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Residue Biochemical Identity Regulates Early Soil Fertility Recovery in Semi-Arid Agroecosystems of Erbil, Kurdistan Region, Iraq

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Abstract

Soil productivity in semi-arid agroecosystems is constrained by prolonged organic matter depletion and nutrient limitation, yet residue-quality–driven fertility pathways remain poorly resolved under field conditions. The objective of this study was to evaluate the effect of different plant residue types on soil fertility and nutrient dynamics in a semi-arid agroecosystem in Erbil, Kurdistan Region, Iraq. We evaluated nine biochemically distinct plant residues (fruit-, woody-, and mixed-derived) applied at 2% (w/w) in a field experiment and quantified short-term shifts in soil physicochemical properties over 60 days. Residue incorporation significantly enhanced soil fertility compared to the control ($p < 0.05$), with responses strongly influenced by residue biochemical quality. Fruit and mixed residues, particularly *Vitis vinifera* and *Punica granatum*, increased soil organic carbon (2.10%), total nitrogen (0.19%), available phosphorus (27%), micronutrient availability, and soil moisture, while slightly reducing pH (6.95–6.70), improving nutrient solubility. Principal Component Analysis explained more than 90% of total variance, indicating a strong residue-quality fertility gradient. These findings demonstrate that residue biochemical characteristics play a key role in regulating early soil fertility processes and provide a practical strategy for improving soil quality in semi-arid environments.

1. Introduction

The degradation of soil fertility is among the most serious constraints on sustainable agricultural productivity in semi-arid areas, as limited rainfall, high evapotranspiration, and inherently low soil organic matter limit nutrient availability and biological activity [1]. These challenges are further intensified by the growing impacts of climate change and environmental pollution, which exacerbate soil degradation, disrupt nutrient cycling, and threaten long-term agricultural sustainability in dryland regions [2-5].

Continuous and intensive cultivation, which depend on mineral fertilizers, also exacerbate these limitations by accelerating the loss of organic carbon and impairing soil structure [6]. In semi-arid environments in the Kurdistan Region of Iraq, it is necessary to regenerate soil fertility using inexpensive, locally accessible organic resources to maintain agricultural production and ecosystem stability [7-9]. Plant residues are essential organic inputs of organic input that influences soil fertility through decomposition, nutrient release, and regulation of soil physicochemical conditions. Nutrient dynamics in agroecosystems are also influenced by environmental and seasonal variability, which can significantly affect nutrient availability and chemical properties [10].

The quality of the residues differs significantly across plant species, especially the carbon-to-nitrogen ratio, lignin, and labile organic substances, which control decomposition rates, and nutrient mineralization [11]. Fruit residues usually decompose more rapidly and release nutrients effectively, whereas woody residues decompose more slowly, thereby reducing the immediate gains in fertility. The impact of residue identity on soil fertility also needs to be comprehended to maximize the use of organic residue in dryland agroecosystems [12]. Although there has been extensive study of organic amendments, significant gaps in the knowledge base remain regarding the comparative impacts of residues from various plant species under practical field conditions [12].

Previous research has tended to focus on laboratory cultures or single-residue therapies, providing inadequate information about the functionality of different types of residues in the remnants of natural environmental variability [13]. In addition, the integrated soil fertility indices, in conjunction with multivariate models, to assess residue-based fertility gradients in semi-arid field systems have not been adequately studied [14]. Therefore, the objectives of this study were to: (i) evaluate the effects of different plant residue types on soil physicochemical properties, macronutrients, and micronutrients; (ii) assess soil fertility using integrated indices; and (iii) identify fertility gradients among residue treatments using multivariate analysis in a semi-arid agroecosystem in Erbil, Kurdistan Region, Iraq. The originality of the paper lies in the area-based, comparative analysis of various types of plant residue under the same conditions, and in the combined analytical system that will clarify the processes of soil fertility regulation mediated by residues in semi-arid systems.

2. Materials and Methods

2.1. Study Area

The field experiment was carried out on agricultural land in the capital of the Kurdistan Region, Erbil City, in Iraq (35°30′-37°15′ N, 43°22′-45°05′ E; 14,818 km²). The region's climate is semi-arid and continental, with hot, dry summers and cool, moderately wet winters. The annual average temperature is 22.5 ^{o}C and the average annual rainfall is 420mm, which falls mostly during November to April. Dryland agroecosystems have sandy loam soils that are slightly alkaline (pH 7.4) and low in organic carbon and micronutrients [15, 16]. The location could be considered representative of local natural agricultural conditions, allowing for realistic residue-soil interactions. Figure (1) shows the map of the geographical location of Erbil City.

