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The Kind of Fertilization and Type of Soil Tillage Affect Soil Fertility and Foliar Nutrient Concentrations in an Experimental Vineyard of Kefalonia

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Abstract: Our study was based on the premise that the type of soil tillage and the kind of fertilization significantly affect soil properties, nutrient availability, and uptake by *Vitis vinifera* L. (cv. 'Robola') plants. For this purpose, a two-year field experiment was conducted, in a 2 × 3 factorial (i.e., two types of soil tillage-conventional and reduced and three kinds of fertilization-conventional, controlled N release and organic), with six treatments derived from the combination of the two tillage and the three fertilization methods. The results showed that the organic matter content (%), as well as the exchangeable Mg, were significantly influenced by the type of tillage. The kind of fertilization affected soil nitrate and leaf N (lower values in the organic fertilization) and P concentrations (higher values in the organic fertilization). Regarding the effect of the type of tillage, foliar Mg was significantly higher in the conventional soil tillage. Finally, both the type of tillage and kind of fertilization significantly affected leaf Zn. Overall, these data show the importance of innovative dual co-application of pomace (an organic by-product of the wine industry) with reduced soil tillage on soil properties and plant nutrition. Thus, it is expected to gain environmental, ecological, and economic benefits for wine producers and also to improve vineyards' sustainability and protected designation of origin (PDO) wine quality under the challenges provoked by climatic and recent energy crises.

Keywords: *Vitis vinifera* L.; cv. Robola; PDO wines; soil management; reduced soil tillage; organic fertilization; wine industry by-products; controlled-release N fertilization; plant nutrition

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Academic Editors: Ming Zhang, Shuang Wang and Yao Zhao

Received: 1 April 2025
Revised: 2 May 2025
Accepted: 5 May 2025
Published: 12 May 2025

Citation: Chatzistathis, T.; Sarropoulou, V.; Fragkos, A.; Katsalirou, E.; Daskalakis, I.; Biniari, K.; Danalatos, G.; Bountla, A. The Kind of Fertilization and Type of Soil Tillage Affect Soil Fertility and Foliar Nutrient Concentrations in an Experimental Vineyard of Kefalonia. *Environments* **2025**, *12*, 160. https://doi.org/10.3390/environments12050160

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1. Introduction

Vitis vinifera L. is one of the most important perennial crops, reaching approximately 73.1 million tons of fresh grapes in 2018 [1,2], while the economic value of fresh grapes and wines to the international trade is equivalent to approximately GEUR 9.4 and GEUR 37.8, accordingly [3]. The increased cultural and economic significance of the viticultural sector in Greece is mostly emphasized by the high wine production in an area of 2,200,000 hL in 2018 [4], the broad outspread of more than 300 native cultivars within the Greek district that stands for oncoming 100,000 ha of land under the PDO indicator [5], and the high wine export rate of up to 274,000 hL in 2016 [6]. Universally, Greek wines have been characterized by high quality, attributable to several value award labels and chaplain discern marks [7]. Greek wines are among the most famous and qualitative European ones according to Stevenson [8] and Staff [9]. Kefalonia produces the famous white wine of 'Robola', which is a PDO product [10–13]. Concerning the distribution pattern of cultivated vines in Greece, the Ionian islands have higher yields than the average one, with Kefalonia as the biggest island in extent in the region. According to the recent agriculture and livestock census of the Hellenic Statistical Authority for the year 2022 [14], the proportion of vines in the Ionian Islands occupies 4% of the agricultural production, whereas the regional average is 2.5%, with 'Robola' covering 1500 acres of mainly organically cultivated vineyards, with 15 wineries in Kefalonia [15]. High elevations (up to 300 m) and cultivation of Robola cultivar in inclined, low in organic matter content, adequate leaching, and pebbly soils are conditions ensuring higher performance yields and wine qualitative traits [16]. The high quality of Robola wine production in Kefalonia has been associated with precocious ripening, elevated acidity, and high concentrations of phenolics [17,18].

The progressive increase in global grape production has led to the intensification of vineyard management practices during the last decades, starting from the early 2000s [1]. A nexus has been found between different tillage systems (i.e., conventional, no-till, and deep tillage) and soil physical properties, affecting directly soil erodibility [19]. Besides weed control, tillage comes with several advantages related to soil fertility, including grinding and soil mixing with leaves, pruning wood, and other organic materials; in addition, tillage positively influences water infiltration and soil organic matter mineralization, while it also affects nutrient release in available forms for plants and the disintegration of soil compacted layers that impede root intrusion and water mobility throughout the soil depth [20]. On the other hand, conventional soil tillage (CT) often leads to diverse drawbacks, including decreased organic C content due to increased decomposition rates of soil organic matter, increased appearance of compacted soil layers, and loss of structure (i.e., reduced aggregate formation, fragmentation, and stability) [21,22]. In addition, conventional soil tillage was related to elevated soil erosion risk, impairment of vine roots' growth due to soil exposure to runoff and rainfall drop water-stress effects, higher water evaporation from soils [23,24], etc. Finally, within the disadvantages that should not be omitted, CT shows a decline in N, P, and K concentrations of the topsoil [25,26], as well as increased nutrient losses with leaching and denitrification [27], higher destruction of the fungal hyphae and the soil fauna habitats, enhanced development of bacterial communities over eukaryotic soil organisms, and imbalanced soil biome [27–31]. Compared to CT and deep tillage, the application of minimum or reduced tillage (RT) may result in higher soil organic matter accumulation and aggregation in terms of carbon stocks, reduced soil erodibility, and enhanced water infiltration [28,32–34]; furthermore, RT leads to better equilibrium among soil biological communities because of the lower destruction rate of soil fungi and bacteria, as well as to enhanced fungi development [35] and generally increased biological activity, both in the topsoil and at deeper soil layers [25,26].

Fertilizer application plays a crucial role in grapevine physiological growth, yields, and quality of grape-wine products [36]. Compared to inorganic fertilizers, organic ones constitute a more environment-friendly approach towards preserving natural resources, improving soil organic carbon and structure, and restricting the negative environmental impacts of mineral fertilizers by also enhancing soil-beneficial microorganisms [37–40]. The application of N controlled-release fertilizers is an efficient soil management practice for sustainable vineyard production [41]. The advantageous effects of N controlled-release fertilizers on crop yields, as well as on grape and wine quality in various grapevine cultivars, compared to the inorganic fertilizers have been extensively demonstrated by several researchers [42–48].

Vine agro-ecosystems face many challenges, consisting of soil compaction and erosion, organic matter decline, and soil and water pollution due to the overuse of chemicals [49–51]. The co-application of soil conventional tillage and inorganic fertilization has been often associated with various negative aspects, including a decline in soil organic matter and nutrient and water availability; deterioration of porosity, aeration, and aggregation; and impairment of soil biological community [51,52]. The co-implementation of minimum- or reduced-sil tillage and organic or controlled-release fertilization constitutes a promising combined soil strategy for the sustainable management of vineyards [53–56]. In Central European vineyards, it was found that the application of compost, fertilizers, or pomace could alleviate the adverse effects of conventional tillage on several soil properties compared to vineyards that have not been submitted to tillage [57]. As an optimum solution for the improvement in soil health, composed of nutrient availability, biodiversity, and sufficient levels of organic carbon, has been proposed the adoption of suitable combined soil tillage methods and fertilizer inputs [58]. A recent study evaluated the influence of conventional and reduced soil tillage practices, co-applied with different N fertilization strategies (conventional, N controlled-release, and organic), on the physiological performance and grape qualitative characteristics of the wine cultivar 'Robola', in the island of Kefalonia, in selected vineyards [13]. More specifically, it was found that the co-application of reduced tillage and controlled N-release fertilization was the most beneficial soil management practice to achieve higher total soluble solids, pH, and titratable acidity in grapes; furthermore, the combination of conventional tillage and organic fertilization was the most advantageous viticultural practice for higher CO_2 assimilation rate and chlorophyll content [13].

Based on the aforementioned information and according to our knowledge, this study is the first one investigating the combinational effects of the type of soil tillage (conventional and reduced) and kind of fertilization (inorganic, N controlled-release, and organic) on soil properties, fertility, and nutrient uptake by plants of the cultivar 'Robola', in the island of Kefalonia (Ionian islands). Compared to other published studies [51,52,55], which investigated the effects of soil management and sustainable practices on the quality of viticultural products and soil health, our data offer, for the first time, a thorough combinational and innovative approach (of the combined effects of soil tillage and fertilization) on soil fertility and plant nutrition in an experimental vineyard of the cv. 'Robola', producing high-quality PDO wines. Thus, our study was based on the premise that the type of soil tillage and the kind of fertilization significantly affect soil properties, nutrient availability, and uptake by *Vitis vinifera* L. (cv. 'Robola') plants.

Therefore, the aims of our study were as follows: (a) to investigate the combinational effects of the type of soil tillage and kind of fertilization on soil properties, fertility, and nutrient uptake by vine plants; (b) to separate, evaluate, and discuss the impact of each one of these parameters (tillage and fertilization) on crucial soil fertility indicators (such as those of nitrate N, exchangeable K, and organic matter) and foliar macro- and micronutrient concentrations.

2. Materials and Methods

2.1. Special Geomorphological, Climatic, and Soil Characteristics of the Island of Kefalonia

Kefalonia, as a member of the wider island area of Greece, has special topological and climatic characteristics. 'Robola' is one of the most important grape cultivars for white wine production in western Greece and the Ionian Islands. It is quite a vigorous and productive cultivar, exhibiting high adaptability to dry, warm, infertile soils of semi-mountainous areas and resulting in high-quality wine products. Kefalonia is the cultivation zone of 'Robola', producing qualitative PDO white wines. The cultivation zone of Robola covers an area of 4900 ha; it extends from south to north-west of Mount Ainos (1628 m). The zone area is mostly semi-mountainous, with sloping, gravelly, calcareous soils. The vineyards start at an altitude of 150 m and end almost at the edge of the Kefalonian fir (*Abies cephalonica*) vegetation zone, at 680 m. Within this area, there are two large tectonic sinkholes (polges), creating the valleys of Omala and Troyannata. The 'Robola' vineyards are not irrigated, except from the first two years after their establishment; therefore, they manage to grow in a harsh environment, where any other crop could survive. However, cv. 'Robola' produces special, high-quality, monovarietal, PDO wines. During the last years, the climatic crisis made the environmental conditions harsher for its cultivation. Thus, the challenges to providing alternative, sustainable, and stable management solutions to help farmers overcome yield and income losses become crucial. Based on the data provided by the three meteorological stations, located within the 'Robola' zone, approximately 1000 mm of rainfall happens per year. However, the majority of this rainfall is mainly distributed from October to March, with little to no rainfall during the rest of the year. All the above, in combination with the sandy gravelly soils, combined with the often high summer temperatures, create problems in the grape-ripening process. Thus, the most crucial issue is to save and highly utilize water from winter rainfalls and make it available for plants in order to overcome summer water stress [59–61].

