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Soil Nutrient Dynamics and Farming Sustainability Under Different Plum Orchard Management Practices in the Pedoclimatical Conditions of Moldavian Plateau

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Abstract: Soil health is essential for sustainable agriculture, influencing ecosystem health and orchard productivity of plum orchards. Global challenges such as climate change and soil contamination threaten to affect fertility and food security, requiring sustainable practices. The study assessed the effect of different orchard management practices on soil quality and nutrient distribution in *Prunus domestica* L. orchard located on the Moldavian Plateau in northeastern Romania under temperate humid subtropical climate conditions. Two systems were analyzed: conventional (herbicide-based) and conservative (cover crop-based). Soil samples (0–20 cm and 20–40 cm) were analyzed for soil organic carbon (SOC), total nitrogen (N_t), available phosphorus (P), and potassium (K). Results showed that conservative management improved soil health by increasing SOC nutrient cycling, mainly through organic matter inputs. Compared to 2022, the effectiveness of phosphorus in the conservative management system significantly increased (by 6%) in 2023, while potassium content decreased (by 30%), suggesting potential nutrient competition or insufficient replenishment under organic practices. SOC levels remained stable, supporting long-term carbon inputs. Conventional management maintained phosphorus and potassium but showed lower SOC levels and higher risks of soil fertility depletion. Strong correlations between SOC and nutrient indicators emphasize the critical role of organic inputs in nutrient mobilization. The findings indicate that cover crops are essential for sustainable soil management by enhancing carbon sequestration and nutrient cycling, thereby supporting the long-term sustainability of agricultural systems.

Keywords: soil quality; orchard management; conservative agriculture; nutrient cycling; soil organic carbon; sustainable farming

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1. Introduction

Soil is a fundamental resource for agriculture and human survival, serving as the foundation for plant growth and ecosystem stability [1]. In fruit production systems, such as plum orchards (*Prunus domestica* L.), soil quality and nutrient distribution directly influence tree growth and fruit yield [2]. Despite its importance, soil health is increasingly threatened by global challenges, including climate change, land degradation, and contamination [3].

Anthropogenic pollutants, heavy metals, and chemical residues with uncertain toxicological profiles disrupt nutrient cycles and compromise food security [4]. These contaminants are problematic due to their persistence in the soil, complicating remediation efforts and posing risks to human health [5].

Current remediation methods—physical, chemical, and biological techniques—have shown limited effectiveness in addressing these problems due to high cost, potential environmental damage, secondary pollution, and lengthy implementation time [6]. This situation necessitates alternative, sustainable strategies to improve soil quality while minimizing ecological disturbances [7].

Sustainable orchard management based on ecological practices, such as conservation agriculture, has emerged as a promising approach to restoring soil functionality [8]. These practices aim to reduce soil disturbance, promote biodiversity, and optimize nutrient cycling, thereby increasing the resilience and productivity of agricultural ecosystems [9].

As illustrated in Figure 1, soil health, quality, and fertility are interconnected yet distinct concepts, each contributing to the overall functionality of agricultural ecosystems. Soil health is the broadest concept, encompassing the biological, physical, and chemical functions that sustain plants, animals, and humans. Within this framework, soil quality refers to the soil's ability to support productivity and ecosystem functions. In contrast, soil fertility, a subset of soil quality, focuses specifically on nutrient availability for plant growth [10].

Figure 1. The relationship between soil health, soil quality, and soil fertility.

These approaches enhance soil resilience, mitigate erosion, and improve soil health by stimulating beneficial microbial communities, increasing organic matter content, and facilitating organic carbon sequestration, thereby aligning with key soil quality guidelines that include essential chemical characteristics such as total carbon (inorganic and organic), organic matter, nutrient content, exchangeable cations, and pH–indicators of soil functionality and ecosystem sustainability [11].

In agriculture, "organic carbon" is associated with organic matter decomposed from plant and animal residues, along with substances released by soil microorganisms. This organic matter, rich in hydrogen, carbon, and oxygen, can retain water and essential nutrients (N, P, K).

The role of Soil Organic Carbon (SOC) as a key indicator of soil health has been extensively studied. Low SOC levels, frequently observed in mountainous and hilly regions utilized for orchards, adversely affect soil structure, aggregate stability, and fertility. Research has consistently demonstrated the effectiveness of ecological practices such as cover crops and organic fertilization in increasing SOC levels and improving soil quality [12,13]. For instance, cover crops increase SOC by 33%, while organic fertilization contributes to a 20% increase. Additionally, organic amendments have shown a higher rate of SOC accumulation compared to cover crops, particularly in olive orchards in Mediterranean areas [12].

The transition to tillage practices, however, presents significant challenges. Cover crops enhance nutrient cycling and may compete with trees for water, while conventional systems relying on herbicides and chemical fertilizers contribute to biodiversity loss, nutrient imbalances, and SOC depletion through mineralization processes [13,14].

Most studies indicate that cover crops significantly increase nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and other soil nutrients compared to conventional systems and also reduce nutrient losses through leaching and runoff by 30–60%, thus maintaining higher nutrient levels in the soil. The dynamics of phosphorus (P) illustrate the complexities inherent in sustainable soil management practices. While conventional systems often exhibit inefficient phosphorus use and ecological risks due to herbicide application, cover crops have demonstrated the potential to enhance P availability through increased root activity and optimized nutrient cycles [15,16].

A key feature of ecological farming management is its lasting effectiveness in enhancing soil quality. Both composted and non-composted soil amendments improved organic matter, cation exchange capacity, and mineral content (K, P, Mg, Zn, and Mn) in sandy soil over a decade [17]. After 14 years of compost application, soil nitrogen stocks increased, indicating higher potentially available nitrogen, while organic manure contributed to the accumulation of red soil organic carbon [18,19]. Biodynamic practices in citrus orchards demonstrated superior soil quality, with better pH, microporosity, and soil fauna than conventional methods. Moreover, organic farming improved several soil properties in mandarin orchards, particularly increasing exchangeable levels of potassium, phosphorus, and magnesium [20].

Although ecological orchard management practices have been extensively researched, studies on ecological orchard management adoption in Romania, particularly in plum orchards, remain few due to economic and policy barriers.

This study examines how conventional and ecological practices affect soil quality and nutrient distribution in plum orchards. The hypothesis is that ecological practices, such as cover crops and organic fertilization, improve soil quality by increasing SOC, optimizing phosphorus (P) and potassium (K) availability, and maintaining stable pH, thereby supporting long-term agricultural sustainability.

The secondary hypothesis is that ecological practices, particularly the use of cover crops, improve organic carbon levels, optimize nutrient distribution, and reduce ecological risks compared to conventional systems. The analysis aims to identify optimal solutions for adopting sustainable practices that balance productivity with environmental protection.