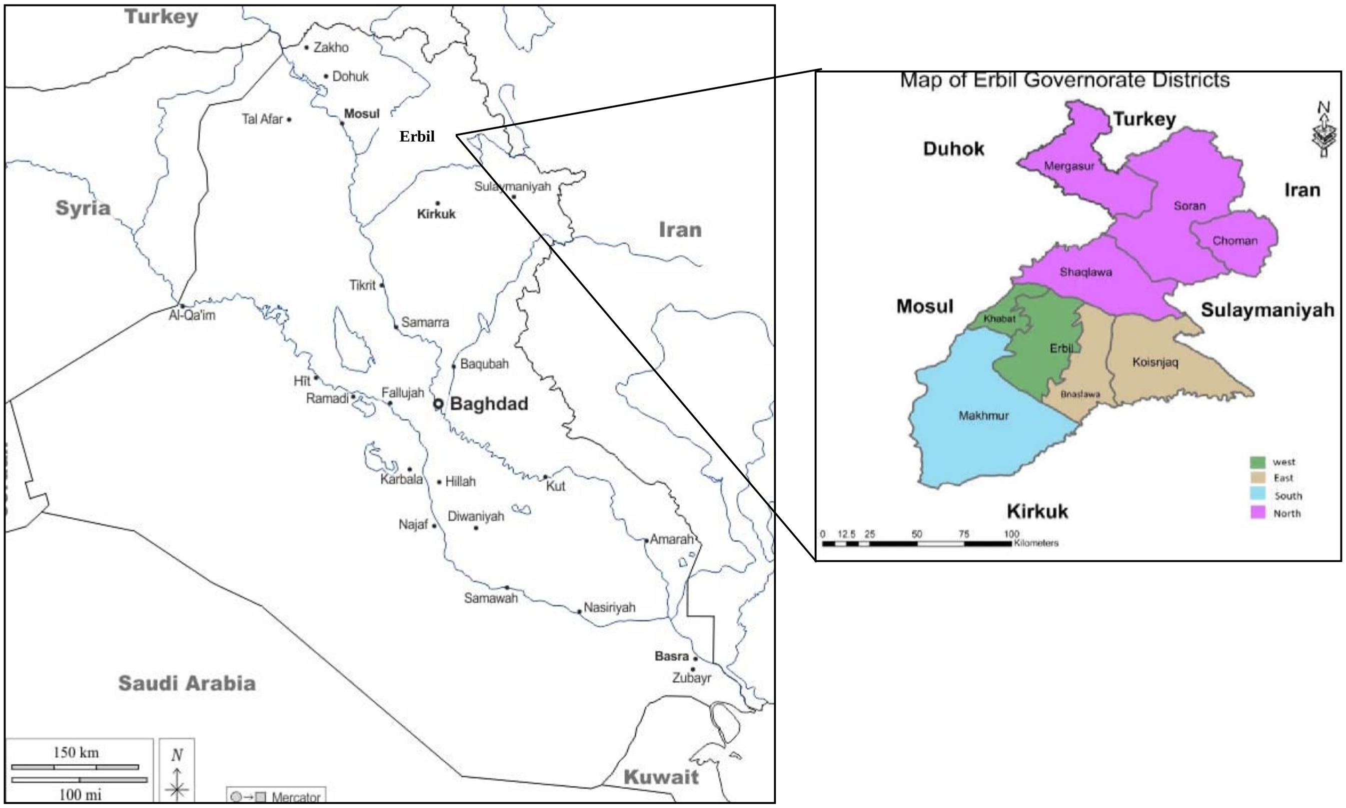

Figure (1): Map of Iraq showing the geographical location of Erbil City.

2.2. Experimental Design and Soil Description

The experiment was conducted using a completely randomized design (CRD) with three replications. Although randomized complete block design (RCBD) is generally preferred for field experiments, CRD was selected due to the relatively homogeneous soil conditions across the study area. Nine plant residue treatments and one control were evaluated. Nine plant residues were used: Pomegranate (*Punica granatum*), Pine (*Pinus* spp.), Orange (*Citrus sinensis*), Olive (*Olea europaea*), Grape (*Vitis virginia*), Fig (*Ficus carica*), Apple (*Malus domestica*), Date (*Phoenix dactylifera*) and a mixed mixture (all residues in equal proportions), and an unamended control. All treatments were applied in 1 m × 1 m plots. The residues were added to the top 20 cm of the soil at a rate of 2% (w/w, dry weight). Prior to the experiment, composite soil samples (0-20 cm) were collected to characterize the soil at baseline. It was sandy loam (Typic Ustifluvent), containing sand 68, silt 20, clay 12, pH 7.4, electrical conductivity (EC) 0.45 dS.m^{-1}, organic carbon 1.20%, total nitrogen 0.09, available phosphorus 15.2 mg.kg $^{-1}$ and available potassium 134.2 mg.kg^{-1}. Micronutrient levels (Fe, Mn, Zn) were below crop sufficiency.

2.3. Residue Collection and Preparation

Fresh plant residues were collected from farms and gardens near Erbil, including leaves, small twigs (<5 mm), and fruit-processing residues (such as peels and pomace, where applicable). The types, classification, and composition of plant residues used in this study are summarized in Table (1), highlighting differences in residue origin and biochemical characteristics. Not all plant species produced identical residue types; therefore, residue composition varied depending on plant characteristics (e.g., date palm residues included fronds rather than leaves). All residues were washed, air-dried at 35°C for 72 hours, oven-dried at 60°C for 48 hours, and ground to pass through a 1 mm mesh. The mixed-residue treatment consisted of equal proportions of all residue types.

Table (1): Classification and composition of plant residues used in the experiment.

Plant	Scientific Name	Residue Type	Components
Grape	*Vitis vinifera*	Fruit residue	Peels, Pomace
Pomegranate	*Punica granatum*	Fruit residue	Peels, Pulp Residues
Orange	*Citrus sinensis*	Fruit residue	Peels, Pulp Residues
Apple	*Malus domestica*	Fruit residue	Peels, Pulp Residues
Fig	*Ficus carica*	Fruit residue	Peels, Pulp Residues
Olive	*Olea europaea*	Mixed	Leaves + Small Twigs
Date	*Phoenix dactylifera*	Vegetative	Fronds
Pine	*Pinus* spp.	Woody	Needles + Small Twigs
Mixed residues		Mixed	Equal Combination of All Above Residues

2.4. Soil Sampling and Analysis

Samples of soil (0-20 cm) were taken in every plot (soil samples) after 60 days with a stainless-steel core sampler. Composite three cores/plot were dried (air) and sieved (2 mm). pH and EC: Measured in 1:2.5 soil to water suspensions (HANNA Instruments HI 5521). Organic Carbon (OC): Walkley-Black dichromate oxidation procedure. Total Nitrogen (TN): Kjeldahl digestion and distillation (VELP Scientifica UDK 152). Phosphorus (P): Olsen bicarbonate extraction; at 880 nm spectrophotometry (Thermo Scientific Evolution 350 UV 6850 UV Vis). Micronutrients (Fe, Mn, Zn): DTPA; extraction; atomic absorption spectrophotometer (PerkinElmer Analyst 400). Soil Moisture: Gravimetric method, dried in an oven at 105 ºC, 24 h. Each analysis was done thrice. The results are presented as mean and standard deviation (SD).