2.2. Selection of the Experimental Vineyard and Treatments

A 6-year-old, fully productive vineyard of the 'Robola' cultivar, grafted onto the rootstock 1103P, was selected for experimentation. This vineyard is located in 'KOKKINOPILIA', in a semi-mountainous area (altitude 464 m), in the northern part of the 'Robola' zone (38°12′, 08.92′ N, 20°33′ 23.35′ E) having a western exposure. The soil belongs to the ENTISOLS and is characterized by medium particle size composition (% content in sand, clay, and silt), retaining limited moisture during the summer period. Meteorological data for the annual (2023 and 2024) precipitation and temperature were the following: mean annual (2023 and 2024) precipitations were 56.9 and 64.4 mm, respectively, while mean annual temperatures for 2023 and 2024 were 15.6 °C and 20.0 °C, respectively. With regard to minimum and maximum average temperatures for 2023 and 2024, the following values were recorded: 5.6 °C, 26.2 °C and 9.2 °C, 28.2 °C, respectively, while the absolute minimum and maximum temperatures for 2023 and 2024 were recorded in February 2023 (−3.1 °C), July 2023 (41.1 °C), as well as in January 2024 (2.6 °C) and August 2024 (40.4 °C), respectively.

The Randomized Complete Block Design was selected as the experimental design. The vineyard was divided into three equal experimental blocks, randomly distributed. Each of these blocks was divided into six randomly distributed experimental units (i.e., 6 treatments), also randomly distributed within the experimental blocks. Each experimental unit (of 66 m^2), within each block, was subjected to 6 treatments as follows:

(1) Conventional tillage (CT) and application of conventional (inorganic) fertilization (CF) (i.e., Control: CT-CF);
(2) Conventional tillage (CT) and application of a N controlled-release fertilizer (CRF) (i.e., CT-CRF);
(3) Conventional tillage (CT) and application of organic fertilization (OF) (i.e., CT-OF);
(4) Reduced tillage (RT) and application of conventional fertilization (CF) (i.e., RT-CF);
(5) Reduced tillage (RT) and application of a N controlled-release fertilizer (CRF) (i.e., RT-CRF);
(6) Reduced tillage (RT) and application of organic fertilization (OF) (i.e., RT-OF).

In the CT-OF and RT-OF treatments, where organic fertilization was applied, organic phosphorus from animal bones was used (i.e., NPK 0-27-0), while in the other treatments, a conventional phosphorus fertilizer was used (NPK 0-46-0). In the CT-CF (control) and RT-CF treatments, conventional N fertilization (NPK 21-0-0) was used; in the treatments CT-CRF and RT-CRF, a N controlled-release fertilizer (NPK 21-0-0) was used. The applied organic compost (pomace, a by-product of the wine industry) had the following nutrient content: N—1.92%, P—0.18%, K—1.50%, Ca—0.89%, Mg—0.13%, Fe—204 mg kg^{-1}, Mn—18 mg kg^{-1}, Zn—13 mg kg^{-1}, Cu—23 mg kg^{-1}, and B—37 mg kg^{-1}. The initial (before treatments' application) soil properties of the vineyard were the following: pH—7.96; EC—0.37; organic matter—3.58%; $CaCO_3$—36.9%; nitrate N—7.28 mg kg^{-1}—Olsen P—6.77 mg kg^{-1}; exchangeable K—527 mg kg^{-1}; exchangeable Mg—120 mg kg^{-1}; DTPA extractable Fe, Mn, Zn and Cu concentrations—8.57, 12.17, 1.09 and 2.02 mg kg^{-1}, respectively; and extractable B was 0.26 mg kg^{-1}. The application rates of all the fertilizers were quantified (based also on preliminary soil fertility analyses, as well as on a special software determination of nutrient application rates) in order to achieve equal nutrient units among the treatments. More specifically, the application rates were the following: pomace—1740 g per plant and NPK (21-0-0) fertilizer (both conventional and N controlled-release)—59 g per plant.

The conventional rototilling method involved soil rot tillage using a machine called a rot tiller during the winter period, aiming at incorporating fertilizers into the soil and destroying weeds, followed by another rot tillage during the spring period. In the conventional tillage treatments (i.e., CT-CF, CT-CRF, and CT-OF), the first soil elaboration was carried out after the first fertilization in order to incorporate the fertilizer. In the reduced tillage treatments (i.e., RT-CF, RT-CRF, and RT-OF), rot tilling was limited to a narrow strip along the row of vines, solely for the purpose of incorporating fertilizer. Every year, the tilled strip alternates between each side of the row. In the rest of the field, native vegetation cutting was performed and the clippings were left on the soil surface.

2.3. Soil and Leaf Sampling and Lab Analysis

Soil sampling was performed during the full blooming period of vines, from the upper 30 cm (where the highest part of the vine root system exists). More specifically, samples were received within the canopies of three selected healthy and well-developed vines per plot. After receiving these samples, they were transferred to a lab, where they were dried at room temperature while stones were also removed; afterward, they were sieved through a 10-plexus dredge prior to chemical analysis. The value of pH, organic matter, NO_3-N and $CaCO_3$ content, available P, exchangeable cations (K and Mg), and the concentrations of micronutrients (Fe, Mn, Zn, Cu, and B) were defined. Particularly, pH was estimated in a soil-distilled water paste (1:1) [62], and the organic matter and $CaCO_3$ content via the potassium dichromate [63] and acid neutralization methods, respectively. The determination of macronutrient concentrations was achieved using the VCl_3/Griess method for nitrate nitrogen (NO_3-N) [64], the Olsen method for available P [65], and the ammonium acetate extraction method for exchangeable K and Mg [66]. The determination of micronutrient concentrations was realized with the method described by Wolf [67] for B, and by the diethylenetriaminepentaacetic acid (DTPA) method (pH 7.3) for Fe, Mn, Zn, and Cu.

Leaf samples were received from healthy youngest mature leaves, randomly selected from well-developed vines per plot; the samples were received during the full blooming period of the vineyard and they were immediately transferred to the lab. Prior to chemical analyses, all the leaf tissues underwent drying, processing until the formation of a fine powder, and sieving via a 30-plexus dredge. Afterward, 0.5 g of the fine powder of each sample was weighed and subjected to incineration for 5 h in a muffle furnace at 515 °C. Dissolution of the ash in 3 mL of 6 N HCl and dilution with double-distilled water, up to 50 mL, were subsequently applied. For the determination of nutrient concentrations, the ICP (OPTIMA 2100 DV optical emission spectrometer, Perkin Elmer, Waltham, MA, USA) spectrometric method was applied for P, K, Ca, Mg, Fe, Mn, Zn, and Cu [68], and the Kjeldahl method for N [69]. Macronutrient concentrations (N, P, K, Ca, and Mg) were expressed in % Dry Weight (DW) and those of micronutrients (B, Fe, Mn, Zn, and Cu) were expressed in mg kg^{-1} DW.

2.4. Statistical Analysis

The data were statistically analyzed using the SPSS statistical program (version 28, IBM, Armonk, NY, USA), the ONE-WAY ANOVA for Post Hoc Multiple Comparisons, the Duncan's multiple range test at the significance level of 0.05 ($p \leq 0.05$) for equal variances assumed, and the General Linear Model to identify the effect of the main factors and their interaction for $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$. For each growing season (1st: winter 2022-autumn 2023 and 2nd: winter 2023-autumn 2024), the experimental design was a 2×3 (=6 treatments) completely randomized factorial, including two soil tillage types (conventional and reduced) and three kinds of fertilization (conventional, N controlled-release, and organic). In each treatment, 3 plants (i.e., replicates) were included; thus, 18 experimental plants were used in total. Descriptive statistics (mean value, standard deviation, standard error, lower and upper bound for mean at 95% confidence interval, and minimum–maximum mean) were used for data processing and interpretation. Tests of between-subject effects included Corrected Model, Intercept, error and total as sources, Type III Sum of Squares, degree of freedom (df), Mean Square, F value, and significance *p*-value between groups, within groups, and total per each evaluated parameter. The Levene statistics and significance *p*-value were used to test the homogeneity of variances. The main effect of factors (tillage type and fertilization kind) and their interaction (tillage×fertilization) were evaluated using the Multivariate Full Factorial General Linear Model at the significance level of 0.05, 0.01, and 0.001, with confidence intervals set at 95.0%. The Pearson correlation coefficient and 2-tailed test of significance (at the 0.05 and 0.01 level) were adopted to identify positive and negative correlations among the different evaluated parameters including the correlation of 'soil tillage type', 'fertilization kind', and 'treatments' (=tillage type × fertilization interaction) as factors with evaluated parameters. The correlation data were visualized in scatterplot matrix (SPLOM) graphs.

3. Results

3.1. Effect of Type of Tillage and Kind of Fertilization on pH, Organic Matter, % $CaCO_3$, and Electrical Conductivity During the First and Second Growing Season

None of the parameters describing soil properties (pH, electrical conductivity-EC, organic matter-OM, and % $CaCO_3$) in the first growing period was significantly affected by the type of tillage and the kind of fertilization (p = 0.074–0.940 > 0.05) (Table 1). In the second growing period, pH was significantly affected only by the type of fertilization ($p = 0.002 \leq 0.05$), and was significantly higher under organic fertilization compared to the conventional regardless of the type of soil tillage (Table 1). Finally, the unique significant difference in % organic matter (OM) content was recorded only in the second growing period between the CT-OF (6.98%) and RT-OF (4.56%) treatments (Table 1) since in all the other cases insignificant differences were found; insignificant were also all the interactions between the type of soil tillage and kind of fertilization for pH, EC, OM, and $CaCO_3$ for both growing periods (Table 1).

Table 1. Effect of type of soil tillage (conventional-CT and reduced-RT) and kind of fertilization (conventional-CF, controlled N release-CRF, and organic-OF) on pH, EC, organic matter, and $CaCO_3$ content (%) during the 1st and 2nd growing periods.