In conclusion, this study was carried out to analyze soil organic carbon (SOC) and nutrient dynamics and the sustainability of agricultural practices in plum orchards of the Moldavian plateau. The Moldavian Plateau has a sculptural origin, formed by intense shaping processes due to the action of the hydrographic network and denudation factors on the easily erodible sandy-clay substratum. In contrast to the surrounding regions, where more resistant oolitic sandstones and limestones predominate, the soils in this area are prone to degradation and loss of fertility. This geomorphologic peculiarity, in combination with climatic influences, leads to high variability in soil nutrient dynamics. Thus, it is essential to assess the impact of different plum orchard management practices on soil fertility and quality, as well as the sustainability of agricultural production. Results show that organic practices, in particular cover crops and organic fertilization, increase SOC levels, improve nutrient cycling (P, K), and contribute to long-term soil fertility. In contrast, conventional management maintains nutrient stability but risks reducing SOC. These findings highlight the importance of sustainable practices in maintaining soil health and ensuring long-term agricultural productivity.

2. Materials and Methods

2.1. Experimental Site and Growing Conditions

The experiment was carried out over two years (2022–2023) in a 10-year-old *Prunus domestica* L. orchard at the Horticultural Research Station in Iasi, Romania. The site is situated at 47°15′ N–27°30′ E, within a temperate humid subtropical climate (C_{fa}) as per the Köppen classification (https://climateknowledgeportal.worldbank.org/country/romania, accessed on 14 November 2024) [21]. The region experiences an average annual temperature of 10 °C and receives approximately 518 mm of precipitation during the growing season, which spans from April to September. The orchard's soil is classified as aric-cambic chernozem with a loamy-clay texture, according to the IUAA Working Group WRB (2014). At the surface, the soil comprises 36% clay, 20.1% silt, and 42.7% sand, while at a depth of 20–40 cm, it consists of 39.4% clay, 28.2% silt, and 32.4% sand. Figure 2 illustrates the monthly average air temperature (°C) and precipitation (mm) over two years, highlighting seasonal variations (https://www.fieldclimate.com, accessed on 27 November 2024) [22].

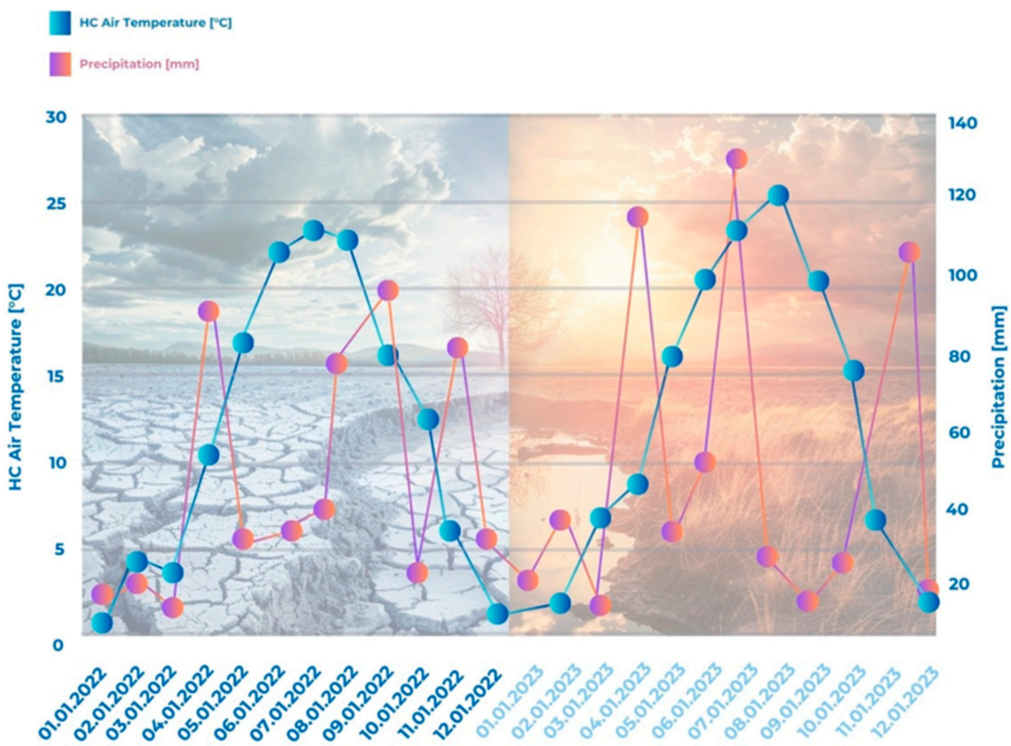

Figure 2. Seasonal variations in air temperature and precipitation for 2022–2023.

Winter temperatures hover around 0 °C, while summer months show values exceeding 25 °C, consistent with typical seasonal patterns. Year-on-year, temperature trends are stable, with no significant anomalies between 2022 and 2023.

Precipitation is highest in April to June, exceeding 100 mm in some months, supporting active plant growth. Drier conditions are evident during the summer months of July and August, with minimal precipitation coinciding with high temperatures.

Spring is characterized by high precipitation and moderate temperatures, creating favorable conditions for crop growth and soil moisture replenishment. Autumn shows moderate rainfall levels, supporting fruit maturation and soil preparation, while winter conditions with low temperatures and minimal precipitation suggest careful management of soil conservation and nutrients.

2.2. Experimental Design and Management Practices

The orchard was planted in 2014 with a 5 m × 5 m spacing arrangement, using a randomized block design, replicated three times. Each replicate contained 30 plum trees and covered an area of 5500 m^2 (Figure 3). Two orchard management systems were compared: conventional management (Cv), which involved herbicide control, and conservative management (Eco), which employed mechanical control. Concerning rootstock, in both ecological and conventional practice, plum trees grew on *Prunus cerasifera* Ehrh. the rootstock of moderate growth strength.

