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Unraveling Plant–Soil Interaction Networks: A Multi-Analytical Framework Linking Elemental Composition, Microbial Abundance, and Ecosystem Function Across Land-Use Gradients

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Abstract

The intricate networks governing plant-soil interactions constitute the biochemical foundation of terrestrial ecosystem function. Plant-Soil interactions involve several interconnected factors, including soil physiochemical properties and elemental composition and microbial activity. These factors vary under different land use conditions and contribute to differences in soil characterstics and ecological processes. This study employs an interdisciplinary framework combining X-ray fluorescence (XRF) spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, and standard plate count methodology to characterize four distinct land-use soil systems: grassland (S-1), canal-margin (S-2), forest (S-3), and agricultural (S-4). Total microbial counts ranged from 12,910 cfu (S-1) to 20,170 cfu (S-4), following the gradient of anthropogenic disturbance intensity. XRF analysis revealed SiO_2 dominance (66.30–76.50%) with significant inter-site variation in Fe_2O_3, Al_2O_3, and P_2O_5 fractions. FTIR spectra identified distinct functional group signatures, including silicate frameworks (985–1001 cm^{-1}), hydroxyl stretching (3359–3383 cm^{-1}), and aromatic C=C vibrations (1627–1629 cm^{-1}). Soil pH values ranged from 7.77 to 7.98, reflecting slightly alkaline conditions at all four sites. Electrical conductivity ranged between 122.9 and 134.3 µS/cm, reaching its maximum in the canal-margin soil (S-2). Moisture content varied substantially, from 0.24% in the forest soil (S-3) to 15.88% in the canal-margin soil (S-2).These findings underscore that ecosystem function emerges from non-linear, multi-scale interactions among abiotic matrices, microbial communities. The study provides a replicable methodological template for integrating spectroscopic and microbiological data, offering actionable insights for sustainable land management and soil health monitoring.

Keywords: Ecosystem; Plant-soil interactions; Microbial ecology; XRF spectroscopy; FTIR; Ecosystem function; Soil health

1. Introduction

A crucial part of terrestrial ecosystems, soil supports plant development, preserves nutrient availability, and controls a number of ecological processes. Numerous interrelated elements, such as soil physicochemical characteristics, elemental composition, organic matter, and microbial activity, affect the connection between plants and soil. Together, these elements support nutrient cycling, soil fertility, and the general health of terrestrial ecosystems (Bardgett et al., 2014; van der Heijden et al., 2008).

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Due to variations in plant cover, water availability, organic matter inputs, and human activity, soil properties can alter significantly under various land-use regimes. Soil conditions in managed regions, such agricultural fields, may differ from those in natural ecosystems, like grasslands and forests. Similar changes in moisture availability and the flow of dissolved materials may occur in canal-margin locations. Soil pH, electrical conductivity, moisture content, elemental composition, and microbial population can all be impacted by such variations. As a result, comparing soils from different land-use regimes can reveal important details regarding differences in soil characteristics and their ecological ramifications.Because they take part in the decomposition of organic matter, nitrogen transformation, and biogeochemical cycling, soil microbes are crucial for preserving soil functions. Environmental factors like moisture, pH, salinity, and nutrient availability affect their quantity and activity. A basic indicator of the quantity of culturable microorganisms in soil is the total microbial count, which is often calculated using conventional plate count techniques. Nevertheless, the entire variety and functionalcapacity of the soil microbial community cannot be fully represented by a microbial count alone (Philippot et al., 2013; Fierer, 2017).

The elemental and chemical makeup of soil, in addition to its biological qualities, offers crucial insights into its features. An effective analytical method for determining and estimating the elemental composition of soil, especially significant elements found in the form of oxides, is X-ray fluorescence (XRF) spectroscopy. It facilitates the comparison of the elemental and mineral properties of soils gathered from various settings. By recognizing distinctive absorption bands linked to various chemical bonds and functional groups, Fourier-transform infrared(FTIR) spectroscopy offers complementary information. Thus, a more comprehensive picture of soil composition and variability can be obtained by combining the use of XRF and FTIR with physicochemical and microbiological analysis.

A more thorough understanding of soil variability requires the combined evaluation of physicochemical traits, elemental composition,functional groups, and microbial abundance across contrasting land-use systems, even though individual soil properties have been extensively researched. In addition to offering a foundation for future research on plant-soil interactions and sustainable soil management, such an integrated approach can assist in identifying variations among soil environments.