Growing Period	Type of Soil Tillage	Kind of Fertilization	pH	EC (mS/cm)	OM (%)	$CaCO_3$ (%)
1st (Winter 2022–Autumn 2023)	CT	CF	7.89 ± 0.11A	0.64 ± 0.07 A	3.58 ± 0.18 A	24.40 ± 8.10 A
		CRF	7.92 ± 0.13 A	0.57 ± 0.19 A	4.09 ± 0.55 A	20.30 ± 9.13 A
		OF	7.92 ± 0.16 A	0.52 ± 0.11 A	4.34 ± 0.81 A	23.60 ± 5.50 A
	RT	CF	7.88 ± 0.08 A	0.67 ± 0.10 A	4.17 ± 0.77 A	30.05 ± 2.25 A
		CRF	7.89 ± 0.14 A	0.80 ± 0.44 A	4.01 ± 1.31 A	29.07 ± 11.11 A
		OF	7.85 ± 0.23 A	0.54 ± 0.11 A	4.26 ± 0.58 A	33.80 ± 12.91 A
2nd (Winter 2023–Autumn 2024)	CT	CF	7.51 ± 0.08 BC	1.59 ± 0.84 A	4.94 ± 0.14 B	23.37 ± 9.95 A
		CRF	7.58 ± 0.15 ABC	1.13 ± 0.43 AB	4.79 ± 0.82 B	21.95 ± 8.55 A
		OF	7.76 ±0.11 A	0.61 ± 0.08 B	4.96 ± 0.66 B	25.37 ± 5.75 A
	RT	CF	7.44 ± 0.09 C	0.80 ± 0.16 B	4.87 ± 0.70 B	26.95 ± 3.05 A
		CRF	7.65 ± 0.08 AB	0.92 ± 0.11 AB	5.62 ± 0.21 AB	25.63 ± 8.80 A
		OF	7.72 ± 0.06 A	0.67 ± 0.03 B	6.98 ± 1.46 A	16.50 ± 5.90 A
General Linear Model—1st growing period (*p*-values)						
Type of soil tillage (A)			0.613 ns	0.343 ns	0.706 ns	0.074 ns
Kind of fertilization (B)			0.984 ns	0.441 ns	0.642 ns	0.737 ns
(A) × (B)			0.940 ns	0.633 ns	0.691 ns	0.903 ns
General Linear Model—2nd growing period (*p*-values)						
Type of soil tillage (A)			0.762 ns	0.118 ns	0.048 *	0.881 ns
Kind of fertilization (B)			0.002 **	0.080 ns	0.432 ns	0.612 ns
(A) × (B)			0.477 ns	0.204 ns	0.071 ns	0.276 ns

Means (n = 3) ± standard deviation (S.D.). Different capital letters in each column for each parameter (pH, EC, OM, and $CaCO_3$) per growing period among the 6 treatments (derived from the combined effect of type of soil tillage and kind of fertilization) symbolize statistically significant differences, at the 5% level (ONE-WAY ANOVA, Duncan's multiple range test, $p \leq 0.05$). ns: non-significant ($p > 0.05$), * significant at the 5% level ($p \leq 0.05$), and ** significant at the 1% level ($p \leq 0.01$) based on the General Linear Model.

3.2. Effect of Type of Soil Tillage and Kind of Fertilization on Nitrate N, Olsen Extractable P, Exchangeable Cations, and DTPA Extractable Micronutrients During the First and Second Growing Season

For both growing periods, Olsen extractable P and exchangeable K concentrations were not significantly affected, neither by the type of soil tillage, nor by the kind of fertilization; in contrast, significant was the effect of soil tillage on exchangeable Mg ($p = 0.045$, ≤ 0.05), but only in the first growing period (Table 2).

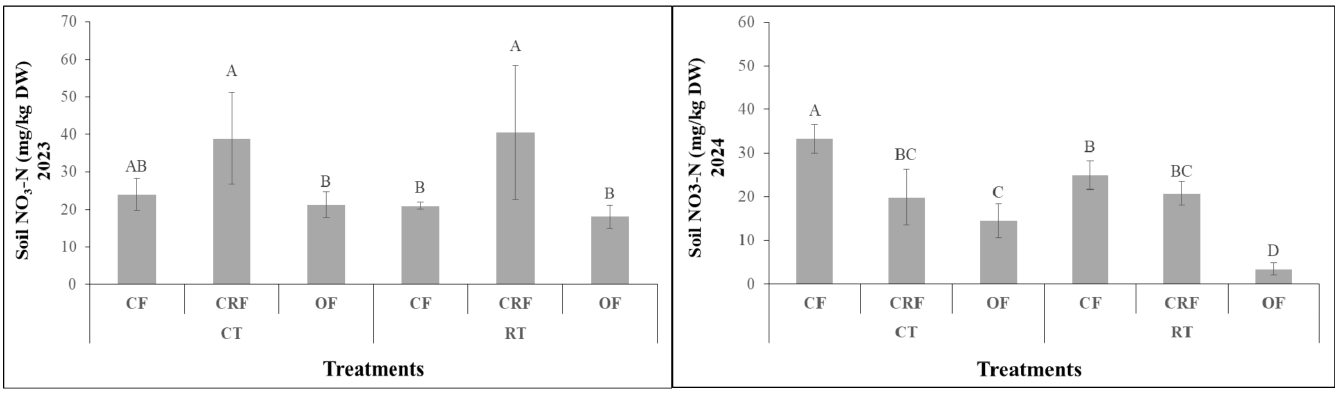
Regarding soil nitrate N, for both growing periods, the kind of fertilization significantly affected nitrate concentrations ($p = 0.000$–0.005) (Figure 1a,b), while the type of soil tillage and their interaction (fertilization × soil tillage) significantly influenced ($p = 0.000$–0.044) soil nitrate concentrations, but only in the second growing period (Figure 1b).

Based on the obtained data for micronutrients, it is clear from Table 3 that only B and Zn were significantly affected by the kind of fertilization ($p = 0.013$ and 0.008, respectively), the first nutrient was affected only in the first growing period and the second one only in the second growing period (Table 3). The influence of soil tillage was non-significant for all the micronutrients and for both growing periods; similarly, all the interaction effects fertilization*soil tillage were non-significant in both growing periods (Table 3).

Table 2. Effect of type of soil tillage (conventional-CT and reduced-RT) and kind of fertilization (conventional-CF, controlled N release-CRF, and organic-OF) on Olsen extractable P, and exchangeable K and Mg concentrations (mg/kg DW) during the 1st and 2nd growing periods.

Growing Period	Type of Soil Tillage	Kind of Fertilization	P (mg kg^{-1} DW)	K (mg kg^{-1} DW)	Exchangeable Mg (mg kg^{-1} DW)
1st (Winter 2022–Autumn 2023)	CT	CF	20.04 ± 8.04 A	649.67 ± 122.85 A	122.67 ± 4.73 AB
		CRF	18.02 ± 7.44 A	667.00 ± 104.36 A	118.67 ± 10.50 AB
		OF	19.26 ± 1.25 A	833.33 ± 109.43 A	142.67 ± 16.50 A
	RT	CF	18.78 ± 6.21 A	574.33 ± 172.14 A	108.67 ± 17.95 B
		CRF	23.33 ± 9.97 A	566.00 ± 182.00 A	112.00 ± 21.93 AB
		OF	21.08 ± 3.68 A	707.00 ± 109.66 A	113.33 ± 16.80 AB
2nd (Winter 2023–Autumn 2024)	CT	CF	21.93 ± 1.51 A	671.33 ± 110.02 A	114.67 ± 14.64 A
		CRF	23.09 ± 3.53 A	706.33 ± 96.03 A	126.33 ± 14.64 A
		OF	29.01 ± 7.44 A	901.00 ± 94.40 A	138.00 ± 13.75 A
	RT	CF	24.67 ± 5.28 A	711.67 ± 110.15 A	121.33 ± 18.90 A
		CRF	31.02 ± 4.83 A	671.33 ± 171.61 A	117.67 ± 14.36 A
		OF	26.06 ± 3.16 A	707.33 ± 231.45 A	115.67 ± 25.77 A
General Linear Model—1st growing period (p-values)					
Type of soil tillage (A)			0.550 ns	0.144 ns	0.045 *
Kind of fertilization (B)			0.948 ns	0.116 ns	0.319 ns
(A) × (B)			0.707 ns	0.950 ns	0.469 ns
General Linear Model—2nd growing period (p-values)					
Type of soil tillage (A)			0.266 ns	0.375 ns	0.346 ns
Kind of fertilization (B)			0.267 ns	0.323 ns	0.691 ns
(A) × (B)			0.174 ns	0.388 ns	0.388 ns

Means (n = 3) ± standard deviation (S.D.). Different capital letters in each column for each parameter (P, K, exchangeable Mg) per growing period among the 6 treatments (derived from the combined effect of type of soil tillage and kind of fertilization) symbolize statistically significant differences, at the 5% level (ONE-WAY ANOVA, Duncan's multiple range test, $p \leq 0.05$). ns: non-significant ($p > 0.05$) and * significant difference at the 5% level ($p \leq 0.05$) based on the General Linear Model.



(**a**) (**b**)

Figure 1. Effect of tillage type (conventional—CT and reduced—RT) and kind of fertilization (conventional—CF, controlled-release—CRF, and organic—OF) on the concentration (mg/kg DW) of NO3-N in soil: (**a**) during the 1st (year 2023) growing season; (**b**) during the 2nd (year 2024) growing season Bars are standard deviations. In each diagram, column bars, accompanied by different capital letters among the six treatments (CT-CF, CT-CRF, CT-OF, RT-CF, RT-CRF, and RT-OF) derived from the combined effect of two tillage types (CT and RT) × three fertilization kinds (CF, CRF, and OF), denote statistically significant differences at the 5% level (ONE-WAY ANOVA, Duncan's test, $p \leq 0.05$).

Table 3. Effect of type of soil tillage (conventional-CT and reduced-RT) and kind of fertilization (conventional-CF, controlled N release-CRF, and organic-OF) on extractable micronutrient concentrations (B, Fe, Zn, Mn, and Cu) (mg/kg DW) during the 1st and 2nd growing periods.