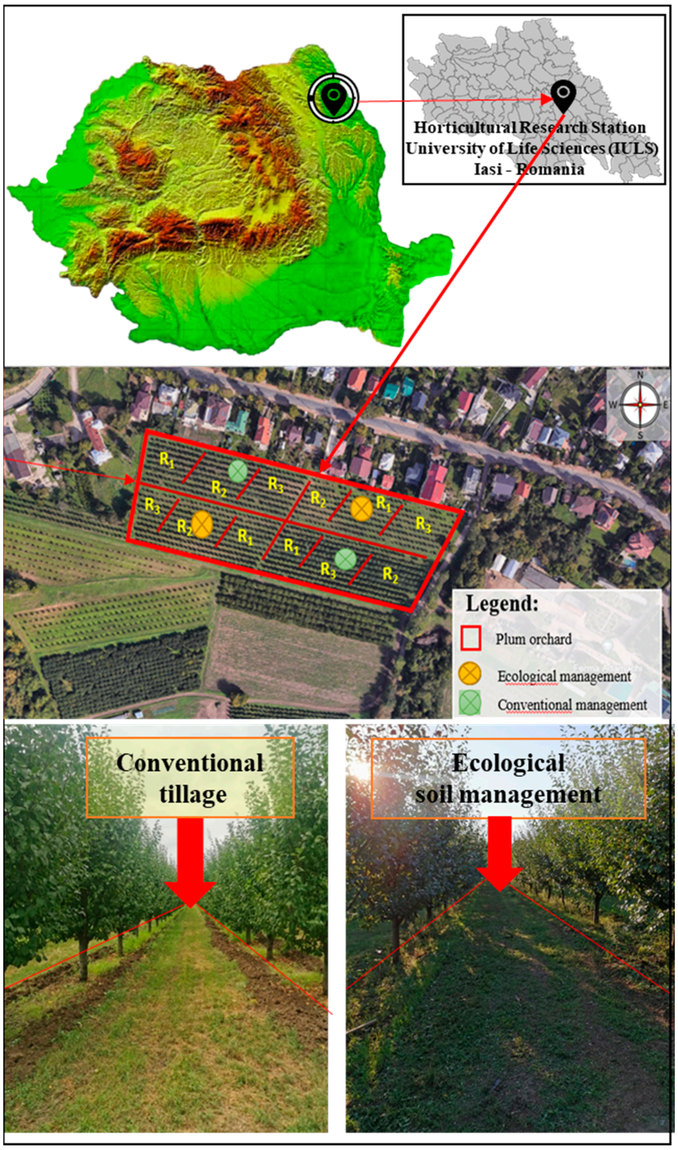

Figure 3. Orchards selected for the study; management practices applied in ecological and conventional systems.

The ecological management system relied on mowing cover crops composed of spontaneous vegetation (*Trifolium pratense*, *Taraxacum officinale*, *Achillea millefolium*, *Vicia cracca*, *Poa pratensis*, *Urtica dioica*) at regular intervals to manage weed growth. In contrast, the conventional system utilized post-emergent, non-selective herbicides, such as fluazifop-P-butyl (150 g/L). Additionally, isopropylamine salt (360 g a.i. L^{-1}) was applied in spring at a rate of 2880 mL/ha (1.39 kg a.i. ha^{-1}) to reduce competition for water and nutrients during the active growth phase of the plum trees. The pruning protocols were standardized across all treatments to ensure consistency in the experimental design.

Both systems received annual fertilization. For the conventional fertilized variants, NPK 16-16-16 from Ameropa Company® (Targu Mures, Romania) was used, and for the ecological (conservative) variants, Orgevit® from MeMon BV (Arnhem, The Netherlands) was used, which contains 4% N, 2.3% K_2O, 2. 5% P_2O_5, 0.02% Fe, 1% MgO, 0.01% Zn, 0.01% Mn, 0.01% B, 0.001% Cu, and 0.001% Mo. Both fertilizers were applied to the soil and the recommended doses recommended by the two manufacturers for plum cultivation were used. The conventional fertilizer was applied at 425 kg/ha. In the case of the ecological variant, the fertilizer was applied at a dose of 2400 kg/ha. Both fertilizers were administered in 4 phenophases: BBCH 01, BBCH 60, BBCH 69, and BBCH 73.

2.3. Collection and Pre-Treatment of Soil Samples

At the end of the harvest period, 72 soil samples were collected in September using a soil auger. Sampling depths of 0–20 cm and 20–40 cm were chosen based on their relevance in assessing soil quality dynamics. Each management system was replicated three times, with three soil samples collected per block for each depth. To prepare samples for analysis, the upper soil layers were carefully scraped to remove stones and plant material. Samples were then dried to a constant weight of 105 °C, finely ground with mortar and pestle, and sieved through a 2 mm mesh [23].

2.4. Soil Analyses

The soil samples underwent the following chemical analyses using well-established methods:

Soil pH was measured in a 2.5:1 water-to-soil suspension using a glass electrode pH meter (WTW Multi 3320, Weilheim, Germany). Electrical conductivity (EC) at 25 °C was determined using the same suspension with an EC meter (Mettler-Toledo S230-USP/EP, Greifensee, Switzerland).

Soil organic carbon (SOC) content was determined using the modified Walkley–Black method, which oxidizes organic matter to quantify organic carbon. Total nitrogen (N_t) was measured using the Kjeldahl method, a widely used technique for nitrogen quantification [24].

Available phosphorus (P) and potassium (K) were extracted with 1N NH_4OAc. Phosphorus concentrations were determined using the colorimetric molybdenum blue method, while potassium levels were measured spectrophotometrically with a Specord Plus UV-Vis device (Analytikjena, Jena, Germany) [25].

The sum of exchangeable bases (SB), including calcium (Ca^{2+}), magnesium (Mg^{2+}), K^+, and sodium (Na^+), was measured after extraction with 1N CH_3COONH_4 at pH 7. Quantification was performed using Atomic Absorption Spectrometry (AAS ContrAA 700, Analytik, Jena, Germany) [26].

Exchange acidity (SH) was assessed using NaOAc solution. Total cation exchange capacity (CEC) was calculated as the sum of SB and SH. The degree of base saturation (V%) and cation exchangeable capacity (T) were derived from the concentrations of extracted cations according to standard soil analytical protocols [27].

2.5. Software and Data Analysis

Software and data analysis play a crucial role in systematically assessing soil health, nutrient dynamics, and the impact of management practices, contributing to statistical rigor and the reproducibility of results. Climatic data were collected and managed using the FieldClimate.com platform, which provided information on temperature and precipitation throughout the experiment, enabling the correlation of environmental conditions with soil quality indicators such as SOC, P, K, and N_t. Soil chemical analyses were preliminarily processed in Microsoft Excel, which was used for data organization, trend visualization, and initial exploration of relationships between variables through graphs and summary tables. All analyses were performed in triplicate to ensure analytical reliability, and quality control measures included blank runs and certified standards.

For statistical testing and validation of significant differences between ecological and conventional management systems, SPSS version 26 was utilized. The analyses included descriptive statistics of soil quality indicators (SOC, P, K, N_t) for 2022 and 2023 to identify differences between treatments.

The Analysis of Variance (ANOVA) is a statistical technique used to determine if there are statistically significant differences between the means of multiple groups. In this analysis, we applied one-way ANOVA for individual factors (Year, System, and Depth) and their combined influence on soil parameters using a two-way ANOVA with interactions. The factors under investigation include the year (2022 vs. 2023), system (conventional vs. ecological–conservative), and depth (0–20 cm vs. 20–40 cm). For each soil parameter (e.g., pH, SOC, P, K, etc.), ANOVA calculates the variance within each group and compares it to the variance between groups [28].

Heatmap for Pearson correlations were also applied to explore the relationships between soil quality indicators.

The rationale for these methods is supported by previous studies that highlight their effectiveness in agricultural research.

3. Results

3.1. Descriptive Statistics of Soil Quality Indicators (SOC, P, K, Nt) for 2022 and 2023

Table 1 presents the evolution of key physico-chemical soil parameters across two agricultural systems, conventional and ecological, analyzed at two depth intervals (0–20 cm and 20–40 cm) in 2022 and 2023. The parameters examined include pH, P, K, N_t, SOC, EC, concentrations of major cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), as well as fertility indicators such as the SB, SH, T, and V. The data reflect the differences between the two systems in terms of soil fertility management and maintenance of physico-chemical balance, highlighting the changes observed during the two years of the study.