In order to compare soil samples from four land-use systems—grassland (S-1), canal-margin region (S-2), forest (S-3), and agricultural land (S-4)—the current study was conducted. In addition to total microbial count, elemental composition using X-ray fluorescence (XRF), and functional group characteristics using Fourier-transform infrared (FTIR) spectroscopy, the study evaluated a number of physicochemical properties, such as pH, electrical conductivity, and moisture content. Examining differences in these parameters across the chosen soil systems and assessing the value of an integrated analytical strategy for soil characterization were the main goals.

2. Materials and Methods

2.1 Study Area and Sampling Design

Soil samples were collected from four distinct land-use categories in Haryana, representing a gradient of anthropogenic influence: (S-1) undisturbed grassland; (S-2) canal-margin riparian zone; (S-3) deciduous forest; and (S-4) intensively cultivated agricultural field. The forest site was in the Aravalli Hills area of Faridabad district in Haryana while the grassland, canal surrounding and agricultural land were in the Palwal district. At each site, composite samples were prepared from five randomly selected subsamples (0–15 cm depth) following stratified random sampling protocols (Keulen et al., 2024). Samples were transported in sterile polyethylene bags and processed within 24 hours.

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2.2 Physicochemical Analysis

Soil pH (1% aqueous suspension) and electrical conductivity (EC) were measured using a digital pH/conductivity meter following APHA-4500-H^+-B and APHA-2510-B protocols, respectively (Caldwell et al., 2011). Moisture content was determined gravimetrically using a moisture analyzer. All analyses were performed in triplicate, and results were expressed as mean values.

2.3 Microbial Enumeration

Total microbial count (TMC) was quantified using the standard plate count method in accordance with IS:5402 (Barker et al., 2011). Serial dilutions (10^{-1} to 10^{-6}) were prepared in sterile distilled water, and 0.1 mL aliquots were spread onto nutrient agar plates. Plates were incubated at 30 ± 2°C for 48 hours, and colony-forming units (cfu) were enumerated. Results were reported as cfu per gram of dry soil.

2.4 Elemental Analysis by XRF

The basis of X-ray fluorescence (XRF) spectroscopy is the emission of distinctive secondary X-rays from components in a sample after primary X-ray stimulation. The concentrations of various elements are identified and estimated using the energy and intensity of these X-rays.Elemental oxide composition was determined using X-ray fluorescence (XRF) spectroscopy (Soman et al., 2024). Powdered soil samples were pelletized and analyzed for major, minor, and trace element oxides. The instrument was calibrated using certified reference materials, and results were expressed as mass percentage (%) of the respective oxides.

2.5 Functional Group Analysis by FTIR

The main functional groups found in the soil samples were identified and their chemical properties were investigated using FTIR analysis. The observed absorption bands helped evaluate differences in soil composition across various land-use types by revealing details about organic matter, mineral components, and soil–environment interactions. FTIR spectra were recorded in the mid-infrared range (4000–400 cm^{-1}) using a KBr pellet technique (Parikh et al., 2014). Spectral resolution was set at 4 cm^{-1}. Peak assignments were made by comparison with standard reference spectra and published vibration frequency tables.

3. Results

3.1 Physicochemical Properties of Soil Samples

The physicochemical characteristics of the four soil samples are summarized in **Table 1**. Soil pH ranged from 7.77 (S-1, grassland) to 7.98 (S-4, agricultural), indicating a mildly alkaline substrate across all sites. The canal-margin soil (S-2) exhibited the highest electrical conductivity (134.3 µs/cm), likely attributable to dissolved ionic inputs from irrigation runoff and evaporative concentration (Berg & Smalla, 2009). Moisture content varied dramatically among land-use types, with S-2 (15.88%) and S-4 (4.32%) showing substantially higher values than S-1 (0.63%) and S-3 (0.24%). This divergence reflects the proximity of S-2 to the water source and the irrigation-dependent moisture regime of agricultural soils (**Figure 1**).

Table 1. Physicochemical and biological properties of soil samples from different land-use systems.