Treatment			Soil Micronutrient Concentration				
Growing Period	Type of Soil Tillage	Kind of Fertilization	B (mg kg^{-1} DW)	Fe (mg kg^{-1} DW)	Zn (mg kg^{-1} DW)	Mn (mg kg^{-1} DW)	Cu (mg kg^{-1} DW)
1st (Winter 2022–Autumn 2023)	CT	CF	2.61 ± 1.01 AB	3.11 ± 0.50 A	1.20 ± 0.35 A	10.97 ± 2.33 A	2.42 ± 0.42 A
		CRF	2.70 ± 1.56 AB	2.90 ± 0.32 A	1.04 ± 0.29 A	10.57 ± 1.82 A	2.37 ± 0.52 A
		OF	0.95 ± 0.03 C	3.14 ± 0.30 A	1.28 ± 0.10 A	12.52 ± 1.07 A	2.63 ± 0.35 A
	RT	CF	2.55 ± 0.82 AB	2.94 ± 0.18 A	1.07 ± 0.29 A	8.97 ± 2.76 A	2.24 ± 0.37 A
		CRF	3.67 ± 1.01 A	3.20 ± 0.45 A	1.20 ± 0.31 A	9.10 ± 3.02 A	2.45 ± 0.43 A
		OF	0.78 ± 0.20 C	3.01 ± 0.14 A	1.14 ± 0.21 A	13.16 ± 0.77 A	2.24 ± 0.47 A
2nd (Winter 2023–Autumn 2024)	CT	CF	3.31 ± 0.54 AB	6.00 ± 0.36 A	0.76 ± 0.17 B	12.37 ± 1.38 A	2.29 ± 0.29 A
		CRF	4.41 ± 2.81 AB	6.31 ± 0.53 A	1.16 ± 0.14 A	14.25 ± 2.18 A	2.36 ± 0.61 A
		OF	3.63 ± 0.27 AB	6.95 ± 0.61 A	1.17 ± 0.11 A	14.98 ± 2.31 A	2.75 ± 0.16 A
	RT	CF	2.81 ± 0.06 B	6.04 ± 0.58 A	0.91 ± 0.25 AB	12.10 ± 2.79 A	2.29 ± 0.61 A
		CRF	4.16 ± 1.47 AB	7.05 ± 0.77 A	1.27 ± 0.29 A	11.85 ± 1.34 A	2.69 ± 0.29 A
		OF	5.73 ± 1.45 A	6.26 ± 0.38 A	1.18 ± 0.08 A	11.78 ± 1.13 A	2.56 ± 0.23 A
General Linear Model—1st growing period			(p-values)				
Type of soil tillage (A)			0.662 ns	0.978 ns	0.774 ns	0.366 ns	0.439 ns
Kind of fertilization (B)			0.013 *	0.972 ns	0.833 ns	0.053 ns	0.908 ns
(A) × (B)			0.662 ns	0.445 ns	0.589 ns	0.544 ns	0.640 ns
General Linear Model—2nd growing period			(p-values)				
Type of soil tillage (A)			0.520 ns	0.914 ns	0.317 ns	0.055 ns	0.784 ns
Kind of fertilization (B)			0.171 ns	0.119 ns	0.008 **	0.595 ns	0.319 ns
(A) × (B)			0.266 ns	0.122 ns	0.795 ns	0.432 ns	0.547 ns

Means (n = 3) ± standard deviation (S.D.). Different capital letters in each column for each parameter (B, Fe, Zn, Mn, and Cu) per growing period among the 6 treatments (derived from the combined effect of type of soil tillage and kind of fertilization) symbolize statistically significant differences, at the 5% level (ONE-WAY ANOVA, Duncan's multiple range test, $p \leq 0.05$). ns: non-significant ($p > 0.05$), * significant at the 5% level ($p \leq 0.05$), and ** significant difference at the 1% level ($p \leq 0.01$) based on the General Linear Model.

3.3. Effect of Type of Tillage and Kind of Fertilization on Foliar Nutrient Concentrations During the 1st and 2nd Growing Season

In the first growing period, significant differences among the treatments existed only for N (Figure 2a), Ca (Figure 2c), and Mg concentrations (Figure 2e), and for the ratio of K/Mg (Table 4). The differences detected were mainly due to the effect of the kind of fertilization ($p = 0.004$) for N, and due to the effect of the type of soil tillage for K, Ca, and Mg concentrations and the K/Mg ratio ($p = 0.038$, 0.001, 0.009, and 0.000, respectively); the ratio of K/Mg was also significantly affected by the interaction type of soil tillage x kind of fertilization ($p = 0.040$) (Tables 4 and 5).

In the second growing period, leaf P concentration was higher in the RT-OF treated plants; the differences in foliar P were owed to the effect of kind of fertilization ($p = 0.000$), as well as to the interaction type of soil tillage x kind of fertilization ($p = 0.013$) (Table 4). With regard to Mg, its highest foliar concentration was found in the CT-CRF treatment (Figure 2f); the differences in Mg concentrations were owed to the main effect of the type of soil tillage ($p = 0.002$) (Table 5).

Regarding micronutrients, in the first growing period, significant differences among the treatments were detected only for Mn; these differences were owed to the main effect of soil tillage ($p = 0.042 \leq 0.05$) (Table 6). In the second growing period, there were significant differences only for Zn and Cu. More specifically, the effect of the type of soil tillage exerted a significant influence both on Zn and Cu concentrations ($p = 0.001$–0.003), while the kind of fertilization significantly affected only leaf Zn ($p = 0.009$) (Table 6).

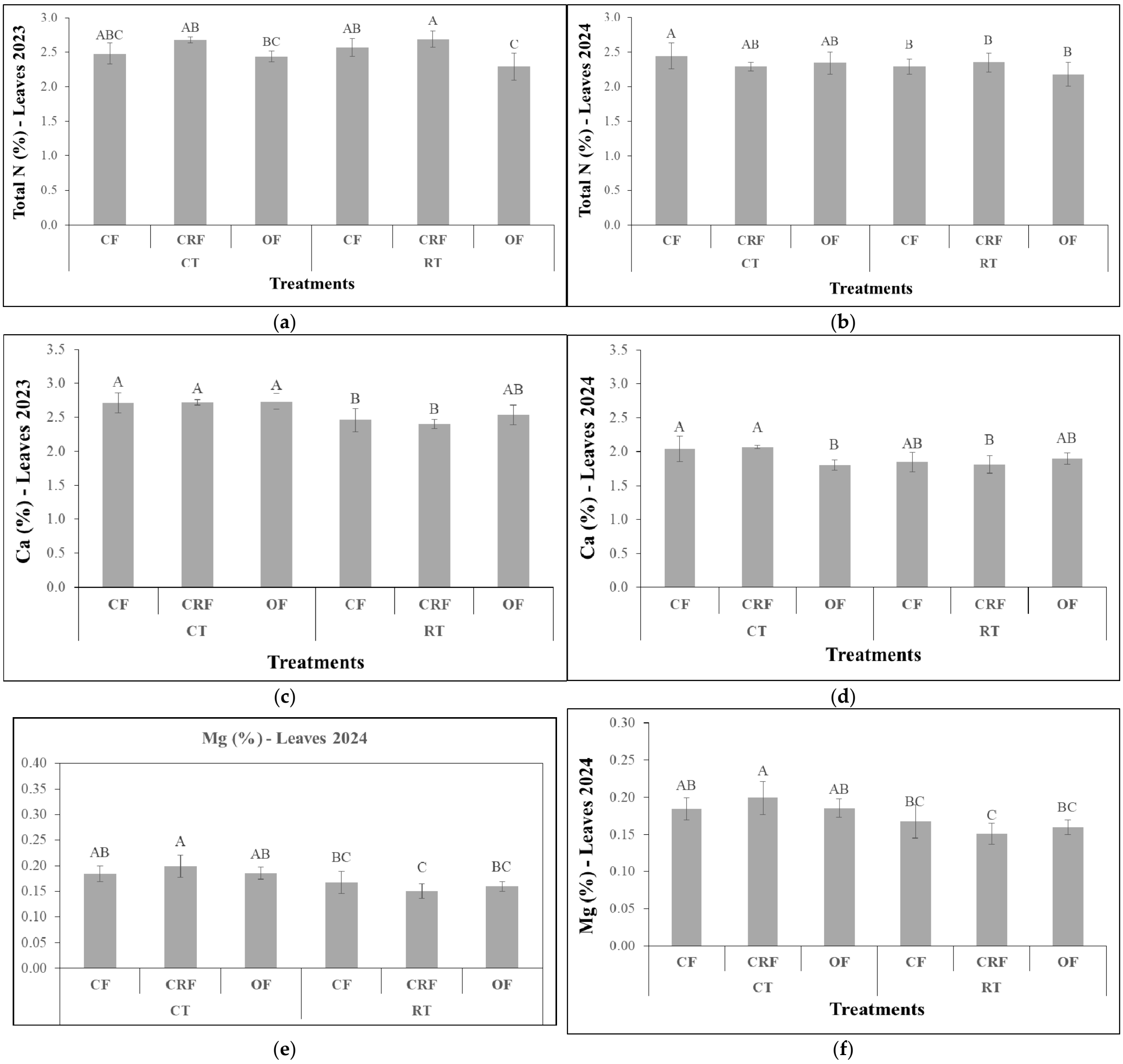


Figure 2. Effect of tillage type (conventional—CT and reduced—RT) and kind of fertilization (conventional—CF, controlled-release—CRF, and organic—OF) on foliar N, Ca, and Mg concentrations during the 1st and 2nd growing seasons: (**a**) total N (%) in the 1st growing period, (**b**) total N (%) in the 2nd growing period, (**c**) Ca (%) in the 1st growing period, (**d**) Ca (%) in the 2nd growing period, (**e**) Mg (%) in the 1st growing period, and (**f**) Mg (%) in the 2nd growing period. Bars are standard deviations. In each diagram, column bars, accompanied by different capital letters among the six treatments (CT-CF, CT-CRF, CT-OF, RT-CF, RT-CRF, and RT-OF), derived from the combined effect of two tillage types (CT and RT) × three fertilization kinds (CF, CRF, and OF), denote statistically significant differences at the 5% level (ONE-WAY ANOVA, Duncan's test, $p \leq 0.05$).

Table 4. Effect of type of soil tillage (conventional-CT and reduced-RT) and kind of fertilization (conventional-CF, controlled N release-CRF, and organic-OF) on foliar P and K concentrations (% DW), as well as on the ratio of K/Mg during the 1st and 2nd growing periods.