2.5. Statistical and Multivariate Analysis

The residual effects on soil properties were evaluated using one-way ANOVA. Tukey, HSD at $p < 0.05$ was used to make mean comparisons. The Shapiro-Wilk and Levene tests were used to assess normality and homogeneity. Pearson correlations were used to assess the relationships among parameters. Multivariate analyses included Principal Component Analysis (PCA) Using Standardized data (Z-scores), with components eliminated if their eigenvalues were less than 1. Hierarchical Cluster Analysis (HCA): Ward linkage, Euclidean distance. Statistical procedures were done with SPSS version 27.0; multivariate analysis was done with R version 4.2.2 (FactoMineR, ggplot2).

2.6. Calculation of Soil Fertility and Quality Indices

Soil fertility improvement was measured using several integrated indices according to standard procedures after applying various residues [17, 18].All parameters were normalized (01) and then aggregated. They were the Soil Fertility Index (SFI-E), Carbon Management Index (CMI), Micronutrient Enrichment Index (MEI), Soil Moisture Retention Index (SMRI), Nutrient Availability Index (NAI), Soil Organic Matter Enhancement Index (SOMEI), Nutrient Enrichment Index (NEI), and Integrated Fertility Index (IFI). The increase in the index levels implies better soil fertility and quality.

2.6.1. Soil Fertility Index (SFI)

This index integrates the main fertility parameters: organic carbon (OC), total nitrogen (TN), and available phosphorus (P)

$$\mathbf{SFI - E = \sum(Wi \times Xi)} \qquad \mathbf{(1)}$$

Where: Wi is the weighting factor derived from principal component loadings, and Xi is the normalized value of each soil property. Higher SFI-E values indicate greater overall improvement in soil fertility.

2.6.2. Carbon Management Index (CMI)

The Carbon Management Index evaluates the change in soil organic carbon quality and quantity relative to the control:

$$\mathbf{CMI} = \frac{\mathbf{SOC\ tret}}{\mathbf{SOC\ ctrl}} \times \mathbf{100} \qquad \textbf{(2)}$$

Where: OC_{treat} and OC_{ctrl} are the organic carbon contents in the treated and control soils, respectively. Values greater than 100 reflect carbon enrichment due to residue incorporation.

2.6.3. Micronutrient Enrichment Index (MEI)

This index quantifies the improvement in micronutrient status

$$\mathbf{MEI} = \frac{\frac{\mathbf{Fe\ tret}}{\mathbf{Fe\ ctrl}} + \frac{\mathbf{Mn\ tret}}{\mathbf{Mn\ ctrl}} + \frac{\mathbf{Zn\ tret}}{\mathbf{Zn\ ctrl}}}{\mathbf{3}} \qquad \textbf{(3)}$$

Fe treat, Mn treat, Zn treat: Micronutrient concentrations under each treatment. Fe Ctrl, Mn Ctrl, Zn Ctrl: Corresponding values in the control soil. MEI > 1 indicates micronutrient enrichment; MEI < 1 indicates depletion.

2.6.4. Soil Moisture Retention Index (SMRI)

Measures the relative improvement in soil moisture content.

$$\mathbf{SMRI} = \frac{\mathbf{M\ tret}}{\mathbf{M\ ctrl}} \times \mathbf{100} \qquad \textbf{(4)}$$

Where: MC treat and MC control denote the soil moisture contents (%) in the treated and control samples. Higher SMRI values indicate greater water retention capacity due to residue addition.

2.6.5. Nutrient Availability Index (NAI)

Represents the overall improvement in soil nutrient availability combining macro- and micronutrients.

$$\mathbf{NAI} = \frac{\frac{\mathbf{Fe\ tret}}{\mathbf{Fe\ ctrl}} + \frac{\mathbf{Mn\ tret}}{\mathbf{Mn\ ctrl}} + \frac{\mathbf{Zn\ tret}}{\mathbf{Zn\ ctrl}}}{\mathbf{4}} \qquad \textbf{(5)}$$

Interpretation: NAI > 1 means improved nutrient availability compared to the control.

2.6.6. Soil Organic Matter Enhancement Index (SOMEI)

Quantifies the relative increase in soil organic carbon due to treatments.

$$\mathbf{SOMEI} = \frac{\mathbf{OC\ tret} - \mathbf{OC\ ctrl}}{\mathbf{OC\ ctrl}} \times \mathbf{100} \qquad \textbf{(6)}$$

Interpretation: Higher SOMEI values indicate stronger buildup of organic matter.

2.6.7. Nutrient Enrichment Index (NEI)

The NEI summarizes the proportional enrichment of major nutrients:

$$\mathbf{NEI} = \frac{\mathbf{1}}{\mathbf{n}}\sum\left(\frac{\mathbf{P\ tret}}{\mathbf{P\ ctrl}} + \frac{\mathbf{N\ tret}}{\mathbf{N\ ctrl}} + \frac{\mathbf{OC\ tret}}{\mathbf{OC\ ctrl}}\right) \qquad \textbf{(7)}$$

Where: n is the number of nutrients considered. Values > 1 indicate nutrient enhancement relative to the control.

2.6.8. Integrated Fertility Index (IFI)

The IFI integrates all fertility indicators (macro- and micronutrients) using a weighted aggregation approach:

$$\mathbf{IFI} = \frac{\sum \mathrm{Wi} \times \mathrm{Xi}}{\sum \mathrm{Wi}} \qquad (8)$$

Where: Wi represents the weighting factor of each parameter obtained from PCA loadings, and Xi represents the normalized value. A higher IFI indicates superior soil fertility performance.