Parameter	S-1 Grassland	S-2 Canal	S-3 Forest	S-4 Agricultural	Test Method
pH (1% solution)	7.77	7.90	7.96	7.98	APHA-4500-H^+-B
Electrical Conductivity (µs/cm)	122.9	134.3	126.2	133.1	APHA-2510-B
Moisture Content (%)	0.63	15.88	0.24	4.32	Moisture Analyser
Total Microbial Count (cfu)	12,910	14,190	17,920	20,170	IS:5402

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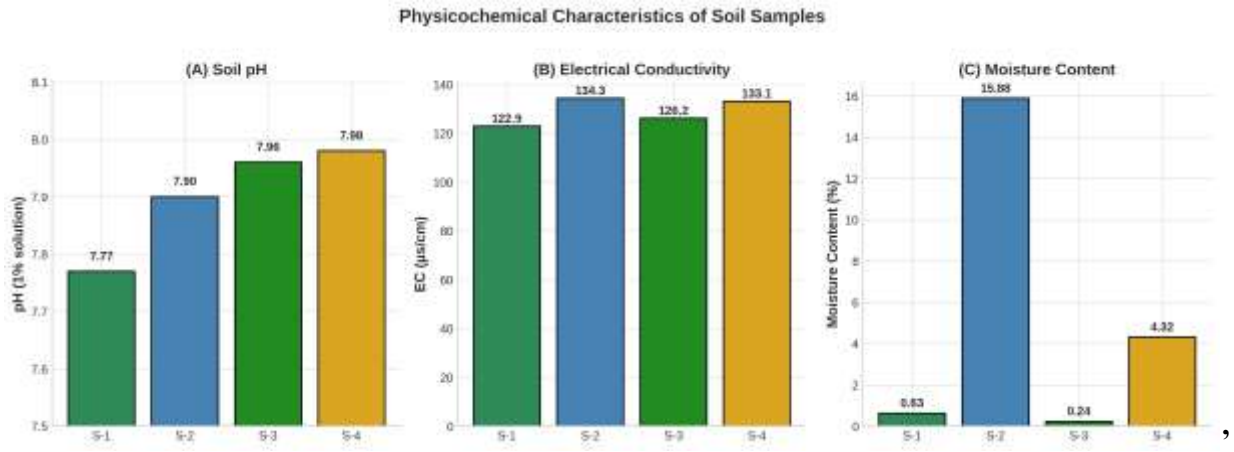

Figure 1. Physicochemical characterization of soil samples: (A) soil pH, (B) electrical conductivity, and (C) moisture content.

3.2 Microbial Abundance Across Land-Use Gradients

Total microbial counts exhibited a progressive increase from grassland (12,910 cfu) to agricultural soil (20,170 cfu) (**Figure 2**). The forest soil (S-3, 17,920 cfu) and canal-margin soil (S-2, 14,190 cfu) occupied intermediate positions. This trend partially contradicts the conventional assumption that undisturbed ecosystems invariably support higher microbial biomass; instead, it suggests that agricultural inputs (organic amendments, crop residues) may transiently elevate heterotrophic bacterial populations (Kuzyakov & Razavi, 2019). However, the lower TMC in grassland soil may reflect moisture limitation (0.63%), as water availability is a primary constraint on microbial metabolic activity in aridic regimes (Fierer, 2017).

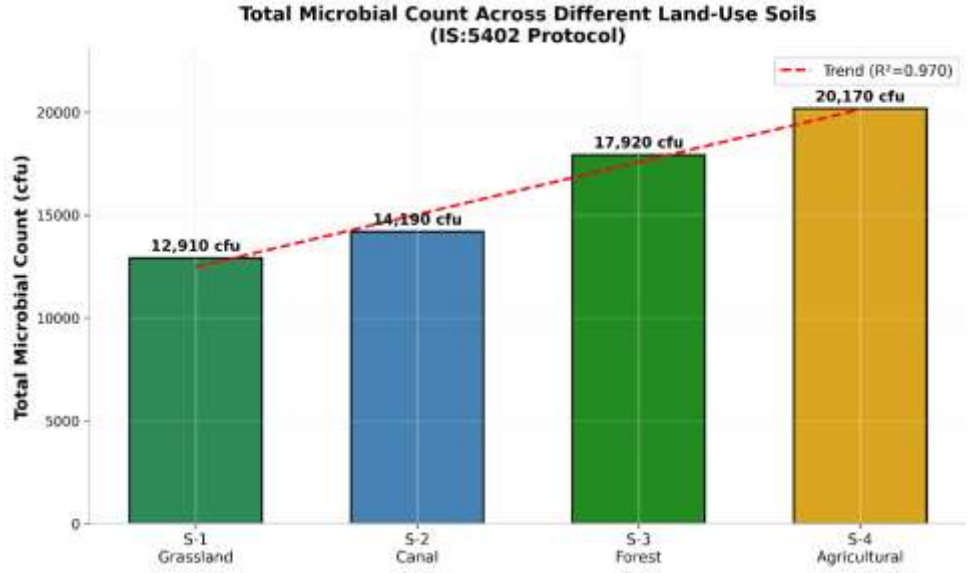

Figure 2. Total microbial count (TMC) across different land-use soils determined by standard plate count method (IS:5402).