Growing Period	Type of Soil Tillage	Kind of Fertilization	P (% DW)	K (% DW)	K/Mg
1st (Winter 2022–Autumn 2023)	CT	CF	0.23 ± 0.01 A	0.63 ± 0.07 A	2.22 ± 0.23 CD
		CRF	0.24 ± 0.04 A	0.60 ± 0.03 A	2.06 ± 0.21 D
		OF	0.24 ± 0.01 A	0.62 ± 0.03 A	2.45 ± 0.15 BC
	RT	CF	0.23 ± 0.01 A	0.67 ± 0.03 A	2.88 ± 0.12 A
		CRF	0.22 ± 0.01 A	0.64 ± 0.01 A	2.59 ± 0.07 AB
		OF	0.23 ± 0.03 A	0.65 ± 0.06 A	2.59 ± 0.13 AB

Table 4. *Cont.*

Growing Period	Type of Soil Tillage	Kind of Fertilization	P (% DW)	K (% DW)	K/Mg
2nd (Winter 2023–Autumn 2024)	CT	CF	0.16 ± 0.006 CD	0.63 ± 0.08 A	3.42 ± 0.43 A
		CRF	0.17 ± 0.010 BC	0.64 ± 0.10 A	3.27 ± 0.70 A
		OF	0.18 ± 0.012 B	0.70 ± 0.03 A	3.77 ± 0.32 A
	RT	CF	0.15 ± 0.004 D	0.66 ± 0.11 A	4.02 ± 1.06 A
		CRF	0.15 ± 0.008 D	0.63 ± 0.07 A	4.24 ± 0.79 A
		OF	0.20 ± 0.004 A	0.64 ± 0.02 A	4.01 ± 0.26 A
	General Linear Model—1st growing period (*p*-values)				
	Type of soil tillage (A)		0.436 ns	0.072 ns	0.000 ***
	Kind of fertilization (B)		0.885 ns	0.418 ns	0.070 ns
	(A) × (B)		0.393 ns	0.955 ns	0.040 *
	General Linear Model—2nd growing period (*p*-values)				
	Type of soil tillage (A)		0.482 ns	0.710 ns	0.340 ns
	Kind of fertilization (B)		0.000 ***	0.779 ns	0.717 ns
	(A) × (B)		0.013 *	0.616 ns	0.655 ns

Means (n = 3) ± standard deviation (S.D.). Different capital letters in each column for each parameter (P, K, and K/Mg) per growing period among the 6 treatments (derived from the combined effect of type of soil tillage and kind of fertilization) symbolize statistically significant differences, at the 5% level (ONE-WAY ANOVA, Duncan's multiple range test, $p \leq 0.05$). ns: non-significant ($p > 0.05$), * significant at the 5% level ($p \leq 0.05$), and *** significant difference at the 0.1% level ($p \leq 0.001$) based on the General Linear Model.

Table 5. Analysis of Variance (ANOVA), *p*-values, and General Linear Model—effect of type of soil tillage and kind of fertilization, as main factors, and their interactions on foliar N, Ca, and Mg concentrations during the 1st and 2nd growing season.

ANOVA/ General Linear Model	1st Growing Period (Year 2023)			2nd Growing Period (Year 2024)		
	Total N (%)	Ca (%)	Mg (%)	Total N (%)	Ca (%)	Mg (%)
Type of soil tillage (A)	0.858 ns	0.001 **	0.009 **	0.135 ns	0.060 ns	0.002 **
Kind of fertilization (B)	0.004 **	0.591 ns	0.439 ns	0.316 ns	0.368 ns	0.936 ns
(A) × (B)	0.306 ns	0.725 ns	0.125 ns	0.200 ns	0.058 ns	0.267 ns

ns: non-significant ($p > 0.05$) and ** significant effect at the 1% level ($p \leq 0.01$).

Table 6. Effect of type of soil tillage (conventional-CT and reduced-RT) and kind of fertilization (conventional-CF, controlled-release-CRF, and organic-OF) on foliar micronutrient concentrations (B, Mn, Zn, Fe, and Cu) during the 1st and 2nd growing periods.

Treatment			Leaf Micronutrient Concentration				
Growing Period	Type of Soil Tillage	Kind of Fertilization	B (mg kg^{-1} DW)	Mn (mg kg^{-1} DW)	Zn (mg kg^{-1} DW)	Fe (mg kg^{-1} DW)	Cu (mg kg^{-1} DW)
1st (Winter 2022–Autumn 2023)	CT	CF	42.43 ± 5.83 AB	37.25 ± 3.63 AB	9.98 ± 3.05 A	111.69 ± 27.25 A	9.59 ± 0.51 A
		CRF	46.04 ± 7.06 A	46.00 ± 5.85 A	9.27 ± 1.44 A	102.90 ± 1.55 A	8.69 ± 0.64 A
		OF	46.22 ± 6.23 A	35.40 ± 2.50 AB	8.84 ± 1.22 A	95.93 ± 4.35 A	9.08 ± 0.54 A
	RT	CF	38.79 ± 4.88 AB	34.71 ± 10.17 AB	8.67 ± 0.55 A	93.15 ± 4.06 A	8.70 ± 0.77 A
		CRF	34.76 ± 0.22 B	33.33 ± 7.73 B	9.92 ± 0.84 A	101.44 ± 4.96 A	9.24 ± 0.91 A
		OF	47.98 ± 4.33 A	30.97 ± 2.47 B	10.67 ± 2.57 A	104.91 ± 22.37 A	9.08 ± 0.74 A
2nd (Winter 2023–Autumn 2024)	CT	CF	54.38 ± 4.26 AB	62.63 ± 14.76 A	6.69 ± 2.20 A	95.33 ± 6.88 A	7.35 ± 0.25 AB
		CRF	56.00 ± 7.03 AB	67.05 ± 22.30 A	5.94 ± 1.60 AB	94.27 ± 18.01 A	7.97 ± 0.48 A
		OF	52.92 ± 3.89 AB	54.82 ± 9.02 A	7.80 ± 0.50 A	91.05 ± 4.99 A	7.85 ± 0.34 A
	RT	CF	46.29 ± 3.76 B	58.28 ± 14.24 A	3.42 ± 0.07 C	84.34 ± 8.27A	6.65 ± 0.55 B
		CRF	50.61 ± 6.40 AB	51.37 ± 1.93 A	4.14 ± 0.58 C	87.32 ± 2.53 A	7.13 ± 0.37 B
		OF	58.18 ± 4.62 A	52.89 ± 0.75 A	6.75 ± 0.68 A	84.15 ± 5.69 A	7.02 ± 0.11 B

Table 6. *Cont.*

Treatment			Leaf Micronutrient Concentration				
Growing Period	**Type of Soil Tillage**	**Kind of Fertilization**	**B (mg kg^{-1} DW)**	**Mn (mg kg^{-1} DW)**	**Zn (mg kg^{-1} DW)**	**Fe (mg kg^{-1} DW)**	**Cu (mg kg^{-1} DW)**
General Linear Model—1st growing period							
Type of soil tillage (A)			0.101 ns	0.042 *	0.666 ns	0.606 ns	0.333 ns
Kind of fertilization (B)			0.079 ns	0.223 ns	0.921 ns	0.968 ns	0.904 ns
(A) × (B)			0.138 ns	0.342 ns	0.362 ns	0.301 ns	0.242 ns
General Linear Model—2nd growing period							
Type of soil tillage (A)			0.282 ns	0.253 ns	0.003 **	0.079 ns	0.001 **
Kind of fertilization (B)			0.252 ns	0.654 ns	0.009 **	0.828 ns	0.060 ns
(A) × (B)			0.099 ns	0.628 ns	0.296 ns	0.907 ns	0.945 ns

Means (n = 3) ± standard deviation (S.D.). Different capital letters in each column for each parameter (B, Mn, Zn, Fe, Cu) per growing period among the 6 treatments (derived from the combined effect of type of soil tillage and kind of fertilization) symbolize significant differences, at the 5% level (ONE-WAY ANOVA, Duncan's multiple range test, $p \leq 0.05$). ns: non-significant ($p > 0.05$), * significant at the 5% level ($p \leq 0.05$), and ** significant difference at the 1% level ($p \leq 0.01$) based on the General Linear Model.

3.4. Pearson Correlation Coefficient Analysis and Scatterplot (SPLOM) Graphs Among the Different Evaluated Parameters

In the first growing period, the Pearson correlation coefficient analysis revealed negative correlations of the combined soil tillage–fertilization treatments with leaf Mg or leaf Zn concentration, whereas the K/Mg ratio in the leaves was positively correlated with the tillage–fertilization combination treatments. There was a positive correlation of soil content in $CaCO_3$ or leaf K/Mg ratio with soil tillage type as an individual factor, whereas exchangeable Mg concentration and leaf Ca, Mg, and Zn concentrations were negatively correlated with soil tillage type. In the case of the kind of fertilization as the main factor, the correlation with soil Mn concentration was positive and with soil B concentration negative. Considering the correlation among the different evaluated parameters, irrespective of treatment, soil pH was negatively correlated with soil EC, in contrast to the positive correlations found between pH and soil organic matter (OM) content or soil P, Zn, and Cu. Positive were the observed correlations between soil EC and $CaCO_3$ or soil NO_3-N concentration or soil B concentration, contrary to the positive correlations of EC with soil concentration in K and Mg. The OM content was positively correlated with soil P, Fe, Zn, or Cu concentrations, but negatively with foliar Cu concentration. Leaf Zn concentration and leaf K/Mg ratio were positively correlated with soil $CaCO_3$ content, contrary to the negative correlation detected by soil K, leaf Mn, and Mg concentration, in both soil and leaves. Significant positive correlations were found between soil NO_3-N—soil B; soil P—soil Zn, Mn, or Cu; soil K—soil Mg; soil Fe—soil Zn or Cu; soil Zn—soil Mn or Cu; soil Mn—soil OM content, soil P or Cu; soil Cu—soil Fe; leaf K—leaf K/Mg ratio; leaf Ca—leaf Mg or B; leaf Mg—leaf Zn; and leaf Fe—leaf Zn or Mn. Accordingly, significant negative correlations were found among soil B—soil K or Mn; leaf K—leaf Zn or Fe; and leaf K/Mg—leaf Ca, Mg, or Zn concentration (Table S1, Figure S1).

In the second growing period, the Pearson correlation coefficient analysis revealed only significantly negative correlations of the combined soil tillage–fertilization treatments with soil EC value, soil NO_3-N concentration, and foliar N, Ca, Mg, Fe, or Cu concentrations. There was a positive correlation of leaf K/Mg ratio with soil tillage type as an individual factor, whereas soil Mn and leaf Mg, Mn, Fe, and Cu concentration were negatively correlated with tillage type (conventional and reduced). In the case of kind of fertilization (conventional, controlled-release, and organic) as the main factor, its correlation with pH, soil Zn, leaf P, and Mn concentration was positive, while with EC value and soil NO_3-N concentration was negative. The following significant positive correlations were found among the different evaluated parameters: soil pH—soil P, Fe, or Cu and leaf P;

soil EC—soil NO_3-N or leaf Ca; soil OM—soil Fe or Cu; soil NO_3-N—leaf total N; soil P—soil Fe, Zn, or Cu; soil exchangeable K—soil Fe or exchangeable Mg; soil exchangeable Mg—leaf Mg, soil Fe or Mn; soil Fe—soil Zn or Cu; soil Zn—soil Cu; soil Mn—leaf Mg, Zn, or Cu; leaf total N—leaf Fe; leaf P—leaf B or Mn; leaf K/Mg ratio—leaf K concentration; leaf Ca—leaf Mg; leaf B—leaf Mn; and leaf Cu—leaf Fe or Mg. Accordingly, significant negative correlations were found between pH—EC; soil NO_3-N concentration—pH, soil Zn or leaf P; leaf Ca—soil P or Fe; leaf K/Mg ratio—soil Mn, leaf Ca, Mg or Zn concentration; leaf Zn—soil Cu or leaf K; and leaf total N—leaf P, leaf or soil B (Table S2, Figure S2).

