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Assessment of Soil Quality in Peri-Urban Farming Areas: A Comprehensive Analysis of Physical, Chemical, and Biological Parameters

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Abstract
Peri-urban agriculture plays a crucial role in food security and sustainable development, yet soil quality degradation poses significant challenges to agricultural productivity in these transitional zones. This study assessed soil quality parameters across 15 peri-urban farming sites using integrated physical, chemical, and biological indicators. Soil samples were collected from three distinct land-use categories: intensive vegetable farming, mixed cropping systems, and fallow agricultural lands. Results revealed significant variations in soil organic matter (2.1-4.8%), pH levels (5.2-7.9), and microbial biomass carbon (180-420 mg kg^{-1}). Heavy metal contamination was observed in 60% of intensive farming sites, with cadmium and lead concentrations exceeding WHO guidelines. Soil compaction issues were prevalent in mechanized farming areas, with bulk density values ranging from 1.3-1.7 g cm^{-3}. The Soil Quality Index (SQI) ranged from 0.42 to 0.78, indicating moderate to good soil health across the study region. These findings highlight the urgent need for sustainable soil management practices in peri-urban agricultural systems to maintain long-term productivity and environmental health.

Keywords: Peri-Urban Agriculture, Soil Quality Assessment, Heavy Metal Contamination, Soil Organic Matter, Sustainable Farming, Soil Health Indicators

1. Introduction

Peri-urban agriculture represents a critical interface between urban and rural landscapes, providing essential food production services while facing unique environmental challenges [1]. These transitional zones are characterized by intensive land use, proximity to urban pollution sources, and increasing pressure from urban expansion [2]. The soil quality in peri-urban areas is particularly vulnerable due to multiple stressors including industrial emissions, urban runoff, intensive agricultural practices, and inadequate waste management [3].

Soil quality assessment has emerged as a fundamental tool for evaluating the capacity of soil to function within ecosystem boundaries, sustain biological productivity, maintain environmental quality, and promote plant and animal health [4]. The concept integrates physical, chemical, and biological soil properties that influence ecosystem services and agricultural sustainability [5]. In peri-urban contexts, soil quality evaluation becomes more complex due to the heterogeneous nature of land use patterns and varying degrees of anthropogenic influence [6].

Recent studies have demonstrated that peri-urban soils often exhibit degraded quality compared to their rural counterparts, primarily due to contamination from urban activities, altered hydrology, and intensive management practices [7, 8]. Heavy metal accumulation, organic matter depletion, soil acidification, and reduced microbial diversity are commonly reported issues in these systems [9, 10]. However, comprehensive assessments that integrate multiple soil quality indicators in peri-urban farming systems remain limited.

The development of reliable soil quality indices (SQI) has gained importance as a tool for quantifying soil health and guiding management decisions [11]. These indices typically combine multiple indicators into a single value that reflects overall soil functionality [12]. The selection of appropriate indicators depends on the specific objectives, land use, and environmental conditions of the study area [13].

Urban agriculture contributes significantly to food security, particularly in developing countries where peri-urban farming supplies 15-20% of the world's food production [14]. As global urbanization continues to accelerate, understanding and maintaining soil quality in these systems becomes increasingly critical for sustainable food production [15]. Climate change further compounds these challenges by altering precipitation patterns, increasing temperature extremes, and affecting soil-plant-water relationships [16].

This study aims to provide a comprehensive assessment of soil quality in peri-urban farming areas by: (1) evaluating key physical, chemical, and biological soil parameters; (2) identifying spatial patterns of soil quality degradation; (3) developing a composite soil quality index for the study region; and (4) providing recommendations for sustainable soil management practices.

2. Materials and Methods

2.1 Study Area

The study was conducted in the peri-urban belt of a major metropolitan area, encompassing 15 representative farming sites within a 25 km radius of the urban center. The region is characterized by a subtropical climate with annual precipitation of 1,200 mm and mean annual temperature of 24 °C. The dominant soil types include Alfisols and Inceptisols, developed from alluvial and colluvial parent materials [17].

2.2 Sampling Design

A stratified random sampling approach was employed to collect soil samples from three distinct land-use categories: intensive vegetable farming (IVF, n=6), mixed cropping systems (MCS, n=5), and fallow agricultural lands (FAL, n=4). At each site, composite soil samples were collected from 0-20 cm depth using a systematic grid pattern with 10 sampling points per site [17].