2.7. Quality Assurance and Control

Analytical accuracy and reproducibility were ensured using strict quality assurance and control (QA/QC) procedures. All the reagents were of analytical grade (Merck, ≥99.9% purity). Glassware used in the laboratory was washed with 10% HNO_3 acid and deionized water. Instrument calibration was performed daily with certified standards, yielding a correlation coefficient (R2) greater than 0.995. In every 10 determinations, duplicate and blank samples were included, and the coefficient of variation (CV percentage) was less than 5%. The analyses were reliable with recovery rates of 95-103 of the measured elements.

3. Results

3.1. Soil Physicochemical Properties under Residue Amendments

The descriptive statistics in Table (2) indicate moderate variability in most soil properties, with higher coefficients of variation observed for total nitrogen (21.4%), available phosphorus (20.4%), and electrical conductivity (20%), reflecting the influence of residue treatments on nutrient dynamics. In contrast, soil pH showed low variability (CV = 3.2%), indicating relative stability across treatments. The observed ranges of organic carbon and micronutrients further confirm the positive effect of residue incorporation on soil fertility. Figures (2 & 3) show significant differences in soil properties after 60 days of field incubation. Significant increases (p=0.05) in organic carbon (OC), total nitrogen (TN), available phosphorus (P), soil moisture, electrical conductivity (EC), and micronutrients (FE, MN, ZN) were observed in all the residue-amended plots relative to the unamended control. The highest organic carbon (2.10%) was observed in the mixed-residue treatment, followed by grape (2.05%) and pomegranate (1.95%), as compared to 1.20% in the control. Total nitrogen increased from 0.09% in the control to 0.19% under mixed residue treatment. The available phosphorous increased by 78%, from 15.2 to 27.0 $mg.kg^{-1}$. The soil moisture levels were 13.0-16.5% in treatments compared to 12% in the control. In all the residue plots, soil pH was slightly reduced (6.70–6.95), indicating mild acidity induced by decomposing organic matter. EC rose to 0.78 $dS.m^{-1}$ (mixed residues), indicating better ionic strength and solubility of nutrients. In mixed residues, micronutrients were highly increased, containing maxima of 38.5 $mg.kg^{-1}$ Fe, 5.9 $mg.kg^{-1}$ Mn, and 2.3 $mg.kg^{-1}$ for Zn (Figures 2 & 3). In general, mixed residues had the best results in terms of soil quality, followed by grape, pomegranate and olive residues.

Table (2): Descriptive statistics of soil physicochemical properties under different plant residue treatments. Values represent mean ± SD (n = 3); CV: coefficient of variation (%).

Parameter	Mean	Std. Dev.	Min	Max	Coefficient of Variation (%)
Soil Organic C (%)	1.72	0.33	1.2	2.1	19.2
Total N (%)	0.14	0.03	0.09	0.19	21.4
Available P ($mg.kg^{-1}$)	20.1	4.1	15.2	27	20.4
Soil moisture (%)	14.2	1.4	12	16.5	9.9
pH	6.95	0.22	6.7	7.4	3.2
EC ($dS.m^{-1}$)	0.6	0.12	0.45	0.78	20
Fe ($mg.kg^{-1}$)	30.1	5.6	22	38.5	18.6
Mn ($mg.kg^{-1}$)	4.7	0.7	3.8	5.9	14.9
Zn ($mg.kg^{-1}$)	1.7	0.4	1.2	2.3	23.5