4. Discussion

The pH, organic matter, electrical conductivity, and $CaCO_3$ were not affected, either by the type of soil tillage or by the kind of fertilization; only pH in the second growing period was significantly affected by the kind of fertilization (Table 1). Soil pH is generally affected by many factors, including the organic matter content, the degree of soil leaching by precipitation, and the applications of lime or acidifying fertilizers [70]. In our study, the lowest pH values were detected in the CF treatment (7.44–7.51, irrespectively of the type of soil tillage), while the maximum ones were recorded in the OF treatment (7.72–7.76) (Table 1), which means that organic fertilizer (composted winery pomace) applications significantly influenced soil pH. Other researchers also found an increase in pH in response to organic fertilizers' application, possibly due to the alkaline effect of the organic fertilizers and due to the formation of organic complexes with exchangeable Al [71]. The content in $CaCO_3$ was not influenced either by the kind of fertilization or by the type of soil tillage (Table 1). This is also in agreement with the data of Neugschwandtner et al. [72], who found insignificant differences in the effect of the type of soil tillage on $CaCO_3$ content.

According to Ruiz-Colmenero et al. [73], reduced tillage does not favor the immediate decomposition of plant residues and therefore, can cause a temporary decrease in the vigor of the vines through the sequestration of nutrients and carbon accumulation on the soil surface in the form of plant residues. In our study, reduced tillage (RT) showed a significant influence on soil organic matter, i.e., significantly higher organic matter content in the second growing period was recorded in the RT-OF treatment (approximately 7%) compared to the CT treatments (approximately 4.80–4.90%), which means that reduced tillage enhanced soil organic C content. Other researchers also found that conventional soil management could result in a decline of soil organic matter due to its direct aeration, decomposition [74,75], and topsoil degradation through aggregate breakdown and loss of organic C in vineyards [76]. In contrast, reduced soil tillage, or no-tillage systems, can enhance soil organic matter and microbial biodiversity [77,78]; this differential pattern in organic matter mineralization among conventional and reduced or no-till systems could explain the differential nutrient availabilities for plant uptake [78]. Indeed, differential NO_3-N concentration pattern was found among the treatments (Figure 1a,b); more specifically, the highest NO_3-N concentrations for the first growing period were detected in CRF irrespectively of the type of soil tillage (Figure 1a), while for both growing periods, the lowest nitrate concentrations were recorded in the OF treatment (Figure 1a,b), showing the low N mineralization rate of the organic material (pomace, by-product of wine industry). The rates of organic C decomposition and N mineralization were found to be significantly influenced by the kind of vegetative litter and other organic materials/amendments [79,80]. In a 'Syrah' grapevine, organic fertilization increased soil organic matter, pH, and nitrate concentration in the 0.20–0.40 m soil layer, making it leachable [81], while in a 'Chardonnay' vineyard, it was found that the application of organic fertilizers (i.e., compost) for over nine experimental years significantly increased organic matter content and nitrate concentrations compared to inorganic fertilization [82], which is in contrast to our data for NO_3-N availability (Figure 1a,b).

While soil nitrate N for both growing periods was significantly affected only by the kind of fertilization (p = 0.000–0.005) (Figure 1a,b), the type of soil tillage and their interaction (fertilization×soil tillage) significantly influenced (p = 0.000–0.044) soil nitrate concentration only in the second growing period (Figure 1b), probably meaning that it takes time to detect changes in nutrient concentration due to changes in tillage method. Ibrahim et al. [83] found a significant decline in N content under conventional tillage due to leaching. Similarly, Neugschwandtner et al. [72] studied the impacts of different tillage systems on soil nutrient availability from 1996 to 2014 and reported that a reduction in tillage intensity resulted in an increase in soil N content at surface soil layers. Our data partially disagree with the findings of the previously mentioned two researchers, since in the second growing period of our study the highest NO_3-N concentration was recorded in conventional soil tillage, and especially in the conventional fertilization (i.e., in the treatment CT-CF) (Figure 1b). Maybe the difference between our results and those of the other researchers could be ascribed to the kind of applied conventional soil tillage method (differences in the intensity and/or soil depth elaboration, etc.). However, additional multi-year research is needed to safely verify the effect of soil tillage on nitrate N, and especially on the nitrification rate.

With regard to the other nutrients (Olsen P, exchangeable K and Mg, micronutrients), extractable P and exchangeable K concentrations were not significantly affected, neither by the type of soil tillage nor by the kind of fertilization, for both growing periods (Table 2). In contrast to our data for P, Wyngaard et al. [84] reported significantly higher soil available P under no-till practices compared to conventional tillage. In the study by Silva et al. [81] it was concluded that P, K, Ca, Mg, and Mn availabilities were positively affected by organic fertilization; however, Cu concentration was negatively influenced due to Cu complexation on organic matter [81], something which is in disagreement to our data. In contrast to our previous results for most macronutrients, significant was the effect of the type of soil tillage on exchangeable Mg (p = 0.045, $\leq$ 0.05), but only in the first growing period (Table 3). Our data for Olsen P did not fully agree with those of other researchers, who found increases in soil available P due to organic fertilizers' applications [71,85,86], maybe due to different organic materials/amendments (containing different P content) used. In our study, the organic material used (pomace, i.e., compost, derived from by-products of the wine industry) had a P content of 0.18% D.W. In the study by Dorneles et al. [87], among different tillage systems and combined organic (poultry manure application) and inorganic (lime and fertilizers' application) fertilization practices, the no-tillage and the reduced tillage practices with organic fertilization resulted in higher availability of P; this probably happened due to minimal disturbance of soil, which decreased contact surface between phosphate ions and adsorption sites [87], something which is not confirmed by our data for P (Table 2). Maybe the difference with regard to Olsen P between our findings and those of Dorneles et al. [87] could be ascribed: (i) to different organic amendments used (composted wine industry pomace vs. poultry manure) and/or (ii) to the different soil conditions existing between the two areas of experimentation and/or (iii) to the kind of applied conventional soil tillage methods (differences in the intensity and/or soil depth elaboration, etc.). In any case, additional multi-year research is needed to safely verify the effect of soil fertilization practices and type of soil tillage on soil P availability.

From micronutrients, only B and Zn were significantly affected (the first one in the first growing period, Zn in the second growing period) by the kind of fertilization (p values 0.013 and 0.008, respectively) (Table 3). In the study by Yagmur et al. [53], the influences of four different tillage practices (mulching, chisel tillage, plow tillage, and conventional tillage) under organic viticulture were investigated, and it was concluded that soil N, P, K, Ca, and Mg were highest under mulching, whereas Fe and Mn were highest under conventional tillage [53]. These data, although not fully comparable to ours, are in partial disagreement with the results of the present study, since in our case only the availability of exchangeable Mg was significantly affected by the type of soil tillage (Table 2), and not those of the other nutrients. Furthermore, other researchers [25,26] found that topsoil total N, P, and K concentrations significantly declined under conventional tillage practices, compared to no tillage. This effect on nutrient availability is explained due to SOM oxidation, leading to nutrient release in plant-available forms, and enhanced losses by leaching and gas emission [27]. In contrast to the previous findings, other researchers [83,88,89] concluded that soil K availability was not influenced by different tillage practices, which is in agreement with our results.

Based on the soil critical nutrient concentrations for grapevines reported in the literature, Lanyon et al. [90] reported that available Fe in vineyard soils should be higher than 4.5 mg/kg, while Holzapfel et al. [91] reported that available Fe in vineyard soils should vary between 4 and 200 mg/kg. Concerning Zn, Lanyon et al. [90] reported that available Zn in vineyard soils is classified as deficient in concentrations lower than 0.5 mg/kg, marginal in concentrations 0.5–1.0 mg/kg, sufficient in concentrations between 1.0 and 2.0 mg/kg and high in concentrations between 2.0 and 20.0 mg/kg. With regard to Mn, Lanyon et al. [90] reported that available Mn levels in soils of vineyards are classified as marginal in concentrations lower than 2.0 mg/kg and sufficient in concentrations varying between 2.0 and 4.0 mg/kg. On the other hand, Holzapfel et al. [91] stated that vineyard soils should contain available Mn levels between 15 and 70 mg/kg Mn. Finally, Lanyon et al. [90] classified available Cu levels of vineyard soils as deficient those existing in concentrations lower than 0.1 mg/kg, marginal levels those in concentrations between 0.1 and 0.2 mg/kg, sufficient those varying between 0.2 and 0.4 mg/kg, and high those in concentrations higher than 0.4 mg/kg. Based on the above classification, it can be concluded that Fe levels were slightly deficient only during the first growing period, while part of the detected available Zn levels were marginal (those existing in CF, in the second period) (Table 3). Finally, all the Mn levels were sufficient to over-sufficient and those of Cu were high to very high (up to 7 times higher than the upper limit of 0.4 mg/kg) (Table 3). The slightly deficient Fe and marginal Zn levels should be ascribed to high pH, varying approximately between 7.5 and 8 (Table 1), limiting the solubility and availability of these micronutrients. Copper levels were very high due to the often used high Cu-containing fungicides in viticulture.

The kind of fertilization significantly influenced only leaf N and P and not the uptake of other nutrients (Tables 4 and 5). More specifically, in the second growing period, the highest foliar P concentration was determined in the OF-treated plants (Table 4), irrespectively of the type of soil tillage, while in contrast, a decline in leaf N (in the first growing period) was found in the OF treatment compared to those of CF and CRF, especially in RT (Figure 2). The decline in leaf N in OF could be possibly explained by the low rates of organic material (pomace) decomposition and nitrification in this treatment, as previously explained, following the trend of decline in soil nitrate concentrations under OF (Figure 1a,b). In another experiment, the comparative effects of conventional fertilization and manure application on the soils of Nemea (Peloponnese) vineyards were studied; it was found that leaf Ca, Mg, Mn, and Zn concentrations in the conventional vineyards were significantly higher, compared to those determined in the organic vineyards [92]. In our study, foliar Ca, Mg, and Mn, as well as the ratio of K/Mg, were significantly influenced by the type of soil tillage (CT or RT), but not by the kind of fertilization (Tables 4–6; Figure 2), while Zn concentration was affected by both soil tillage type and kind of fertilization, i.e., CF, CRF, or OF (Table 6). It is clear that different treatments were applied between our experiment and the study by Michopoulos and Solomou [92] since dual factors (fertilization and soil tillage) were included in our study compared to only one factor (fertilization, i.e., conventional or organic) in the study by Michopoulos and Solomou [92]. Furthermore, in the second study, manure was chosen as the organic material for soil amendment, while in our case, composted winery pomace of the wine industry was preferred to improve soil properties and fertility. Finally, Reeve et al. [93] concluded that leaf N, K, Ca, Mg, B, Zn, and Fe concentrations in Californian vineyards were lower in organic plots compared to non-organic ones, which is in agreement with our results only for N (Figure 2a).