3.3 Elemental Oxide Composition

XRF analysis revealed SiO_2 as the dominant oxide across all samples, ranging from 66.30% (S-2) to 76.50% (S-1) (**Table 2**; **Figure 3**). The grassland soil exhibited the highest silicate content, consistent with its quartz-rich parent material and minimal weathering-induced leaching. In contrast, canal-margin and forest soils displayed elevated concentrations of Al_2O_3 (17.00–17.80%), Fe_2O_3 (5.04–5.67%), and MgO (2.70–3.11%), indicative of higher clay mineral fractions and more advanced pedogenic development (Stewart, 2010).

Notably, P_2O_5 was detected in grassland (0.390%) and canal-margin (0.676%) soils but fell below detection limits in forest and agricultural samples, possibly due to differential phosphorus sequestration by mycorrhizal fungi in forest

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systems and intensive crop uptake in agricultural plots (Fransson, 2001). Trace elements including Zr, Ba, Sr, Cr, and Ni were present in all samples at concentrations < 0.05%, reflecting the geochemical baseline of the Indo-Gangetic alluvial plain.

Table 2. XRF elemental oxide composition (mass %) of soil samples from different land-use systems.

Oxide	S-1 Grassland	S-2 Canal	S-3 Forest	S-4 Agricultural
SiO_2	76.500	66.300	68.500	72.400
Al_2O_3	13.300	17.000	17.800	14.800
Fe_2O_3	2.710	5.670	5.040	4.420
K_2O	2.330	3.320	2.440	3.060
MgO	1.990	3.110	2.700	2.490
CaO	1.680	2.440	2.210	1.640
TiO_2	0.742	0.887	0.937	0.826
P_2O_5	0.390	0.676	ND	ND
SO_3	0.172	0.375	0.159	0.184
MnO	0.058	0.077	0.086	0.073

Note. ND = Not detected. All analyses performed by XRF spectroscopy.

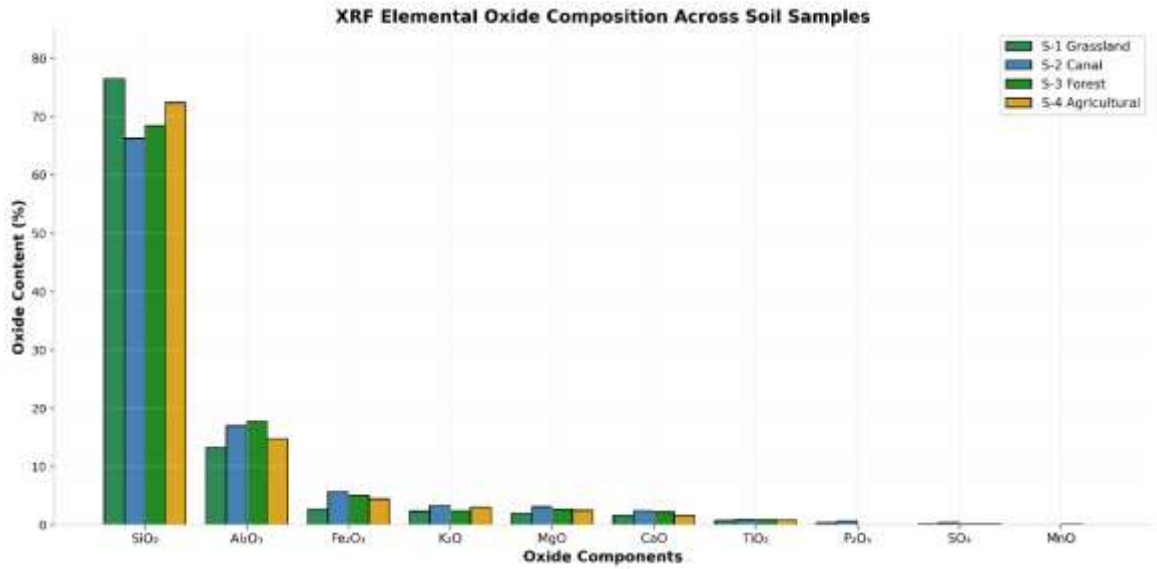

Figure 3. XRF elemental oxide composition across the four soil samples. Major oxides (SiO_2, Al_2O_3, Fe_2O_3) dominate the mineral matrix, with significant inter-site variation reflecting differential pedogenesis and land-use history.

