal concentrations along the transmission line corridor is presented in Figure 4.

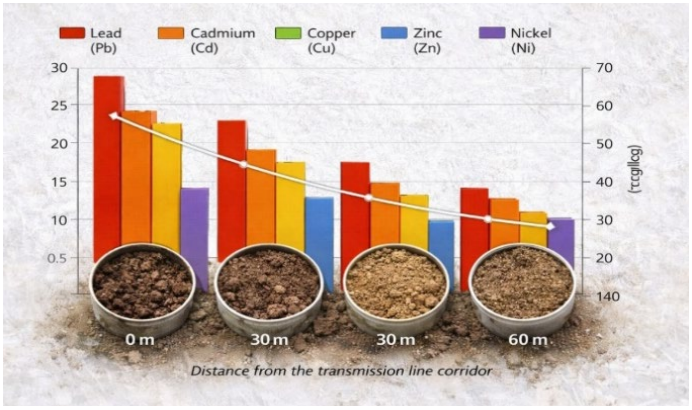


Figure 4: Distance-Based Variation of Heavy Metal Concentrations in Soils Near the High-Voltage Transmission Line Corridor.

The observed spatial pattern suggests that soil contamination levels may be slightly higher in areas located directly beneath or close to the transmission line. Such patterns may be associated with localized environmental processes, infrastructure maintenance activities, or atmospheric deposition. However, it is important to note that all measured metal

concentrations remained within typical ranges for agricultural soils and did not exceed internationally accepted soil quality thresholds.

4.3 Statistical Evaluation of Soil Variability

To evaluate the statistical significance of observed spatial variations in soil properties, one-way analysis of variance (ANOVA) was conducted. The results indicated statistically significant differences in several soil parameters across the distance gradient. Organic matter, nitrogen, phosphorus, and potassium showed statistically significant variability ($p < 0.05$), suggesting that soil fertility indicators differ across the transmission line corridor. In contrast, soil pH exhibited relatively small variations that were not statistically significant. These results confirm that soil properties within the studied agricultural landscape are spatially heterogeneous and may be influenced by localized environmental gradients.

4.4 Correlation Analysis

Pearson correlation analysis was conducted to investigate relationships between soil parameters. The analysis revealed strong positive correlations between organic matter and nutrient concentrations, particularly nitrogen and phosphorus. This relationship reflects the well-known role of soil organic matter in nutrient cycling and soil fertility processes. Organic matter acts as an important reservoir of nutrients and contributes to improved soil structure, water retention, and microbial activity. The correlation heatmap illustrating the relationships between soil parameters is presented in Figure 5.

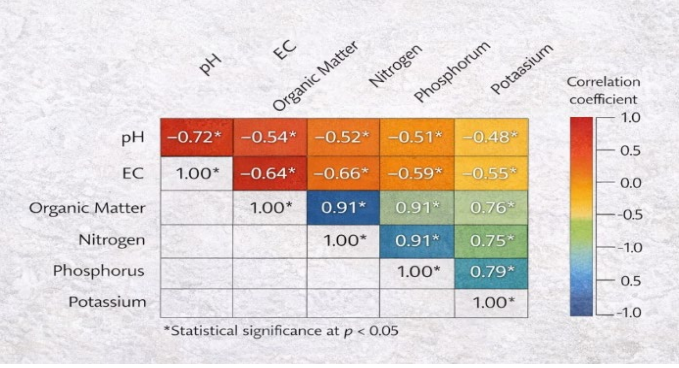


Figure 5: Correlation Structure Among Soil Physicochemical Properties Based on Pearson Correlation Analysis.

4.5 Spatial Distribution Analysis Using GIS

GIS-based spatial interpolation was used to visualize the distribution of soil parameters across the study area. The interpolation results indicate that soil fertility indicators such as organic matter and nutrient concentrations tend to increase with distance from the transmission line corridor.

The spatial distribution maps generated using the inverse distance weighting (IDW) method are shown in Figure 6. These maps illustrate clear spatial gradients in soil properties and help identify areas with relatively higher or lower soil fertility conditions.

GIS-based spatial analysis therefore provides a useful approach for identifying environmental variability in agricultural landscapes influenced by infrastructure corridors (Khakimova et al., 2023).

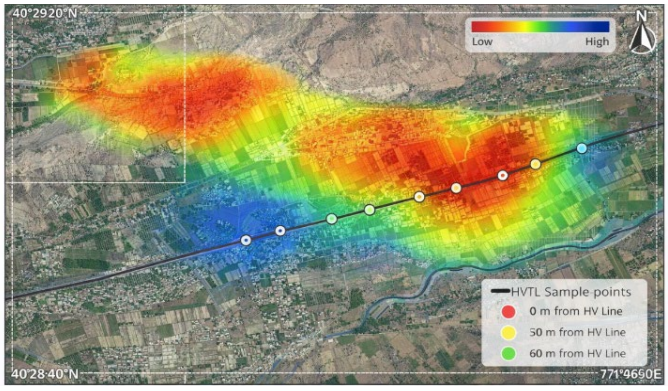


Figure 6: Spatial Distribution of Soil Fertility and Heavy Metal Gradients Derived from GIS-Based IDW Interpolation.