Table 1 displays a comparison of data from 2022 and 2023, emphasizing significant shifts in soil characteristics across conventional and ecological agricultural systems, analyzed at two soil depths (0–20 cm and 20–40 cm).

Ecological systems maintained stable soil pH, while conventional systems showed slight acidification, especially at 20–40 cm. P increased in both systems at 0–20 cm but remained higher in ecological soils. K levels showed a slight increase at 0–20 cm but demonstrated greater retention in ecological systems at depth. N_t showed a general decline in conventional systems between 2022 and 2023. At 0–20 cm, nitrogen levels dropped from 0.201% to 0.189%, and at 20–40 cm, they decreased from 0.148% to 0.132%. Ecological c systems, however, showed an increase in nitrogen at 0–20 cm, from 0.215% to 0.227%, and near-constant levels at 20–40 cm, with 0.157% in 2022 and 0.159% in 2023. SOC decreased in conventional systems at both depths. At 0–20 cm, SOC fell from 2.29% in 2022 to 2.19% in 2023, while at 20–40 cm, it decreased from 1.68% to 1.53%. In ecological systems, SOC increased at 0–20 cm, from 2.48% to 2.63%, and remained relatively stable at 20–40 cm, with 1.82% in 2022 and 1.85% in 2023, reflecting better management of organic matter. EC showed a slight reduction across both systems, with greater stability in organic soils.

Table 1. Physico-chemical characteristics of soil by agricultural system and depth for 2022 and 2023.

Year	System	Depth	pH	P (ppm)	K (ppm)	Nt (%)	SOC (%)	EC (µS/cm^2)	me/100 g Soil			me/100 g Soil				V (%)
									Ca^{2+}	Mg^{2+}	K^+	Na^+	SB	SH	T	
2022	Cv	0–20	6.9	68	268	0.201	2.29	158	15.99	6.70	1.34	0.87	24.9	0.61	25.51	97.6
		20–40	6.0	59	217	0.148	1.68	121	10.36	8.38	1.26	0.88	20.9	2.10	23.0	90.9
	Eco	0–20	7.0	65	279	0.215	2.48	156	16.31	6.04	1.28	0.52	24.2	0.53	24.73	97.8
		20–40	6.1	60	244	0.157	1.82	119	11.74	7.89	1.15	0.96	21.7	1.96	23.66	91.7
2023	Cv	0–20	6.8	70	274	0.189	2.19	151	14.30	7.21	1.04	0.53	23.1	0.43	23.53	98.2
		20–40	5.9	62	221	0.132	1.53	118	11.76	7.95	0.90	0.84	21.5	2.43	23.93	89.9
	Eco	0–20	7.0	72	282	0.227	2.63	149	15.21	6.10	0.70	0.54	22.6	0.83	23.43	96.5
		20–40	6.1	63	251	0.159	1.85	116	12.37	6.44	0.86	0.75	20.4	2.17	22.57	90.4

For cations (Ca^{2+}, Mg^{2+}, K^+, Na^+), calcium levels in 2023 decreased in conventional systems at 0–20 cm, from 15.99 to 14.30 me/100 g, and at 20–40 cm, from 10.36 to 11.76 me/100 g. Organic systems maintained higher calcium values, with 15.21 me/100 g at 0–20 cm. Magnesium levels were similar between the two years but slightly higher in conventional systems at greater depths. Potassium levels decreased in both systems, with a sharper decline in conventional systems, from 1.34 to 1.04 me/100 g at 0–20 cm. Sodium levels were lower in organic systems, reducing salinization risks.

Fertility indicators (SB, SH, T, and V) also highlight the advantages of ecological systems. In 2023, SB slightly decreased in both systems but was balanced in ecological systems, measuring 22.6 me/100 g at 0–20 cm. SH was higher in conventional systems, indicating progressive acidification. T was higher in organic systems, suggesting better nutrient retention. V exceeded 90% in both systems but was more stable in organic systems, with 96.5% at 0–20 cm in 2023 compared to 98.2% in conventional systems.

Conservative soils demonstrated better fertility maintenance between the two years, with increases in organic carbon and total nitrogen, as well as greater stability in pH and electrical conductivity. Conventional soils, in contrast, showed signs of degradation, including declines in nitrogen and organic carbon, along with more pronounced acidification.

In conclusion, the results indicate that conservative practices significantly enhance soil quality. Soil organic carbon levels were higher in the conservative management system, with an increase attributed to cover crops, while organic fertilization contributed to a notable increase. The enhanced variability in phosphorus values suggests localized effects of intensified biological activity and differential recycling in ecologically managed soils. Notably, potassium levels exhibited a decline, likely due to higher K uptake by crops under ecological systems.

Table 2 presents the descriptive values for SOC, including pH, P, K, N_t, SOC, EC, Ca^{2+}, Mg^{2+}, Na^+, SB, SH, T, V (%), measured across 2022 and 2023. The table highlights the minimum, maximum, mean, standard deviation, and distribution statistics (skewness and kurtosis) for each variable, providing insights into year-to-year trends and variability. These values offer a comprehensive overview of the soil's chemical properties and their changes under different conditions, serving as a foundation for further analysis.

Table 2 highlights soil variations between 2022 and 2023, correlated with agricultural management practices (ecological vs. conventional) and environmental conditions.

Table 2. Descriptive statistics of soil quality indicators for 2022 and 2023.