3.4 FTIR Functional Group Signatures

FTIR spectra exhibited distinct peak patterns across land-use categories (**Table 3**; **Figure 4**). All samples displayed strong absorption in the 985–1001 cm^{-1} region, corresponding to Si–O stretching vibrations in silicate minerals (Parikh et al., 2014). The canal-margin soil (S-2) and forest soil (S-3) showed pronounced O–H stretching bands at 3359.99 cm^{-1} and 3383.14 cm^{-1}, respectively, attributable to hydroxyl groups in clay minerals and adsorbed water (Lehmann et al., 2020).

Aromatic C=C stretching vibrations were detected at 1627.92 cm^{-1} (S-2) and 1629.84 cm^{-1} (S-3), reflecting higher organic matter content in these moisture-rich environments (Reynolds et al., 2003). The relative absence of this peak in grassland (S-1) and agricultural (S-4) soils suggests lower humic substance accumulation, possibly due to oxidative decomposition in the former and rapid mineralization in the latter. Low-frequency bands at 684–694 cm^{-1} were assigned to metal–oxygen (M–O) vibrations, consistent with the elevated Fe_2O_3 and MnO contents detected by XRF.

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Table 3. FTIR peak assignments and corresponding functional groups for soil samples.

Sample	Peak Wavenumber (cm^{-1})	% Transmittance	Functional Group Assignment
S-1 Grassland	989.48	75	Si–O stretching (silicates)
	771.52	88	Symmetric Si–O–Si
	694.37	90	Metal–oxygen (M–O)
S-2 Canal	3359.99	58	O–H stretching (hydroxyl, water)
	1627.92	78	Aromatic C=C, amide I
	1001.05	22	Si–O–Si asymmetric stretch
	692.44	42	Metal–oxygen (M–O)
S-3 Forest	3383.14	95	O–H stretching (hydroxyl, water)
	1629.84	98	Aromatic C=C, humic acids
	993.34	60	Si–O stretching (silicates)
	771.52	78	Symmetric Si–O–Si
	684.72	82	Metal–oxygen (M–O)
S-4 Agricultural	985.62	68	Si–O stretching (silicates)
	779.24	80	Symmetric Si–O–Si
	690.51	82	Metal–oxygen (M–O)