According to Feng and Balkcom [94], tillage practices can substantially alter soil physical properties, microbial biodiversity, and nutrient cycling processes; thus, they influence nutrient uptake and plant growth. The effects of different tillage methods (conventional, reduced, and mulch) on the leaf nutrient concentrations of the organically grown Sultani Çekirdeksiz grape variety were investigated by Ateş et al. [95]. They found that the applied tillage method clearly influenced nutrient uptake by plants, which partially confirmed our results (Tables 4–6; Figure 2); more specifically, the highest N, P, K, Ca, Mg, and Fe concentrations of the leaf blade and petiole were recorded under the mulch tillage method, while the highest leaf blade and petiole Cu and Mn concentrations were determined under the conventional tillage and the highest Zn concentrations of the leaf blade and petiole were found in the reduced tillage [95].

5. Conclusions

In conclusion, our study provides evidence that the kind of fertilization (inorganic, controlled-release, and organic) and the type of soil tillage (conventional and reduced), as well as their interaction, significantly influenced soil properties, nutrient availability, and uptake by *Vitis vinifera* L. (of the cv. 'Robola') plants. In enough cases, the organic fertilization (OF) together with the reduced tillage (RT) provided promising results; thus, it could constitute, in the near future, an alternative cultivation strategy towards decreasing the high costs of fertilization and soil elaboration for the wine producers. However, more long-term experimentation is needed to obtain more reliable results and to safely verify our hypothesis. The obtained environmental, ecological, economic, and wine qualitative benefits derived from the innovational dual application of the composted wine industry pomace, together with the reduced soil tillage practices, should be simultaneously examined under the light of the following: i) the challenges of the climatic change, ii) the higher cost production for the wine producers, due to the recent energy crisis, and iii) the opportunity to enhance the production of more qualitative (e.g., with enhanced phenolic content) PDO wines.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/environments12050160/s1, Table S1: Pearson correlation coefficient analysis and significance *p*-value (2-tailed) among the different evaluated parameters in the LANOU vineyard after treatment with different types of soil tillage and kinds of fertilization in the 1st growing period (year 2023); Figure S1: Presentation of Pearson correlation analysis data among the different evaluated parameters in scatterplot matrix (SPLOM) graphs in the LANOU vineyard after treatment with different types of soil tillage and kinds of fertilization in the 1st growing period (year 2023); Table S2: Pearson correlation coefficient analysis and significance *p*-value (2-tailed) among the different evaluated parameters in the LANOU vineyard after treatment with different types of soil tillage and kinds of fertilization in the 2nd growing period (year 2024); Figure S2: Presentation of Pearson correlation analysis data among the different evaluated parameters in scatterplot matrix (SPLOM) graphs in the LANOU vineyard after treatment with different types of soil tillage and kinds of fertilization in the 2nd growing period (year 2024).

Author Contributions: Conceptualization, T.C., E.K., K.B. and G.D.; methodology, T.C. and A.B.; software, V.S.; validation, T.C., E.K. and K.B.; formal analysis, V.S.; investigation, T.C., V.S., A.F., E.K. and I.D.; resources, T.C. and G.D.; data curation, T.C., V.S. and A.B.; writing—original draft preparation, T.C. and V.S.; writing—review and editing, T.C., V.S., E.K. and K.B.; visualization, V.S.; supervision, T.C.; project administration, T.C.; funding acquisition, T.C., E.K. and K.B. All authors have read and agreed to the published version of the manuscript.

Funding: These data derived from the project, entitled «Water saving and reduction infertilizer inputs in the vineyards of Kefalonia», with acronym 'VINEYARDS OF KEFALONIA' and code M16SYN2-00196 of action 2, of the sub-measure 16.1–16.5 "Establishment and operation of Operational Groups of the European Innovation Partnership for the productivity and sustainability of agriculture" of the Rural Development Program (RDP) 2014–2020 (special application service of RDP, collaboration and innovation unit), which was supported and co-funded by the European Agricultural Fund of Rural Development and Greek national resources.

Data Availability Statement: The original contributions presented in this study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

CT	conventional tillage
RT	reduced tillage
CF	conventional fertilization
CRF	controlled-release fertilization
OF	organic fertilization
ANOVA	Analysis of Variance
PDO	protected designation of origin
PGI	Protected Geographical Indication
TGI	Traditional Specialty
N	nitrogen
P	Phosphorous
K	potassium
Ca	Calcium
Mg	Magnesium
Mn	Manganese
Zn	Zinc
Cu	Copper
B	Boron
Fe	Iron
CaCO3	Calcium carbonate
OM	organic matter
EC	electrical conductivity

References

1. International Organisation of Vine and Wine Intergovernmental Organisation (OIV). 2019 Statistical Report on World Vitiviniculture. 2019. Available online: http://oiv.int/public/medias/6782/oiv-2019-statistical-report-on-world-vitiviniculture.pdf (accessed on 30 March 2025).
2. United States Department of Agriculture, Foreign Agricultural Service (USDA). Fresh Apples, Grapes, and Pears: World Markets and Trade. 2024. Available online: https://apps.fas.usda.gov/psdonline/circulars/fruit.pdf (accessed on 30 March 2025).

3. International Organisation of Vine and Wine Intergovernmental Organisation (OIV). *Annual Assessment of the World Vine and Wine Sector in 2022*; International Organisation of Vine and Wine: Dijon, France, 2023. Available online: https://www.oiv.int/sites/default/files/documents/OIV_Annual_Assessment-2023.pdf (accessed on 30 March 2025).
4. 2019 Statistical Report on World Vitiviniculture. Available online: https://www.oiv.int/public/medias/6782/oiv-2019-statisticalreport-on-world-vitiviniculture.pdf (accessed on 6 January 2022).
5. Koufos, G.C.; Mavromatis, T.; Koundouras, S.; Fyllas, N.M.; Theocharis, S.; Jones, G.V. Greek wine quality assessment and relationships with climate: Trends, future projections and uncertainties. *Water* **2022**, *14*, 573. [CrossRef]
6. OIV Statistical Report on World Vitiviniculture. 2016. Available online: https://www.oiv.int/public/medias/5029/world-vitiviniculture-situation-2016.pdf (accessed on 6 January 2022).
7. Karavasili, A.; Arfanis, D.; Roukos, K. An Analysis of Wine-making Sector. Master's Thesis, Technological Educational Institute of Western Greece, Patras, Greece, 2017.
8. Stevenson, T. *The Sotheby's Wine Encyclopedia*, 5th ed.; DK Publishing: London, UK, 2011; Volume 1, pp. 1–736.
9. Staff, P. *Greek Wine: The Ultimate Guide to the Wines and Wine Regions of Greece*; CreateSpace Independent Publishing Platform: Scotts Valley, CA, USA, 2018.
10. Banilas, G.; Korkas, E.; Kaldis, P.; Hatzopoulos, P. Olive and grapevine biodiversity in Greece and Cyprus. A review. In *Sustainable Agriculture Reviews. Climate Change, Intercropping, Pest Control and Beneficial Microorganisms*; Lichtfouse, E., Ed.; Springer: Berlin/Heidelberg, Germany, 2009; Volume 2, pp. 401–428.
11. Chatzinikolaou, D.; Vlados, C. Evolution of business physiology in the wine industry: Insights from the Stra.Tech.Man Scorecard in the Cephalonian Robola sector. *J. Wine Res.* **2023**, *34*, 210–231. [CrossRef]
12. Communicating the Approval of a Standard Amendment 'Ρομπόλα Κεφαλληνίας'. PDO-GR-A1240-AM01. Date of Communication: 18 January 2022. Published by the Official Journal of the European Union (2023/C 135/05) and Commission Delegated Regulation (EU) 2019/33. Available online: http://www.minagric.gr/images/stories/docs/agrotis/POP-PGE/2021/prodiagrafh_rompola_kef170122.pdf (accessed on 30 March 2025).
13. Biniari, K.; Fragkos, A.; Chatzistathis, T.; Katsalirou, E.; Gerakis, A.; Stika, D.M.; Daskalakis, I.; Bouza, D.; Stavrakaki, M. Effect of soil management techniques and different vine nutrient methods on the physiology and grape quality of vines of cv. 'Robola' (*Vitis vinifera* L.) in Kefalonia. *Not. Bot. Horti Agrobot.* **2024**, *52*, 13954. [CrossRef]
14. Hellenic Statistical Authority (ELSTAT) 2022. Agriculture-Livestock Census Results 2021. Hellenic Statistical Authority Commission Delegated Regulation (EU) 2019/33 (2023/C 135/05). Available online: https://www.statistics.gr/en/agricultural-2021 (accessed on 30 March 2025).
15. Greek Gastronomy Guide 2022. Ρομπόλα Κεφαλονιάς. Available online: https://www.greekgastronomyguide.gr/item/robola-kefalonia/ (accessed on 30 March 2025).
16. Lazarakis, K. *The Wines of Greece*; Hachett: London, UK, 2005.
17. Robinson, J. *Jancis Robinson's Guide to Wine Grapes*, 1st ed.; Oxford University Press: New York, NY, USA, 1996; Volume 1, pp. 1–240.
18. Kallithraka, S.; Arvanitoyannis, I.S.; Kefalas, P.; El-Zajouli, A.; Soufleros, E.; Psarra, E. Instrumental and sensory analysis of Greek wines; implementation of principal component analysis (PCA) for classification according to geographical origin. *Food Chem.* **2001**, *73*, 501–514. [CrossRef]
19. Bogunović, I.; Pereira, P.; Kisić, I.; Sajko, K.; Sraka, M. Tillage management impacts on soil compaction, erosion and crop yield in Stagnosols (Croatia). *Catena* **2018**, *160*, 376–384. [CrossRef]
20. Triplett, G.B.; Dick, W.A. No-tillage crop production: A revolution in agriculture! *Agron. J.* **2008**, *100*, S153–S165. [CrossRef]
21. Six, J.; Paustian, K. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. *Soil Boil. Biochem.* **2014**, *68*, a4–a9. [CrossRef]
22. Littrell, J.; Xu, S.; Omondi, E.; Saha, D.; Lee, J.; Jagadamma, S. Long-term organic management combined with conservation tillage enhanced soil organic carbon accumulation and aggregation. *Soil Sci. Soc. Am. J.* **2021**, *85*, 1741–1754. [CrossRef]
23. Schwartz, R.C.; Baumhardt, R.L.; Evett, S.R. Tillage effects on soil water redistribution and bare soil evaporation throughout a season. *Soil Till. Res.* **2010**, *110*, 221–229. [CrossRef]
24. Buesa, I.; Mirás-Avalos, J.M.; De Paz, J.M.; Visconti, F.; Sanz, F.; Yeves, A.; Guerra, D.; Intrigliolo, D.S. Soil management in semi-arid vineyards: Combined effects of organic mulching and no-tillage under different water regimes. *Eur. J. Agron.* **2021**, *123*, 126198. [CrossRef]
25. Nunes, M.R.; Karlen, D.L.; Moorman, T.B.; Cambardella, C.A. How does tillage intensity affect chemical soil health indicators? A United States meta-analysis. *Agrosyst. Geosci. Environ.* **2020**, *3*, e20083. [CrossRef]
26. Nunes, M.R.; Karlen, D.L.; Veum, K.S.; Moorman, T.B.; Cambardella, C.A. Biological soil health indicators respond to tillage intensity: A US meta-analysis. *Geoderma* **2020**, *369*, 114335. [CrossRef]
27. Linares, R.; de la Fuente, M.; Junquera, P.; Lissarrague, J.R.; Baeza, P. Effects of soil management in vineyard on soil physical and chemical characteristics. *BIO Web Conf.* **2014**, *3*, 01008. [CrossRef]