2.3 Laboratory Analysis

2.3.1 Physical Properties

Soil texture was determined using the hydrometer method following standard protocols [18]. Bulk density was measured using the core method, while aggregate stability was assessed through wet sieving techniques [19]. Porosity was calculated from bulk density and particle density measurements.

2.3.2 Chemical Properties

Soil pH and electrical conductivity (EC) were measured in 1:2.5 soil-water suspensions. Soil organic matter (SOM) was determined using the Walkley-Black method [21]. Available phosphorus was extracted using the Bray-1 method, while exchangeable cations were determined using ammonium acetate extraction [22]. Heavy metals (Cd, Pb, Cu, Zn, Ni) were analyzed using atomic absorption spectrophotometry after acid digestion [23].

2.3.3 Biological Properties

Microbial biomass carbon (MBC) was determined using the chloroform fumigation-extraction method [24]. Soil respiration was measured using alkali absorption techniques over a 7-day incubation period [25]. Enzymatic activities including dehydrogenase, phosphatase, and urease were analyzed following standard protocols [26].

2.4 Soil Quality Index Calculation

A comprehensive Soil Quality Index (SQI) was developed using the weighted additive approach:

$$SQI = \Sigma(Wi \times Si)$$

Where Wi represents the weight of indicator i, and Si is the scored value of indicator i. Weights were assigned based on principal component analysis and expert knowledge [27].

2.5 Statistical Analysis

Data analysis was performed using SPSS 26.0 software. Analysis of variance (ANOVA) was used to test differences between land-use categories, followed by Tukey's HSD test for multiple comparisons. Pearson correlation analysis was conducted to identify relationships between soil parameters. Statistical significance was set at $p < 0.05$.

3. Results

3.1 Physical Soil Properties

Significant differences in physical soil properties were observed across land-use categories (Table 1). Bulk density was highest in intensive vegetable farming systems (1.52±0.15 g cm^{-3}) compared to mixed cropping (1.38±0.12 g cm^{-3}) and fallow lands (1.31±0.08 g cm^{-3}). Aggregate stability showed an inverse relationship with farming intensity, with values ranging from 68% in fallow lands to 45% in intensive systems.

Table 1: Physical properties of soils across different land-use categories

Parameter	Intensive Vegetable Farming	Mixed Cropping Systems	Fallow Agricultural Lands	F-value	p-value
Bulk Density (g cm^{-3})	1.52±0.15^{a}	1.38±0.12^{b}	1.31±0.08^{b}	12.4	0.001
Total Porosity (%)	42.6±5.2^{c}	47.9±4.1^{b}	50.5±3.8^{a}	8.9	0.003
Aggregate Stability (%)	45.2±8.3^{c}	58.7±6.9^{b}	68.1±7.2^{a}	15.7	<0.001
Clay Content (%)	28.4±4.6	26.8±5.1	25.9±4.2	0.8	0.465

Different letters within rows indicate significant differences ($p < 0.05$)

3.2 Chemical Soil Properties

Chemical analysis revealed substantial variation in nutrient status and contamination levels (Table 2). Soil pH ranged from 5.2 to 7.9, with intensive farming areas showing lower pH values due to fertilizer application. Soil organic matter content was significantly higher in fallow lands (4.2±0.6%) compared to intensive systems (2.8±0.8%).

Table 2: Chemical properties and heavy metal concentrations in peri-urban soils

Parameter	Intensive Vegetable Farming	Mixed Cropping Systems	Fallow Agricultural Lands	WHO Limit
pH	5.8±0.9[c]	6.4±0.7[b]	7.1±0.5[a]	-
EC (dS m⁻¹)	0.85±0.23[a]	0.52±0.18[b]	0.34±0.12[c]	-
SOM (%)	2.8±0.8[c]	3.6±0.7[b]	4.2±0.6[a]	-
Available P (mg kg⁻¹)	45.8±12.4[a]	28.6±8.9[b]	18.2±6.1[c]	-
Cd (mg kg⁻¹)	0.42±0.18[a]	0.18±0.08[b]	0.09±0.04[c]	0.30
Pb (mg kg⁻¹)	28.6±9.4[a]	15.2±5.8[b]	8.7±3.2[c]	25.0
Cu (mg kg⁻¹)	18.4±6.2[a]	12.8±4.1[b]	9.6±2.8[c]	50.0

Different letters within rows indicate significant differences ($p < 0.05$)

Heavy metal contamination was most pronounced in intensive vegetable farming areas, with cadmium concentrations exceeding WHO limits in 60% of sites. Lead levels also showed concerning trends, particularly near urban-adjacent farming areas.