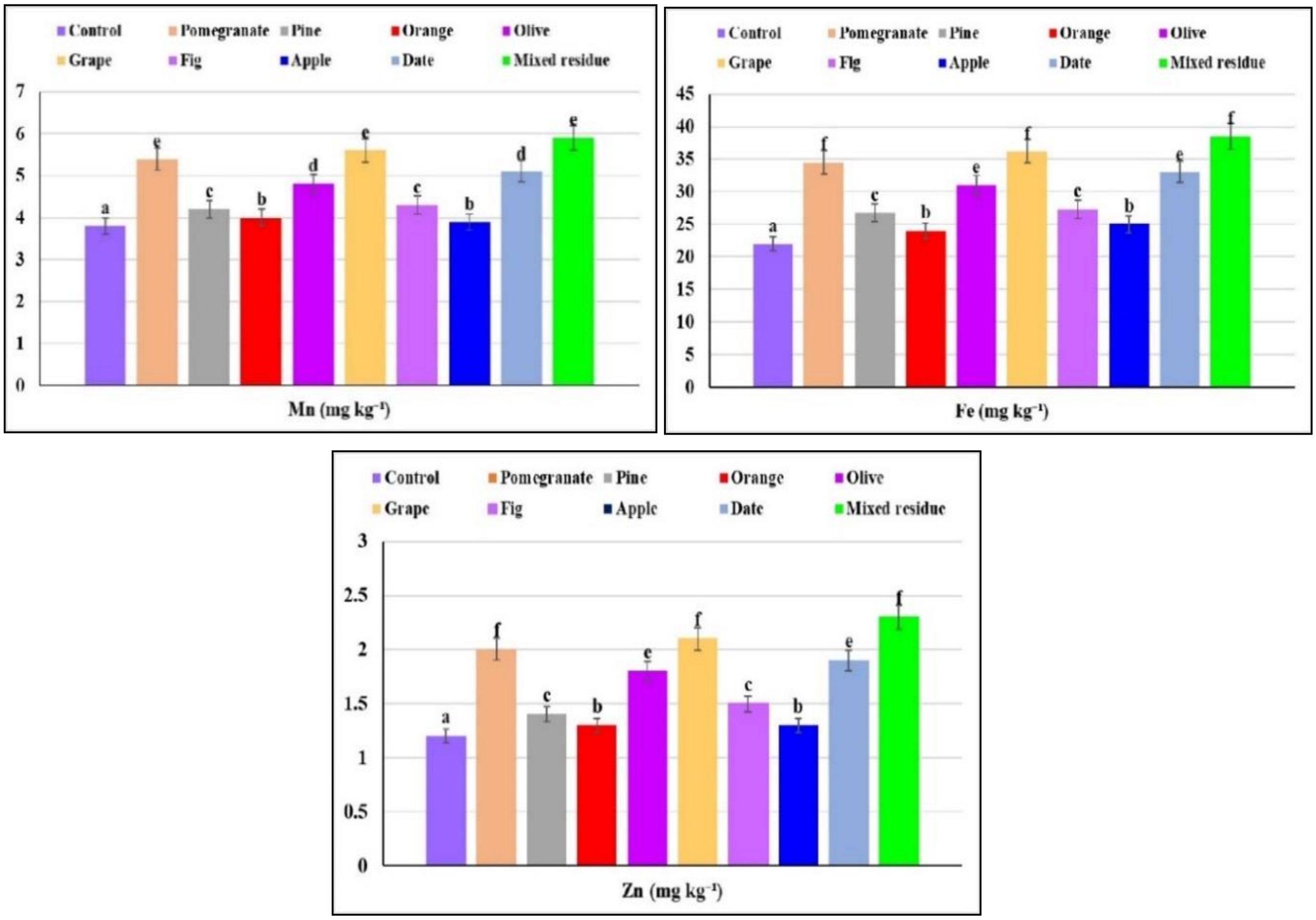

Figure (2): Effects of different plant residue amendments on soil Manganese, Ferrous and Zinc content after 60 days of incubation. Data are mean ± SD (n = 3). Letters indicate significant differences at $p < 0.05$.

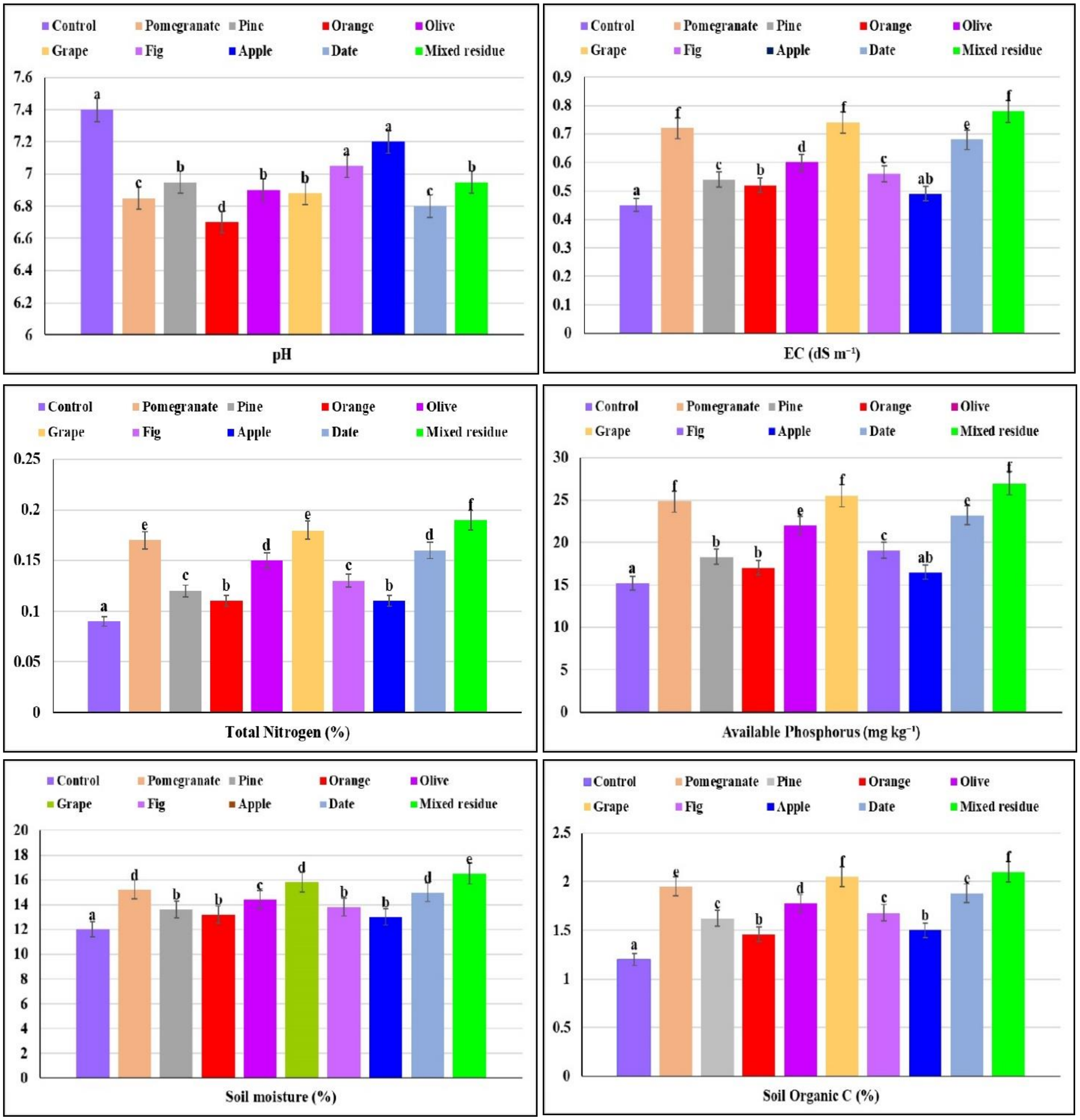

Figure (3): Effects of different plant residue amendments on soil physicochemical properties after 60 days of incubation. Data are mean ± SD (n = 3), letters indicate significant differences at $p < 0.05$.