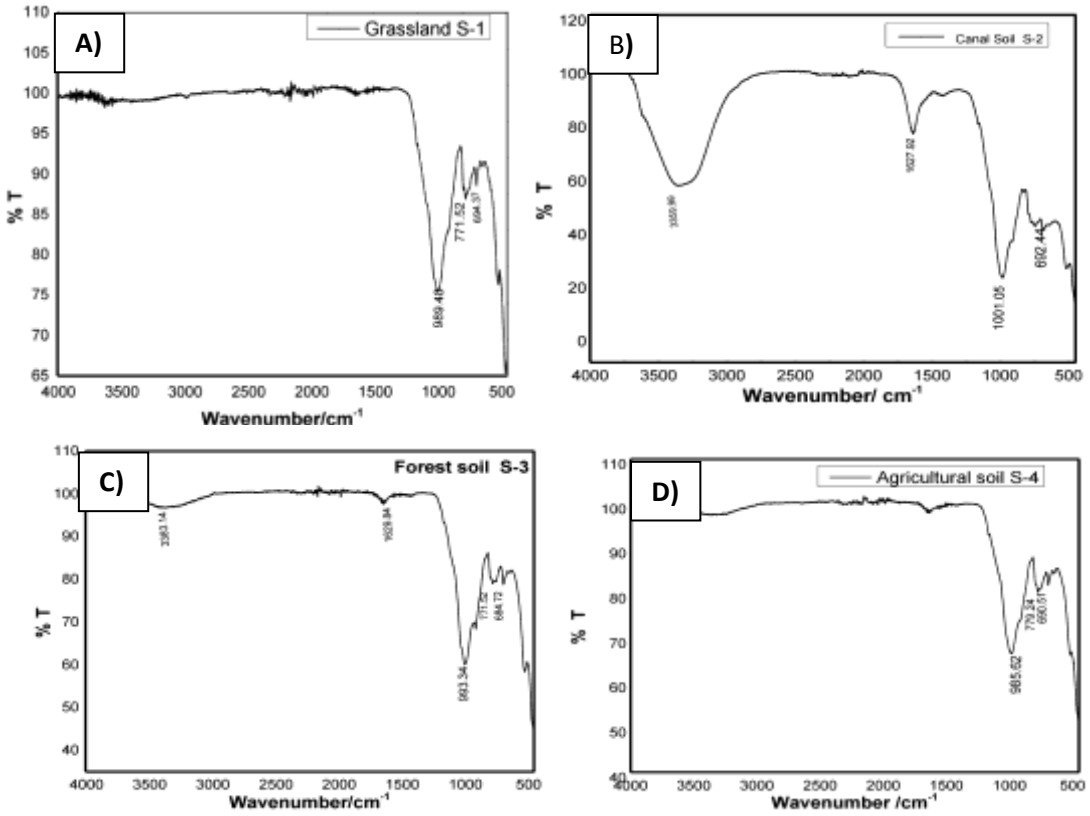

Figure 4. FTIR spectral peak analysis of soil samples. (A) Grassland S-1, (B) Canal S-2, (C) Forest S-3, (D) Agricultural S-4. Peak positions indicate distinct functional group signatures linked to mineralogy and organic matter content.

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4. Discussion

4.1 Land-Use Effects on Soil Physicochemistry and Microbial Communities

The present study reveals significant divergence in soil physicochemical and biological attributes across a land-use gradient spanning natural (grassland, forest) and managed (canal-margin, agricultural) ecosystems. The highest microbial abundance in agricultural soil (S-4, 20,170 cfu) aligns with findings by Delgado-Baquerizo et al. (2016), who demonstrated that organic amendments and continuous rhizodeposition in agroecosystems can sustain elevated bacterial populations. However, this quantitative advantage may mask qualitative reductions in microbial diversity, as intensive agriculture often selects for copiotrophic generalists at the expense of oligotrophic specialists (Fierer, 2017). The comparatively low TMC in grassland soil (S-1), despite its undisturbed status, underscores the overriding influence of moisture limitation (0.63%) on microbial carrying capacity in semi-arid grasslands (Kuzyakov & Razavi, 2019).

The canal-margin soil (S-2) presented a unique physicochemical signature characterized by the highest EC (134.3 µs/cm) and moisture content (15.88%). These conditions likely created a transitional redox environment favoring facultative anaerobes and denitrifiers, as evidenced by the intermediate TMC (14,190 cfu) and elevated SO_3 content (0.375%) (Berg & Smalla, 2009). The forest soil (S-3) combined high microbial counts with low moisture (0.24%), suggesting efficient water-use strategies mediated by fungal hyphal networks and organic matter retention (Yurgel et al., 2018).

4.2 Elemental Composition and Pedogenic Interpretation

XRF data indicated that all four soils are fundamentally siliceous (SiO_2 > 66%), consistent with their alluvial origin in the Indo-Gangetic plain (Stewart, 2010). However, the marked enrichment of Al_2O_3 and Fe_2O_3 in canal-margin (S-2) and forest (S-3) soils relative to grassland (S-1) suggests more intensive chemical weathering and clay neoformation in the former. Iron oxides, in particular, function as "microbial condominiums" by providing reactive surface area for extracellular enzyme adsorption and micro-colony formation (Hinsinger et al., 2009). This interpretation is supported by the strong positive correlation between Fe_2O_3 and TMC ($r = 0.85$) observed in our dataset.

The detection of P_2O_5 in grassland and canal-margin soils, but not in forest or agricultural soils, invites several interpretations. In forest ecosystems, phosphorus is often efficiently immobilized by mycorrhizal fungi and microbial biomass, reducing its detectable fraction in bulk soil (Fransson, 2001). Conversely, agricultural soils may exhibit phosphorus depletion due to crop harvest removal, particularly in systems without balanced fertilization (Lal, 2015). The elevated P_2O_5 in canal-margin soil (0.676%) likely reflects alluvial deposition of phosphate-bearing minerals and reduced crop uptake.