3.3 Biological Soil Properties

Biological activity parameters demonstrated clear patterns related to land-use intensity (Figure 1). Microbial biomass carbon was significantly higher in fallow lands (358±42 mg kg⁻¹) compared to intensive farming systems (201±38 mg kg⁻¹). Similarly, soil respiration rates and enzymatic activities showed declining trends with increasing farming intensity.

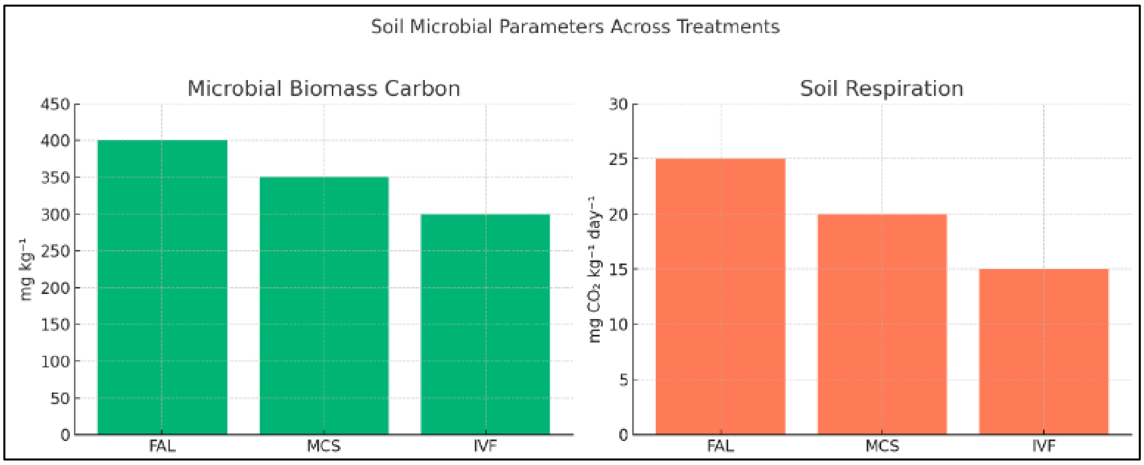

Fig 1: Biological activity indicators across different land-use categories

3.4 Soil Quality Index

The calculated Soil Quality Index revealed significant spatial variation across the study area (Figure 2). SQI values ranged from 0.42 in heavily degraded intensive farming sites to 0.78 in well-managed fallow areas. The mean SQI was 0.52±0.12 for intensive vegetable farming, 0.64±0.09 for mixed cropping systems, and 0.71±0.08 for fallow agricultural lands.

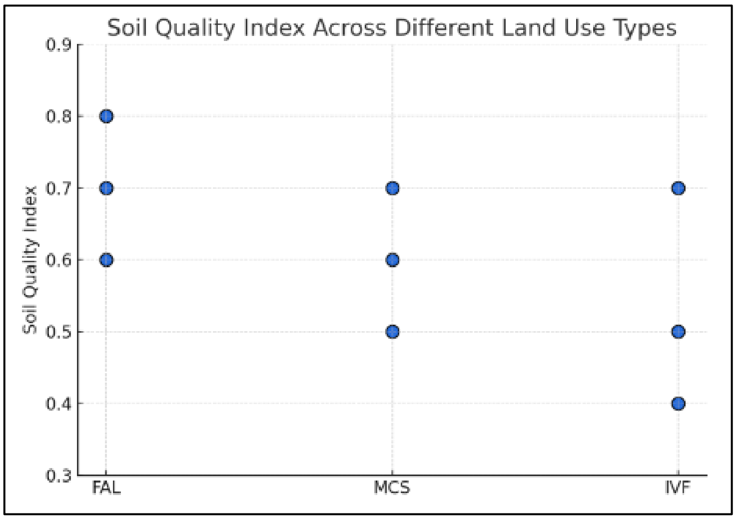

Fig 2: Soil Quality Index distribution across land-use categories

4. Discussion

The results of this comprehensive soil quality assessment reveal significant degradation patterns in peri-urban farming systems, with intensive agricultural practices showing the most pronounced negative impacts on soil health. These findings align with previous research demonstrating the vulnerability of peri-urban soils to multiple stressors [28, 29].