3.2. Correlation Analysis

According to the Pearson correlation analysis (Table 3), the positive correlation among most soil parameters is strong. OC had high correlation with TN (r = 0.99), available P (r = 0.97), moisture (r = 0.99), EC (r = 0.97), and micronutrients (Fe: r = 0.98, Mn: r = 0.96, Zn: r = 0.96). OC showed a negative correlation with pH (r = -0.58), indicating that increased organic matter weakly acidifies the soil. These correlations show that residue amendments improve nutrient availability, moisture and fertility at the same time.

Table (3): Pearson correlation matrix among soil physicochemical parameters.

Variables	OC	TN	Avail P	Moisture	pH	EC	Fe	Mn	Zn
OC	1	0.99**	0.97**	0.99**	−0.58*	0.97**	0.98**	0.96**	0.96**
TN		1	1.00**	0.99**	−0.53*	0.99**	1.00**	0.99**	0.99**
Avail P			1	0.99**	−0.52*	0.99**	1.00**	1.00**	1.00**
Moisture				1	−0.56*	0.99**	0.99**	0.98**	0.98**
pH (water)					1	−0.54*	−0.48*	−0.48*	−0.47*
EC (dS.m^{-1})						1	0.99**	0.99**	0.98**
Fe (mg.kg^{-1})							1	0.99**	0.99**
Mn (mg.kg^{-1})								1	1.00**
Zn (mg.kg^{-1})									1

Note: ** and * indicate significance at $p < 0.01$ and $p < 0.05$, respectively.

3.3. Soil Fertility Indices under Different Plant Residue Amendments

The combined soil quality indices indicated strong odds of improved soil fertility, enhanced nutrient levels, and increased moisture retention after applying organic residues to the fields (Table 4 and Figure 4). The analysis of the Carbon Management Index (CMI) showed a significant improvement in soil organic carbon processes, with results ranging from 122% (orange) to 175% (mixed residue). Similarly, the Micronutrient Enrichment Index (MEI) rose from 1.06 (apple) to 1.73 (mixed residue), indicating notable enrichment of Fe, Mn, and Zn. The Soil Moisture Retention Index (SMRI) ranged from 108.3 to 137.5, indicating enhanced water-holding capacity across all treatments, with the highest value observed in the mixed residue plot. The Nutrient Availability Index (NAI) ranged from 1.07 to 1.74, indicating greater availability of macro- and micronutrients. The Soil Organic Matter Enhancement Index (SOMEI) increased to a maximum of 75% in the mixed treatment, and then grape (70.8) and pomegranate (62.5). Both the Soil Fertility Index (SFI-E) and the Integrated Fertility Index (IFI) established that the mixed and fruit-based residues exhibited the best fertility performance with the least improvement being recorded with the apple and orange residues. The Soil Quality Index (SQI) also identified the following rankings of the treatments: Mixed > Grape > Pomegranate > Date > Olive > Fig > Pine > Orange > Apple > Control (Table 4).

Table (4): Integrated Fertility Index (IFI) and Soil Quality Index (SQI) of soils amended with different plant residues.

Plant Residue	Nutrient Enrichment Index (NEI)	Integrated Fertility Index (IFI)	Soil Quality Index (SQI)
Pomegranate	1.51	0.782	0.607
Pine	1.183	0.282	−0.366
Orange	1.105	0.158	−0.485
Olive	1.359	0.565	0.211
Grape	1.572	0.876	0.801
Fig	1.23	0.349	−0.293
Apple	1.105	0.161	−0.737
Date	1.442	0.676	0.452
Mixed residue	1.656	1	1.018
Control	N/A	N/A	−1.207