	Minimum Statistic	Maximum Statistic	Mean		Std. Deviation Statistic	Variance Statistic	Skewness		Kurtosis	
			Statistic	Std. Error			Statistic	Std. Error	Statistic	Std. Error
pH_2022	6.0	7.0	6.500	0.261	0.523	0.273	0.000	1.014	−5.639	2.619
pH_2023	5.9	7.0	6.450	0.266	0.532	0.283	0.000	1.014	−4.655	2.619
P_2022	59	68	63.00	2.121	4.243	18.000	0.367	1.014	−3.438	2.619
P_2023	62	72	66.75	2.496	4.992	24.917	0.103	1.014	−5.027	2.619
K_2022	217	279	252.00	13.766	27.532	758.000	−0.626	1.014	−1.307	2.619
K_2023	221	282	257.00	13.681	27.362	748.667	−0.857	1.014	−0.684	2.619
N_t_2022	0.148	0.215	0.180	0.016	0.033	0.001	0.091	1.014	−4.762	2.619
N_t_2023	0.132	0.227	0.176	0.020	0.041	0.002	0.329	1.014	−0.854	2.619
SOC_2022	1.68	2.48	2.067	0.189	0.379	0.144	0.096	1.014	−4.184	2.619
SOC_2023	1.53	2.63	2.050	0.236	0.471	0.222	0.314	1.014	−0.782	2.619
EC_2022	119	158	138.50	10.697	21.393	457.667	0.000	1.014	−5.913	2.619
EC_2023	116	151	133.50	9.544	19.088	364.333	0.000	1.014	−5.891	2.619
Ca^{2+}_2022	10.36	16.31	13.600	1.500	3.001	9.004	−0.170	1.014	−4.919	2.619
Ca^{2+}_2023	11.76	15.21	13.410	0.808	1.616	2.612	0.145	1.014	−3.872	2.619
Mg^{2+}_2022	6.04	8.38	7.252	0.536	1.073	1.151	−0.140	1.014	−3.346	2.619
Mg^{2+}_2023	6.10	7.95	6.925	0.413	0.826	0.683	0.502	1.014	−1.845	2.619
K^+_2022	1.15	1.34	1.257	0.039	0.079	0.006	−0.894	1.014	1.668	2.619
K^+_2023	0.70	1.04	0.875	0.069	0.139	0.020	−0.208	1.014	1.123	2.619
Na^+_2022	0.52	0.96	0.807	0.098	0.196	0.038	−1.739	1.014	3.300	2.619
Na^+_2023	0.53	0.84	0.665	0.077	0.154	0.024	0.281	1.014	−4.349	2.619
SB_2022	20.9	24.9	22.925	0.963	1.926	3.709	−0.034	1.014	−4.554	2.619
SB_2023	20.4	23.1	21.900	0.601	1.203	1.447	−0.524	1.014	−1.711	2.619
SH_2022	0.53	2.10	1.300	0.423	0.845	0.715	0.016	1.014	−5.819	2.619
SH_2023	0.43	2.43	1.465	0.492	0.984	0.968	−0.081	1.014	−4.868	2.619
T_2022	23.00	25.51	24.225	0.557	1.114	1.242	0.112	1.014	−2.382	2.619
T_2023	22.57	23.93	23.365	0.286	0.572	0.328	−1.128	1.014	2.099	2.619
V_2022	90.9	97.8	94.500	1.855	3.710	13.767	−0.038	1.014	−5.755	2.619
V_2023	89.9	98.2	93.750	2.109	4.219	17.803	0.127	1.014	−5.139	2.619

The descriptive statistics table provides a detailed summary of key soil quality indicators measured over 2022 and 2023, capturing their means, variability, and distribution. The pH levels are consistent across years, with means of 6.5 in 2022 and 6.45 in 2023, showing minimal variation and negative kurtosis, indicating flatter distributions. In the ecological system, pH values at depth remain stable (pH 7.0 at 0–20 cm and pH 6.1 at 20–40 cm), whereas in the conventional system, there is a slight acidification observed in 2023.

P levels show an increase in 2023, with a higher mean (66.75 compared to 63.00 in 2022) and greater variability, as reflected in the higher standard deviation and variance. This suggests more dispersion in phosphorus availability in 2023, particularly in the ecological system.

K levels are stable between years, with slight increases in the mean values for total potassium (257.00 in 2023 vs. 252.00 in 2022) but a notable decline in available potassium (0.875 in 2023 vs. 1.257 in 2022), pointing to potential nutrient depletion or higher plum trees uptake. N_t levels are relatively consistent across years, with slightly higher variability in 2023, as shown by an increase in the standard deviation and variance. In the conventional system, average N_t values decreased from 0.175 in 2022 to 0.161 in 2023. Conversely, in the ecological system, values increased from 0.186 in 2022 to 0.193 in 2023.

SOC showed minor declines (2.0675 in 2022 to 2.050 in 2023), with higher variability in 2023, indicating potential effects of management practices or climatic conditions. EC levels decreased in 2023 (133.50 compared to 138.50 in 2022), suggesting a reduction in soluble salts in the soil.

Ca^{2+} and Mg^{2+} slightly declined in 2023, reflecting reduced availability or uptake by plants. Na^+ also decreased in mean values in 2023, particularly in exchangeable forms, as evidenced by a lower mean (0.6650 in 2023 vs. 0.8075 in 2022) and reduced variance.

SB and SH exhibit stable trends, with SB slightly decreasing in 2023 and SH showing slightly higher variability. V% also shows a marginal decline in 2023 (93.75 vs. 94.50 in 2022), indicating consistent nutrient availability but with small year-on-year changes.

The data suggest stable soil conditions with some nutrient-level fluctuations, particularly in phosphorus and potassium, which may reflect differences in nutrient cycling, uptake, or external influences such as precipitation and management practices. Overall, the results emphasize the importance of monitoring specific nutrient dynamics to maintain soil health and productivity.

The analysis confirms the central hypothesis that ecological practices, such as the use of cover crops and organic fertilizers, improve soil quality indicators. These practices were shown to increase SOC, optimize the availability of essential nutrients such as P and K, and maintain stable pH levels compared to conventional management systems. The findings demonstrate that conservative management contributes significantly to sustainable soil health and long-term agricultural productivity.

3.2. Evaluation of the Impact of Analytical Factors on Soil Properties—pH, P, K, SOC, EC

Each parameter was analyzed to assess the impact of year, system, and depth individually or jointly contributing to significant variation in soil properties. Through these hypotheses, ANOVA allowed us to identify which factors significantly influence the distribution of soil parameters and to quantify their effects. The following hypotheses were tested for each soil parameter:

- Null Hypothesis (H_0): There are no significant differences in the mean values of soil parameters between levels of year, system, or depth. For instance, SOC does not differ between ecological and conventional systems, years, or depths.
- Alternative Hypothesis (H_1): At least one group mean is significantly different. For example, SOC is higher in the ecological system or varies significantly between depths (0–20 cm vs. 20–40 cm).

Table 3 presents the influence of year, tillage system, and depth on soil properties—pH, P, K, SOC, and EC. Tillage system and depth significantly influenced most parameters, while the year had a varied impact. The results are summarized with *p*-values and statistical significance for each variable.

Table 3. Effects of year, tillage system, and depth on soil properties.

Variable	Year (*p*-Value)	Year (Significance)	System (*p*-Value)	System (Significance)	Depth (*p*-Value)	Depth (Significance)
pH	0.116	Not significant	0.0039	Significant	0.000004	Highly significant
P	0.022	Significant	0.820	Not significant	0.0016	Highly significant
K	0.357	Not significant	0.016	Significant	0.00091	Highly significant
SOC	0.792	Not significant	0.0119	Significant	0.000403	Highly significant
EC	0.0074	Significant	0.011	Significant	0.000004	Highly significant

In parallel, the table is supported by Figure 4. This represents the *p*-values from the ANOVA tests for key soil parameters (pH, P, K, SOC, and EC) grouped by the factors of year, system, and depth. Lower bars ($p < 0.05$) indicate significant effects, while higher bars ($p \geq 0.05$) denote non-significant results