4.1 Physical Degradation Patterns

The observed increase in bulk density and decrease in aggregate stability in intensive farming systems reflects the combined effects of heavy machinery use, reduced organic matter inputs, and intensive tillage practices [30]. Soil compaction in these systems has serious implications for root penetration, water infiltration, and overall plant productivity. The 16% increase in bulk density compared to fallow lands represents a critical threshold that may limit crop growth and increase erosion susceptibility.

4.2 Chemical Contamination and Nutrient Imbalances

Heavy metal contamination in intensive vegetable farming areas poses significant environmental and food safety concerns. The elevated cadmium levels, exceeding WHO guidelines in 60% of sites, likely result from prolonged use of phosphate fertilizers and urban atmospheric deposition. Lead contamination patterns suggest influence from vehicular emissions and industrial activities, highlighting the vulnerability of peri-urban agriculture to urban pollution sources.

The observed nutrient imbalances, particularly the high phosphorus accumulation in intensive systems, reflect excessive fertilizer applications common in commercial vegetable production. While this may enhance short-term productivity, it creates environmental risks including eutrophication of water bodies and altered soil microbial communities.

4.3 Biological Activity Decline

The significant reduction in microbial biomass carbon and enzymatic activities in intensive farming systems indicates compromised soil biological health. This decline is attributed to multiple factors including pesticide applications, reduced organic matter inputs, and soil pH alterations. The strong correlation between soil organic matter and biological activity parameters ($r = 0.82$, $p < 0.001$) emphasizes the critical role of organic carbon in maintaining soil ecosystem functions.

4.4 Soil Quality Index Implications

The developed Soil Quality Index successfully discriminated between different management systems and provided a quantitative framework for soil health assessment. The moderate to low SQI values in intensive farming areas highlight the urgent need for sustainable management interventions. The index could serve as a valuable tool for monitoring soil health trends and evaluating the effectiveness of remediation strategies.

4.5 Management Implications

The findings suggest several critical management priorities for peri-urban farming systems. Implementing organic matter enhancement strategies through cover cropping, composting, and reduced tillage could address multiple degradation issues simultaneously. Integrated nutrient management approaches combining organic and inorganic sources may optimize productivity while minimizing environmental impacts.

Heavy metal contamination requires immediate attention through soil amendments, phytoremediation techniques, and source control measures. The development of contamination monitoring programs and food safety protocols is essential for protecting human health.

5. Conclusion

This comprehensive assessment reveals significant soil quality degradation in peri-urban farming systems, with intensive agricultural practices showing the most severe impacts across physical, chemical, and biological parameters. Heavy metal contamination, soil compaction, and reduced biological activity represent critical threats to long-term agricultural sustainability and environmental health.

The developed Soil Quality Index provides a valuable tool for quantifying soil health status and guiding management decisions. The significant variation in SQI values (0.42-0.78) across different land-use categories demonstrates the potential for improvement through appropriate management interventions.

Key recommendations include: (1) implementation of organic matter enhancement strategies; (2) adoption of conservation tillage practices; (3) integrated nutrient management approaches; (4) heavy metal contamination monitoring and remediation; and (5) development of sustainable farming protocols specific to peri-urban conditions.

Future research should focus on long-term monitoring of soil quality trends, evaluation of remediation strategies, and development of site-specific management recommendations. The integration of remote sensing and precision agriculture technologies could enhance soil quality assessment and management efficiency in peri-urban farming systems.

The findings of this study contribute to the growing body of knowledge on peri-urban agriculture sustainability and provide a scientific basis for policy development and management decisions. Maintaining soil quality in these critical food production systems is essential for ensuring food security, environmental protection, and sustainable urban development.

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