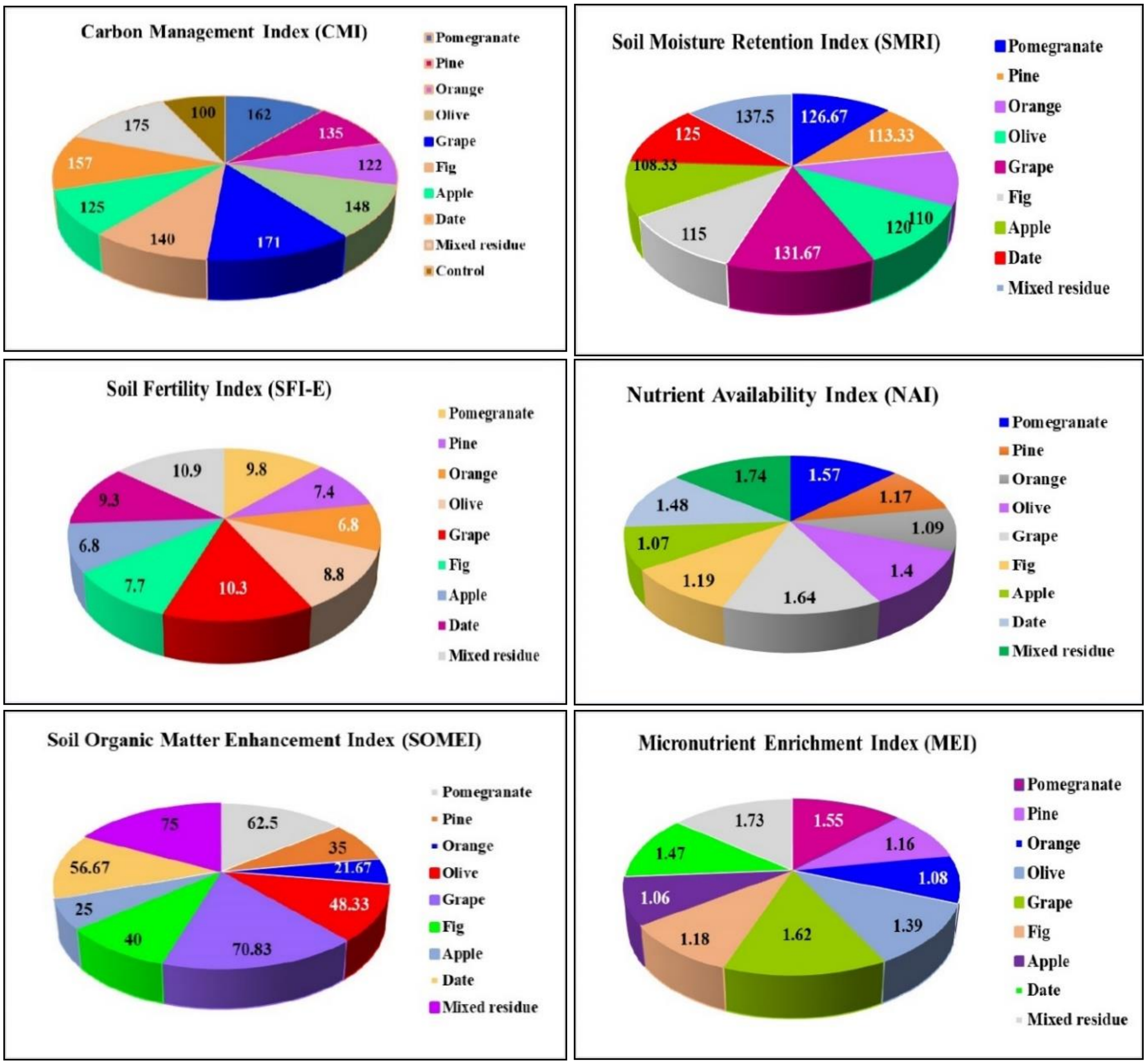

Figure (4): Soil fertility and quality indices (CMI, MEI, SMRI, NAI, SOMEI, SFI-E) of soils amended with different plant residues.

3.4. Multivariate Analysis

The Principal Component Analysis (PCA) biplot (Figure 5), showed clear differentiation of treatments by soil fertility variables. Field treatment differences were well summarized by the first two components (PC1 and PC2), which explained 91.1% and 8.9% of the total variance, respectively. The clustering group of residues was mixed, grape, pomegranate, reflecting their strong association with soil fertility improvement, and the woody ones (pine, fig, orange) have been clustered in the low quartile of fertility. These groupings were confirmed by Hierarchical Cluster Analysis (HCA), as shown in Figure (6), which indicated that they yielded two large clusters corresponding to fertility-enhancing and low-performing treatments. The strong similarity between the PCA and HCA patterns indicates that multivariate methods are effective at separating field-based treatment effects on soil fertility.

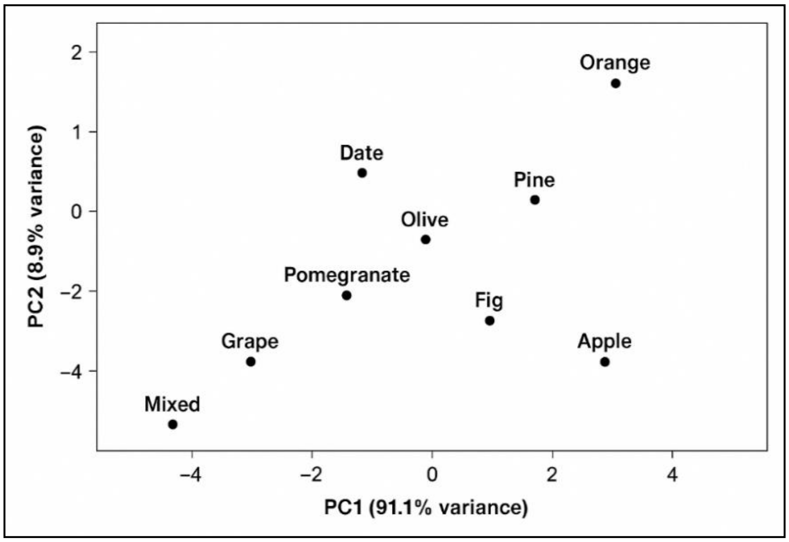

Figure (5): Principal Component Analysis (PCA) biplot showing the spatial distribution of residue treatments based on soil physicochemical properties.

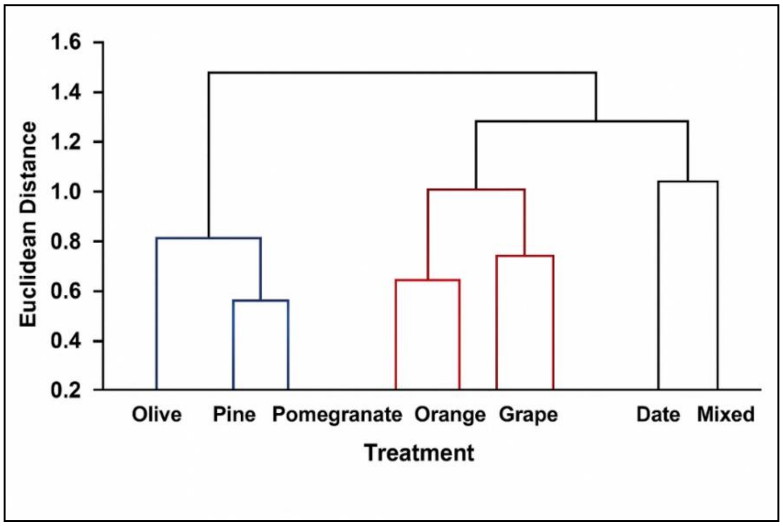

Figure (6): Hierarchical Cluster Analysis (HCA) dendrogram of soil fertility treatments, illustrating similarity among plant residue amendments based on Euclidean distance and Ward’s method.