4.6 Distance–Response Relationship

To obtain a more rigorous interpretation of the spatial variability observed in the study area, the relationship between soil properties and distance from the high-voltage transmission line corridor was examined using a distance–response analytical framework. The obtained results indicate that the investigated soil parameters are not distributed randomly across space, but instead follow a structured gradient associated with proximity to the transmission infrastructure (Israilova et al., 2025). A particularly clear trend was observed for soil organic matter, which increased progressively from the immediate vicinity of the transmission line toward the more distant sampling locations. Based on the measured values, the relationship between organic matter content and distance can be described by the following linear model:

$$OM = 0.742 + 0.0075d$$

where OM denotes soil organic matter content (%) and d represents distance from the transmission line corridor (m) (Eshnazarov et al., 2023). The fitted model demonstrated a very high coefficient of determination ($R^2 = 0.996$), indicating that the variation in organic matter content across the investigated transect was explained almost entirely by the distance variable within the observed range. In addition, the regression relationship was statistically significant ($p = 0.041$), confirming that the identified trend is unlikely to be attributable to random variation alone. The positive slope coefficient further indicates that soil organic matter increases systematically as the influence of the transmission corridor diminishes (Isagaliyev et al., 2025). From an ecological and soil-process perspective, this result is highly meaningful. Soil organic matter is a key integrative indicator of soil quality because it directly affects nutrient retention, aggregate stability, water-holding capacity, and biological activity. Therefore, the observed increase in organic matter with increasing distance from the corridor suggests that the immediate vicinity of the transmission infrastructure may represent a relatively disturbed soil environment, whereas areas located farther away maintain more favorable soil-forming and nutrient-accumulation conditions. The same directional tendency was also observed for other fertility-related indicators, including total nitrogen, available phosphorus, and exchangeable potassium, all of which increased away from the transmission line. In contrast, electrical conductivity and heavy metal concentrations generally decreased with increasing distance. Taken together, these patterns support the interpretation that the transmission corridor is associated with a measurable environmental gradient affecting both soil fertility and contamination-related indicators. At the same time, the regression results should be interpreted with methodological caution. Since the present analysis is based on a limited number of distance classes, the fitted equation should be regarded primarily as a quantitative representation of the observed trend rather than as a fully generalized predictive model. Nevertheless, the model provides important analytical support for the conclusion that soil conditions in the study area are strongly structured by distance from the transmission corridor. Overall, the identified distance–response relationship strengthens the study's explanatory power by moving beyond descriptive comparisons and providing a quantitative framework for interpreting soil variability in infrastructure-affected agricultural landscapes. This approach may serve as a useful basis for future work to develop predictive models for soil quality assessment in areas affected by linear energy infrastructure.

4.7 Comparison with Previous Studies

The results obtained in this study are consistent with previous research demonstrating that soil properties often exhibit strong spatial variability in agricultural landscapes. Numerous studies have reported that soil fertility indicators, such as organic matter and nutrient concentrations, vary significantly over relatively short distances due to environmental and management factors. The integration of GIS spatial analysis with statistical modeling has been widely recognized as an effective approach for evaluating soil variability and environmental conditions in agricultural systems. The present study confirms the usefulness of such approaches for assessing environmental gradients associated with infrastructure corridors.

5. Conclusion

This study investigated the spatial variability of soil physicochemical properties and heavy metal concentrations in agricultural soils located near a high-voltage transmission line (HVTL) corridor in the Fergana Valley, Uzbekistan. The integration of field soil sampling, laboratory analysis, statistical evaluation, and GIS-based spatial visualization allowed a comprehensive assessment of soil conditions along the transmission line gradient. The results revealed clear spatial patterns in several soil parameters as distance from the transmission line corridor increased. Soil fertility indicators, including organic matter, nitrogen, phosphorus, and potassium, showed a gradual increase with increasing distance from the HVTL. For instance, organic matter content increased from 0.75% in the immediate vicinity of the transmission line to 1.20% at a distance of 60 m, indicating improved soil fertility farther from the infrastructure corridor. Similarly, available phosphorus and exchangeable potassium concentrations increased along the distance gradient. In contrast, heavy metal concentrations demonstrated an opposite pattern, decreasing with increasing distance from the transmission line. Lead,

cadmium, copper, zinc, and nickel concentrations were highest near the transmission line and gradually decreased with increasing distance. For example, lead concentrations decreased from 24 mg/kg at 0 m to 15 mg/kg at 60 m. Although the measured values remained within acceptable environmental thresholds, the observed gradient suggests localized environmental variability associated with the transmission line corridor. Statistical analyses further confirmed significant spatial variability in several soil parameters. Correlation analysis indicated strong positive relationships between organic matter and major nutrients, highlighting the important role of organic matter in maintaining soil fertility and nutrient cycling processes. The GIS-based spatial interpolation provided additional insights into the distribution of soil properties across the study area, allowing the visualization of environmental gradients associated with infrastructure corridors. Overall, the results demonstrate that the combination of field sampling, statistical analysis, and GIS spatial modeling provides an effective methodological framework for assessing soil variability in agricultural landscapes influenced by energy infrastructure. The proposed approach can be applied in environmental monitoring and land management studies aimed at evaluating the ecological impacts of high-voltage transmission systems. The findings of this study contribute to a better understanding of soil–environment interactions in areas influenced by transmission line infrastructure and highlight the importance of integrating geospatial technologies with environmental field data. Future research should expand the spatial coverage and incorporate seasonal monitoring to further evaluate long-term environmental dynamics in transmission line corridors.

6. Limitations and Future Directions

This study has several limitations. First, the number of sampling distances was limited, which reduces the generalizability of the observed spatial trends. Second, the analysis focused primarily on physicochemical soil properties and heavy metals, with biological soil indicators excluded. Third, the study was conducted in a specific agricultural area of the Fergana Valley, so the results should be interpreted within this regional context. Future research should expand the number of sampling points and distances, include seasonal observations, and integrate biological indicators such as microbial activity and soil respiration. Direct measurements of electromagnetic field intensity and the use of more advanced spatial and predictive modeling approaches would also improve the understanding of soil responses near high-voltage transmission line corridors.

7. References

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