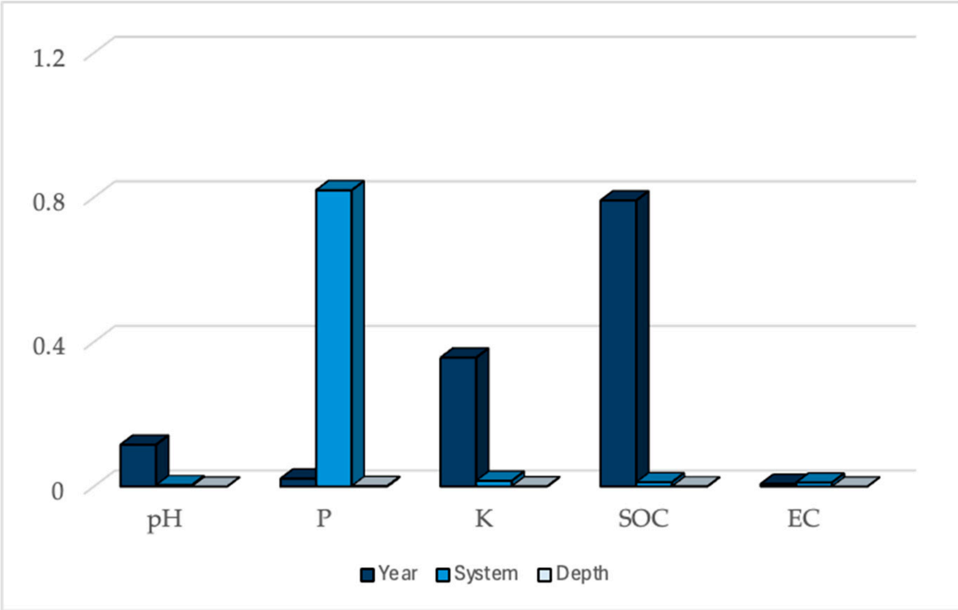

Figure 4. Effects of year, tillage system, and depth on soil properties.

This chart visually complements the *p*-value table, making it clear which factors (year, system, depth) are significant for each parameter: Lower Bars (significant): depth consistently demonstrates a highly significant effect across all parameters, reinforcing its importance in soil property variations; Higher Bars (non-significant): year shows no significant effect for most parameters (except EC and P), highlighting stability over time; System Effects: differences between ecological and conventional systems are significant for pH, P, SOC, and EC, emphasizing the ecological system's superiority in maintaining soil health.

In conclusion, the analysis of system, depth, and year effects on soil parameters revealed significant results. In terms of system-level effects, the organic system can outperform the conventional system in terms of critical parameters such as pH, SOC, P, and EC, thus demonstrating superior soil fertility and sustainability practices. Regarding the depth level effects, most parameters, including pH, P, SOC, and EC, are significantly better in the surface layer (0–20 cm). This reflects the impact of organic inputs and reduced erosion in ecological systems, which emphasizes the importance of proper soil management. In terms of year effects, although its overall impact is lower, significant improvements were observed for P and EC, indicating progress in soil management over time.

3.3. Pearson Correlations Between Soil Quality Indicators (SOC, P, K, N_t) for 2022 and 2023

The Tukey HSD test enabled pairwise comparisons between factor levels (year, system, and depth) following verification of ANOVA assumptions (normality and homogeneity of variances) (Table 4). The results reveal significant differences in specific soil properties, with at least one parameter showing a notable change between 2022 and 2023. Additionally, the system type does not exert a statistically significant effect on soil properties. Regarding depth, the Tukey test confirms that deeper soil layers exhibit distinct characteristics compared to surface layers.

Table 4. Tukey HSD test results.

Factor	Comparison	*p*-Value	Significance
Year	2023–2022	0.0074916	Significant
System	Ecologic–Conventional	0.116117	Not Significant
Depth	20–40–0–20	3.1×10^{-6}	Highly Significant

Table 5 presents the results of the correlation analysis, highlighting strong relationships between SOC, essential nutrients (P, K), and N_t. These findings illustrate complex dynamics that may be influenced by agricultural management practices. These relationships can be explained by biological and chemical processes in the soil, as well as the specific characteristics of ecological and conventional systems, which impact nutrient cycles and carbon accumulation.

Table 5. Pearson correlations between soil quality indicators (SOC, P, K, N_t) for 2022 and 2023.

	SOC_2022	SOC_2023	P_2022	P_2023	K_2022	K_2023	N_t_2022	N_t_2023
SOC_2022	1							
SOC_2023	0.973 *	1						
P_2022	0.877	0.757	1					
P_2023	0.997 **	0.952 *	0.897	1				
K_2022	0.778	0.622	0.868	0.827	1			
K_2023	0.765	0.612	0.836	0.815	0.998 **	1		
N_t_2022	0.894	0.765	0.971 *	0.924	0.955 *	0.938	1	
N_t_2023	0.737	0.56	0.926	0.785	0.968 *	0.950 *	0.962 *	1

*. Correlation is significant at the 0.05 level (2-tailed); ** Correlation is significant at the 0.01 level (2-tailed).

In Table 3, the significant correlation between SOC in 2022 and SOC in 2023 (r = 0.973, p = 0.027) highlights stability in organic carbon levels across years. This consistency may be attributed to the steady contribution of organic matter through cover crops in ecological systems or the influence of organic and mineral fertilizer applications in both systems. SOC is a slow-changing indicator of soil quality, with increases or decreases occurring gradually, which explains this stability.

The very strong relationship between SOC in 2022 and P in 2023 (r = 0.997, p = 0.003) may be due to the role of soil organic matter in gradually releasing phosphorus through the decomposition of plant residues and microbial activity. In ecological systems where cover crops are utilized, this process can be more pronounced, suggesting an improvement in phosphorus availability over the long term.

Phosphorus in 2022 shows a significant correlation with total nitrogen in 2022 (r = 0.971, p = 0.029), which can be explained by the role of organic matter and biological activity in simultaneously mobilizing both nutrients. Soil microorganisms play a critical role in nitrogen mineralization and phosphorus release, and ecological management practices, such as maintaining cover crops, can stimulate these processes.

The very strong correlation between K in 2022 and K in 2023 (r = 0.998, p = 0.002) indicates continuity in potassium availability across years, likely due to the natural potassium reserves in the soils studied and similar agricultural management interventions. Additionally, the relationship between K and N_t (r = 0.955, p = 0.045 for 2022 and r = 0.968, p = 0.032 for 2023) suggests a strong connection between these nutrients. This can be explained by the importance of potassium in plant metabolic processes and the role of nitrogen in supporting biomass growth, which influences potassium demand.

Total nitrogen exhibits a significant correlation between 2022 and 2023 (r = 0.962, $p = 0.038$), indicating the stability of this element over time. This stability may be due to the regular application of organic fertilizers and the contribution of cover crops in ecological systems, which reduce nitrogen losses through erosion and runoff.

Overall, the significant correlations reflect how agricultural practices, especially ecological ones, positively influence nutrient dynamics and the storage of organic carbon in soil. Ecological practices promote natural cycles by maintaining cover crops and reducing chemical interventions, which can contribute to improved soil quality and ecosystem functionality. This interpretation is supported by the role of organic matter in mobilizing essential nutrients and maintaining soil health, explaining the close relationships between SOC, P, K, and N_t.

3.4. Comparative Trends in SOC Levels Between Management Tillage (2022–2023)

SOC is a critical indicator of soil health, reflecting the impacts of agricultural management practices and environmental conditions. Comparing the two years highlights potential changes in organic carbon storage and the effects of ecological or conventional practices on soil quality.