4. Discussion

This study demonstrated that plant residue identity was a primary control of the soil fertility and nutrient cycle within a semi-arid agroecosystem. The significant variations between the treatments of residues revealed that the quality of residues had a strong effect on the accumulation of organic matter, nutrient availability and integrated soil performance of the soil in terms of its fertility. The results indicate that residue biochemical quality is a major determinant of soil fertility improvement. The superior performance of fruit-based and mixed residues suggests that residues rich in labile organic compounds and lower carbon-to-nitrogen ratios enhance nutrient mineralization and soil quality under semi-arid conditions. The increase in soil organic carbon under fruit residues can be attributed to their low C:N ratio and high labile carbon content. Similar findings were reported by Roy, et al. [10]

OC showed a negative correlation with pH (r = -0.58), indicating that increased organic matter weakly acidifies the soil. These correlations indicate that residue amendments simultaneously enhance nutrient availability, moisture retention, and overall soil fertility. Similar patterns of nutrient variability influenced by environmental conditions have been reported in previous studies Roy, et al. [10] and Kumar, et al. [19], supporting the role of dynamic environmental factors in regulating nutrient availability.

Grape, pomegranate and mixed vegetation residues increased soil organic carbon, total and available phosphorus more than wheat residues because of their lower carbon-to-nitrogen ratios and large shares of labile organic compounds. These features enhanced microbial decomposition and nutrient mineralization. Woody residues (pine and orange), on the other hand, exhibited slower nutrient release, attributed to their higher lignin and cellulose contents, which inhibited microbial activity and nutrient turnover. These results highlighted that the quality of the residue, rather than its quantity, controlled soil fertility improvement in semi-arid systems[20-22]. The observed improvements in soil nutrient availability and chemical properties following residue incorporation are consistent with broader findings on nutrient variability under environmental influences. [10, 23], reported that nutrient concentrations are strongly affected by seasonal and environmental factors, suggesting that residue-driven changes in soil systems may interact with these dynamics to regulate nutrient availability in semi-arid agroecosystems.

Mild soil acidification was induced by residue incorporation, which was likely driven by the production of organic acids during decomposition. Such a change in pH increased the solubility of micronutrients through chelation and improved the mobility of metals, which explained the interaction between organic carbon accumulation and micronutrient enrichment was strong across treatments. These findings aligned with those of other researchers, who reported increased micronutrient availability when organic residue was amended into dryland soils [20-22].

The combined use of the soil fertility index and multivariate analysis provided a holistic evaluation of the impact of the residue on soil functioning. The widespread dominance of a single fertility gradient, accounting for more than 90% of the total variance, suggested a synergistic rather than independent interaction among shifts in organic matter, nutrient availability, and moisture retention. A strong match between principal component analysis and hierarchical clustering demonstrated the stability of treatment groupings and enhanced the interpretation of residue-driven fertility patterns [24-26].

In terms of land management, the present study demonstrated that fruit-based (grape and pomegranate) and mixed residues produced the highest improvements in soil organic carbon (up to 2.10%), total nitrogen (0.19%), and available phosphorus (27 mg kg^{-1}), along with enhanced moisture retention. These improvements can be attributed to the lower C:N ratio and higher content of labile organic compounds in fruit-derived residues, which promote rapid decomposition and nutrient mineralization. Similar findings have been reported in previous studies, where organic residues significantly enhanced nutrient availability and soil quality under different environmental conditions [27-29]. The incorporation of such residues also reduces dependence on mineral fertilizers and improves agroecosystem resilience. Despite the relatively short experimental duration, the consistency of these responses suggests potential applicability in other semi-arid regions with comparable climatic and soil conditions [30, 31]

Future studies are necessary to provide longer-term field-scale estimates of the stability of fertility improvements and to examine underlying biological processes, such as microbial community dynamics and carbon stabilization. In addition, the potential impacts of residue incorporation on greenhouse gas emissions (e.g., CO_2, N_2O, and CH_4) should be considered, as these processes are closely linked to organic matter decomposition and nutrient cycling. However, the current results provide solid empirical support for the importance of managing plant residues in regulating soil fertility and nutrient dynamics in semi-arid agroecosystems. These findings are consistent with previous studies showing that organic amendments improve nutrient availability and soil quality by enhancing mineralization and microbial activity under variable environmental conditions.

5. Conclusions

This study demonstrated that plant residue identity is a key determinant of short-term soil fertility dynamics in semi-arid agroecosystems. Fruit-based residues (grape and pomegranate) and mixed residues produced the greatest improvements in soil organic carbon, total nitrogen, available phosphorus, micronutrient availability, and moisture retention. Integrated fertility indices and multivariate analyses consistently confirmed their superior performance compared to woody residues and the control. These findings highlight that selecting high-quality residues, rather than simply increasing residue quantity, is critical for effective soil restoration in dryland systems. The incorporation of fruit-based and mixed residues represents a practical, low-cost strategy to enhance nutrient cycling, improve soil quality, and strengthen agroecosystem resilience in semi-arid regions. Further long-term studies are recommended to evaluate the persistence of these improvements and their effects on soil biological processes and carbon stabilization.

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Ethical Approval

This study was reviewed and approved by the Medical Ethics Committee of Hawler Medical University, Erbil, Iraq, during its eighth meeting (Paper Code: D) in September 2024. All study procedures were conducted in accordance with the ethical principles outlined in the Declaration of Helsinki.

Conflict of Interest: The authors declare that there are no conflicts of interest associated with this research project. We have no financial or personal relationships that could potentially bias our work or influence the interpretation of the results.

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