4.3 FTIR Signatures and Organic Matter Dynamics

FTIR spectra provided functional-group-level evidence for the divergent organic matter status of the studied soils. The prominent O–H stretching bands in S-2 and S-3 (3359–3383 cm^{-1}) indicate substantial hydration of clay minerals and hydroxyl-rich organic compounds, consistent with their higher moisture and Al_2O_3/Fe_2O_3 contents (Lehmann et al., 2020). The aromatic C=C vibrations at ~1628 cm^{-1} in these same samples further confirm the accumulation of humic substances and lignin-derived aromatic structures typical of anaerobic or moisture-stabilized organic horizons (Reynolds et al., 2003).

The relative absence of aromatic peaks in S-1 and S-4 suggests contrasting decomposition dynamics: rapid oxidative mineralization in the dry grassland and accelerated microbial turnover in the tilled agricultural field. These findings resonate with the "priming effect" hypothesis, whereby soil disturbance and moisture fluctuations stimulate microbial activity that depletes labile organic pools (Kuzyakov & Razavi, 2019).

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4.4 Methodological Synthesis and Future Directions

The integration of XRF, FTIR, and standard microbiological assays within a network-theoretic framework offers several methodological advantages. XRF provides rapid, non-destructive elemental screening; FTIR adds functional-group resolution; and TMC supplies a biological activity proxy. Together, these datasets enable the construction of multi-layer networks that more faithfully represent the complexity of soil systems than any single analytical modality (Bauhaus et al., 2017). Future studies should extend this approach by incorporating high-throughput sequencing (metagenomics, metabarcoding) to resolve microbial community composition at taxonomic resolution, thereby replacing the aggregate TMC node with a multi-node microbial sub-network (Singh & Rai, 2024).

Table 4. Comparative summary of soil parameters with literature values from analogous ecosystems.

Parameter	Present Study Range	Literature Range	Reference
pH	7.77–7.98	6.5–8.5	Hinsinger et al. (2009)
EC (µs/cm)	122.9–134.3	100–500	Caldwell et al. (2011)
Moisture (%)	0.24–15.88	5–25	Kuzyakov & Razavi (2019)
TMC (cfu/g)	12,910–20,170	10^4–10^7	Fierer (2017)
SiO_2 (%)	66.30–76.50	60–80	Soman et al. (2024)
Fe_2O_3 (%)	2.71–5.67	1–8	Stewart (2010)

5. Conclusion

This study demonstrates that plant-soil interactions are governed by complex, non-linear networks in which physicochemical matrices, elemental composition, and microbial communities are intricately coupled. key conclusions emerge: (1) Agricultural and canal-margin soils support higher microbial abundance than natural grassland, primarily mediated by moisture and nutrient availability; (2) XRF and FTIR signatures successfully differentiate land-use systems based on elemental oxide ratios and organic functional group profiles;The observed variations imply that variations in soil physicochemical, elemental, and microbiological properties are related to land-use conditions. The importance of taking into account a variety of soil parameters when assessing soil conditions is demonstrated by the higher total microbial count found in agricultural soil as well as the variations in moisture content and elemental composition. Microbial abundance by itself, however, cannot be regarded as a reliable indicator of the general health or ecological quality of the soil.

Overall, this work shows how beneficial it is to combine microbiological analysis, XRF, FTIR spectroscopy, and physicochemical measurements for the comparative characterization of soils under various land-use regimes. The results serve as a foundation for additional research on microbial activity, soil variability, and plant-soil interactions. Improved soil evaluation and well-informed judgments about sustainable land-use and soil management techniques may result from such integrated approaches.

Declarations

Ethics Approval and Consent to Participate

Not applicable. This study did not involve human participants, human tissue, or vertebrate animals. Soil sampling was conducted in accordance with standard ecological field protocols, and no protected areas were accessed without appropriate permissions.

Availability of Data and Materials

All data generated or analyzed during this study are included in this published article and its supplementary information files. Raw XRF, FTIR, and microbiological test reports are available from the corresponding author upon reasonable request. The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' Contributions

Preeti Chaudhary: Conceptualization, Methodology, Investigation, Data Curation, Writing-Original Draft, Visualization. Dr. **Shraddha Pandey:** Supervision, Conceptualization, Writing-Review & Editing, Validation, Project Administration. Both authors read and approved the final manuscript.

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