Figure 5 illustrates the modeled trends of SOC levels for 2022 and 2023, highlighting annual differences.

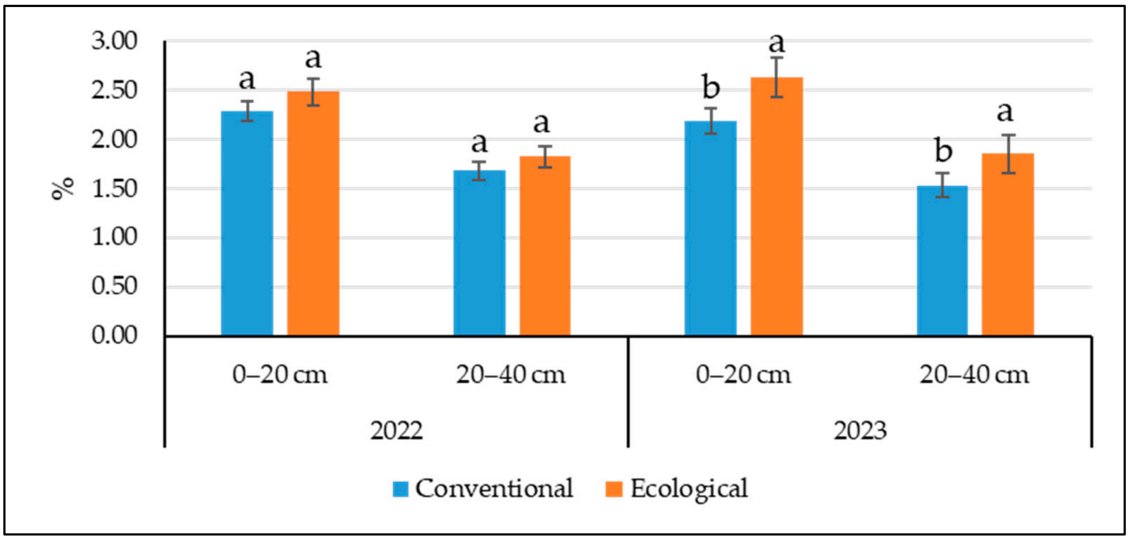

Figure 5. Comparative trends in SOC levels for 2022 and 2023. Averages with different letters "a", "b" in the columns signify statistically significant differences ($p < 0.05$).

Data reveal a more pronounced increase in SOC in the top layer (0–20 cm) of ecological compared to conventional soils, highlighting the positive effects of ecological practices on soil fertility. The observed decline may stem from varying climatic conditions and the impact of management practices, such as inadequate organic matter input or accelerated decomposition due to environmental factors. In the lower layer (20–40 cm), although the differences are smaller, the ecological system showed a steady accumulation of SOC. These results emphasize the need and the importance of optimizing agricultural practices to maintain and enhance organic carbon levels in the long term. By promoting soil sustainability, the organic system presents itself as a viable solution to combat soil degradation and climate change.

4. Discussion

Ecological farming practices are widely recognised for their benefits to soil health and the environment, providing a sustainable alternative to conventional systems. In particular, the use of cover crops plays a crucial role in improving soil quality by increasing Soil Organic Carbon (SOC) levels, optimising nutrient cycles, and mitigating risks associated with ecological degradation. The organic matter generated by cover crops stimulates soil biological activity, enhances soil structure stability, and promotes the gradual release of nutrients essential for plant development.

In contrast, conventional systems rely on chemical interventions, such as the use of mineral fertilizers and herbicides, which can negatively impact soil biodiversity and lead to imbalances in nutrient distribution. While these practices may ensure stable production levels in the short term, they increase the risks of soil fertility loss and pollution of surrounding ecosystems.

The central hypothesis of this study was that ecological practices, particularly the use of cover crops, enhance organic carbon levels, optimize nutrient distribution (such as phosphorus, potassium, and total nitrogen), and reduce ecological risks compared to conventional systems. To test this hypothesis, we analyzed soil quality indicators under two agricultural systems (ecological and conventional) during 2022 and 2023, focusing on the dynamics of organic carbon, the distribution of essential nutrients, and their variability.

The statistical analyses revealed significant insights into the dynamics of SOC, P, K, and N_t under varying management practices and across study years. The findings demonstrated that management practices, particularly ecological approaches, play a critical role in improving soil health and optimizing nutrient cycling. Consistent with the existing literature, SOC levels were found to change slowly, while nutrient availability showed notable year-on-year variations [29,30].

SOC levels were remarkably consistent between 2022 and 2023, with a slight increase in variability in the latter year. Significant correlations between SOC levels in both years (r = 0.973, p = 0.027) highlight temporal stability in organic carbon accumulation, a trend well-supported by studies like Cárceles Rodríguez (2022) [31]. This consistency aligns with the hypothesis that SOC responds gradually to ecological interventions, such as the application of organic amendments and cover crops. However, the slight variability observed in 2023 likely reflects site-specific climatic effects on organic matter decomposition [32,33]. In Mediterranean climates, studies on fruit orchards typically show moderate rates of SOC accumulation, often ranging from a 0.2 to 0.5% increase per year, depending on the intensity of ecological management practices, such as the use of cover crops, reduced tillage, and organic amendments [34]. Similar trends are observed in olive orchards, with a slight increase in SOC under ecological management, particularly with organic fertilization and mulching. However, the rate of SOC accumulation in the plum orchards studied appears to be slightly lower, possibly due to differences in climate, soil type, or specific management practices such as irrigation strategies or cover crop selection [12].

Phosphorus levels displayed an increase in mean values in 2023, coupled with an extremely strong correlation between SOC in 2022 and P in 2023 (r = 0.997, p = 0.003). These results reinforce the role of SOC in P mobilization, mediated by microbial decomposition of organic residues. The findings are consistent with studies emphasizing the synergy between organic carbon and phosphorus cycling in ecological systems [35,36]. The enhanced variability in p values in 2023 suggests localized effects of intensified biological activity and differential recycling in ecologically managed soils, particularly those under cover cropping systems. These systems support increased microbial activity, which in turn can enhance the recycling of P, reducing its loss via erosion and run-off. The presence of cover crops helps maintain soil structure and improves nutrient cycling by facilitating organic matter decomposition, thus minimizing phosphorus leaching. These crops also reduce the need for external fertilizers by increasing nutrient use efficiency, thus contributing to sustainable soil management in ecologically managed systems [30,37,38].

Potassium exhibited a notable decline in 2023 despite strong year-to-year correlations (r = 0.998, p = 0.002), indicating stable reserves in the soil. This decline may be attributed to higher K uptake by crops under ecological systems [39,40]. The close interrelation between K and N_t levels (r = 0.955 in 2022, p = 0.045) reflects their co-dependence in plant nutrient uptake and metabolic processes [41]. Although a decline in potassium (K) levels was observed, the fertilization regime was tailored to meet the recommended nutrient requirements for plum cultivation. However, further research into potassium dynamics, including nutrient cycling, leaching, and plant uptake efficiency, is needed to assess the adequacy of nutrient replenishment and long-term soil fertility maintenance.

Total nitrogen remained relatively stable throughout the years, albeit with increased variability in 2023. Correlations between N_t and P (r = 0.971, p = 0.029) and N_t and K indicate strong nutrient interdependencies within the soil system. The literature, such as Grzyb et al. (2021) and Valenzuela et al. (2023), emphasizes that nitrogen availability is closely tied to microbial mineralization processes, particularly under conservative management [42,43]. Recent studies by Tian et al. (2022) and Das et al. (2022) further highlight that nitrogen availability supports the efficient utilization of P and K in soils where microbial activity dominates nutrient cycling [44,45].

In agreement with expectations, pH levels remained stable in the ecological system, averaging 7.0 across both years. This is consistent with Zhou et al. (2023), who observed similar values in ecological soils under comparable conditions [46]. In contrast, pH in conventional systems showed a slight decline from 6.9 in 2022 to 6.8 in 2023, aligning with observations from Mihai et al. (2023) [47]. Organic fertilization in ecological systems likely buffered pH fluctuations, contributing to enhanced soil stability. Nutrient concentrations further illustrate the distinct impacts of management systems. Phosphorus levels in ecological systems ranged between 65 and 72 ppm, closely aligned with findings from Xiong et al. (2023), while conventional systems showed slightly lower levels, consistent with data from Amri et al. (2023) [48,49]. Potassium concentrations in the ecological system were higher (279–282 ppm) compared to conventional soils (268–274 ppm), reflecting the potential of ecological practices to maintain K levels, even under intensive cropping systems. These findings are supported by Abdullah et al. (2022) and Wang et al. (2012) [50,51]. Total nitrogen concentrations in ecological systems (0.215–0.227%) closely matched those reported by Liu et al. (2021), highlighting the gradual accumulation of nitrogen under organic inputs [52]. Conventional systems showed lower values (0.189–0.201%), consistent with Kravchenko et al. (2022), suggesting limited nitrogen retention in chemically fertilized soils [53]. SOC stocks in ecological systems (2.48–2.63%) significantly exceeded those in conventional systems (2.19–2.29%), reaffirming the role of organic practices in promoting carbon sequestration. These trends align with Liu et al. (2014), who similarly documented higher SOC levels in organic systems compared to conventional counterparts [54]. Finally, soil Ca^{2+} levels showed higher values in ecological systems (15.21–16.31 me/100 g soil) compared to conventional systems (14.30–15.99 me/100 g soil). Mg^{2+} levels were relatively lower in ecological soils (6.04–6.44 me/100 g soil), possibly due to enhanced microbial activity depleting exchangeable Mg [49].

Statistically, the ecological system proves to be superior in maintaining soil health and fertility, demonstrating higher levels of SOC, pH, and P in both years analyzed. In contrast, the conventional system shows signs of degradation, particularly in SOC and EC, highlighting the long-term difficulties of maintaining soil fertility without the use of organic amendments. In addition, inter-annual differences show that the organic system provides greater stability between 2022 and 2023, whereas the conventional system shows a decline in the main parameters, especially at greater depths [55,56].

Climatic conditions directly influence soil chemical properties by modifying nutrient availability, pH levels, and organic matter decomposition processes [57]. Analysis of meteorological data collected in 2023, characterized by higher rainfall and higher temperatures, confirms the impact of climate on soil characteristics. In general, warmer and wetter climates favor the formation of soils with increased fertility, while regions characterized by lower temperatures and lower humidity determine the development of soils poorer in micro/macroelements [58]. In arid tropical ecosystems, soils in areas with higher humidity recorded carbon and nitrogen stocks that were 15.1% and 17.0% higher, respectively, compared to those in semi-arid climates [59].

In conclusion, ecological systems demonstrated consistent benefits in nutrient retention, soil stability, and organic carbon accumulation. Variations in soil properties between systems and across years reflect complex interactions among management practices, microbial activity, and climatic conditions. These findings highlight the long-term potential of ecological approaches to improve soil health and sustain agricultural productivity in diverse environments.

5. Limitations and Future Directions

Ecological farming offers many benefits but faces economic, technical, and knowledge-related challenges, including high costs, limited expertise, and the need for supportive policies. The potential limitations of the study are a two-year study period and biological indicators. Ecological management systems enhance nutrient dynamics through natural processes, mitigate nutrient loss risks, promote soil carbon sequestration, outperforming conventional systems in long-term soil health metrics. While these practices align with sustainable agriculture goals, further research, such as long-term studies (e.g., 5–10 years), is essential to fully assess their impacts on nutrient balance, microbial activity, and orchard yield stability. The proposed timeline for longitudinal soil health monitoring spans 10 years, beginning with baseline data collection in the first 1–3 years, focusing on soil organic carbon, pH, and nutrient levels. Over the next 4–6 years, interim indicators like microbial diversity and nutrient cycling efficiency will be assessed to track trends in soil health. From years 7 to 10, the focus shifts to evaluating the long-term impact of management practices on soil fertility, carbon sequestration, and microbial activity, ensuring sustainability. Key indicators for long-term monitoring include soil carbon stocks, nutrient availability, and soil microbial health.

6. Conclusions

This study underscores the importance of sustainable orchard management practices in improving soil quality and nutrient cycling within plum orchards in the Moldavian Plateau.

The research findings demonstrate that ecological practices, such as cover crops and organic matter application, boost soil SOC stability—evidenced by consistent SOC levels between 2022 and 2023—and improve nutrient availability. Phosphorus levels increased in 2023, with strong correlations between SOC-P and indicating efficient recycling in ecologically managed soils, reducing reliance on external inputs.

However, declining potassium levels underscore the need for targeted monitoring and management in nutrient-limited soils, as prolonged K depletion could threaten orchard productivity. Total nitrogen showed interannual variability, but its strong interdependence with phosphorus and potassium underscores the synergistic roles these nutrients play in supporting plant metabolic functions.

The research findings demonstrate that ecological practices, such as cover crops and organic matter application, boost SOC stability—evidenced by consistent SOC levels between 2022 and 2023—and improve nutrient availability. Phosphorus levels increased in 2023, with strong SOC-P correlations indicating efficient recycling in ecologically managed soils. To ensure sustainable yields, a minimum SOC content of 2–3% is recommended for maintaining soil fertility and productivity over time. A stepwise transition from conventional to ecological practices should start with gradual reductions in chemical inputs, incorporating organic fertilizers and cover crops to improve soil structure and biodiversity. Over 3–5 years, this transition can include phased adoption of no-till practices and agroforestry methods. Cost–benefit estimates for the initial phases suggest moderate investment in soil amendments and training, with long-term benefits from enhanced soil health, reduced input costs, and increased resilience to climate variability. The transition should be monitored for both economic viability and ecological impact. Future research should also explore region-specific strategies for potassium replenishment and evaluate the economic viability of ecological practices at scale. By prioritizing such systems, stakeholders can foster resilient agroecosystems that balance productivity with environmental stewardship in the Moldavian Plateau and beyond.

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