28. Laudicina, V.A.; Palazzolo, E.; Catania, P.; Vallone, M.; Garcia, A.D. Soil quality indicators as affected by shallow tillage in a vineyard grown in a semiarid Mediterranean environment. *Land Degrad. Dev.* **2017**, *28*, 1038–1046. [CrossRef]
29. Belmonte, S.A.; Celi, L.; Stahel, R.J.; Bonifacio, E.; Novello, V.; Zanini, E.; Steenwerth, K.L. Effect of long-term soil management on the mutual interaction among soil organic matter, microbial activity and aggregate stability in a vineyard. *Pedosphere* **2018**, *28*, 288–298. [CrossRef]
30. Garcia, L.; Damour, G.; Gary, C.; Follain, S.; Le Bissonnais, Y.; Métay, A. Trait-based approach for agroecology: Contribution of service crop root traits to explain soil aggregate stability in vineyards. *Plant Soil* **2019**, *435*, 1–14. [CrossRef]
31. Bordoni, M.; Vercesi, A.; Maerker, M.; Ganimede, C.; Reguzzi, M.C.; Capelli, E.; Wei, X.; Mazzoni, E.; Simoni, S.; Gagnarli, E.; et al. Effects of vineyard soil management on the characteristics of soils and roots in the lower Oltrepo Apennines (Lombardy, Italy). *Sci. Total Environ.* **2019**, *693*, 133390. [CrossRef] [PubMed]
32. Garcia-Diaz, A.; Marqués, M.J.; Sastre, B.; Bienes, R. Labile and stable soil organic carbon and physical improvements using groundcovers in vineyards from central Spain. *Sci. Total Environ.* **2018**, *621*, 387–397. [CrossRef]
33. Abad, J.; Hermozo de Mendoza, I.; Marin, D.; Orcaray, L. Cover crops in viticulture. A systematic review (1): Implications on soil characteristics and biodiversity in vineyard. *Oeno One* **2021**, *55*, 295–312. [CrossRef]
34. Gristina, L.; Novara, A.; Minacapilli, M. Rethinking vineyard ground management to counter soil tillage erosion. *Soil Till. Res.* **2022**, *217*, 105275. [CrossRef]
35. Abbott, L.; Murphy, D. *Soil Biological Fertility: A Key to Sustainable Land Use in Agriculture*, 1st ed.; Springer: Berlin/Heidelberg, Germany, 2007; p. 264. [CrossRef]
36. Brunetto, G.; de Melo, G.W.B.; Toselli, M.; Quartieri, M.; Tagliavini, M. The role of mineral nutrition on yields and fruit quality in grapevine, pear and apple. *Rev. Bras. Frutic.* **2015**, *37*, 1089–1104. [CrossRef]
37. Ball, K.R.; Baldock, J.A.; Penfold, C.; Power, S.A.; Woodin, S.J.; Smith, P.; Pendall, E. Soil organic carbon and nitrogen pools are increased by mixed grass and legume cover crops in vineyard agroecosystems: Detecting short-term management effects using infrared spectroscopy. *Geoderma* **2020**, *379*, 114619. [CrossRef]
38. Wilson, S.G.; Lambert, J.J.; Dahlgren, R. Compost application to degraded vineyard soils: Effect on soil chemistry, fertility, and vine performance. *Am. J. Enol. Vitic.* **2021**, *72*, 85–93. [CrossRef]
39. Lazcano, C.; Gonzalez-Maldonado, N.; Yao, E.H.; Wong, C.T.F.; Merrilees, J.J.; Falcone, M.; Peterson, J.D.; Casassa, L.F.; Decock, C. Sheep grazing as a strategy to manage cover crops in Mediterranean vineyards: Short-term effects on soil C, N and greenhouse gas (N_2O, CH_4, CO_2) emissions. *Agric. Ecosyst. Environ.* **2022**, *327*, 107825. [CrossRef]
40. Mtanda, A.A.; Mwamahonje, A.; Massawe, C. Integrated use of organic and inorganic fertilizer in grape (*Vitis vinifera*) production: A review. *Türk Bilimsel Derlemeler Dergisi* **2024**, *17*, 1–17. Available online: https://www.tari.go.tz/assets/uploads/documents/8621a24519251302e93f3b44d470ca44.pdf (accessed on 30 March 2025).
41. James, A.; Mahinda, A.; Mwamahonje, A.; Rweyemamu, E.W.; Mrema, E.; Aloys, K.; Swai, E.; Mpore, F.J.; Massawe, C. A review on the influence of fertilizers application on grape yield and quality in the tropics. *J. Plant Nutr.* **2022**, *46*, 2936–2957. [CrossRef]
42. Ali-Mervet, A. Response of flame seedless grapevines to slow release nitrogen fertilizers. *Minia J. Agric. Res. Develop.* **2000**, *20*, 239–255.
43. Ahmed, F.F.; Abada, M.A.M. Response of Thompson seedless grapevines to some slow release N, P and K fertilizers. *Egypt. J. Agric. Res.* **2012**, *90*, 1–16.
44. Ahmed, F.F.; Abada, M.A.M.; Ali, H.A.; Allam, H.M. Trials for replacing Inorganic N partially in Superior vineyard by using slow release N fertilizers, humic acid and EM. *Stem Cell* **2014**, *5*, 16–28. Available online: https://www.sciencepub.net/stem/stem0502/003_24933stem050214_16_29.pdf (accessed on 30 March 2025).
45. Ahmed, M.M.A.; Abdelaal, A.M.K.; Abada, M.A.M.; Hann, M.N.I. Effect of some slow release n fertilizers on growth and fruiting in early sweet grapevines. *N. Y. Sci. J.* **2019**, *12*, 40–47. [CrossRef]
46. Gatti, M.; Schippa, M.; Garavani, A.; Squeri, C.; Frioni, T.; Dosso, P.; Poni, S. High potential of variable rate fertilization combined with a controlled released nitrogen form at affecting cv. Barbera vines behavior. *Eur. J. Agron.* **2020**, *112*, 125949. [CrossRef]
47. El-Saman, A.Y.; Habasy, R.E.Y.; Saied, H.H.M. Impact of slow-release and organic fertilizers on growth, yield, and cluster quality of thompson seedless grapevines (H4 strain) growing in sandy soil. *Int. J. Mod. Agric. Environ.* **2024**, *4*, 1–22. Available online: https://journals.ekb.eg/article_360743_41575f8e1a8a4c04b0728d303e2772ad.pdf (accessed on 30 March 2025).
48. Lucchetta, M.; Pii, Y.; Cagnin, A.; Lovat, L.; Romano, A.; Correddu, F.; Gaiotti, F. Controlled-release nitrogen technology as a sustainable nutrition management in lean-soil vineyards. *Acta Hortic.* **2024**, *1387*, 135–141. [CrossRef]
49. Viers, J.H.; Williams, J.N.; Nicholas, K.A.; Barbosa, O.; Kotzé, I.; Spence, L.; Webb, L.B.; Merenlender, A.; Reynolds, M. Vinecology: Pairing wine with nature. *Conserv. Lett.* **2013**, *6*, 287–299. [CrossRef]
50. Giffard, B.; Winter, S.; Guidoni, S.; Nicolai, A.; Castaldini, M.; Cluzeau, D.; Coll, P.; Cortet, J.; Le Cadre, E.; d'Errico, G.; et al. Vineyard management and its impacts on soil biodiversity, functions, and ecosystem services. *Front. Ecol. Evol.* **2022**, *10*, 850272. [CrossRef]

51. Visconti, F.; López, R.; Olego, M.Á. The health of vineyard soils: Towards a sustainable viticulture. *Horticulturae* **2024**, *10*, 154. [CrossRef]
52. Cataldo, E.; Fucile, M.; Mattii, G.B. A review: Soil management, sustainable strategies and approaches to improve the quality of modern viticulture. *Agronomy* **2021**, *11*, 2359. [CrossRef]
53. Yagmur, B.; Ozlu, E.; Ates, F.; Simsek, H. The response of soil health to different tillage practices in organic viticulture farming. *J. Soil Sci. Plant Health* **2017**, *1*, 2003–2005. Available online: https://www.scitechnol.com/peer-review/the-response-of-soil-health-to-different-tillage-practices-in-organic-viticulture-farming-i9Av.pdf (accessed on 30 March 2025).
54. Kaya, O.; Delavar, H.; Ates, F.; Yilmaz, T.; Sahin, M.; Keskin, N. Fine-tuning grape phytochemistry: Examining the distinct influence of oak ash and potassium carbonate pretreatments on essential components. *Horticulturae* **2024**, *10*, 95. [CrossRef]
55. Kaya, O.; Yilmaz, T.; Ates, F.; Kustutan, F.; Hatterman-Valenti, H.; Hajizadeh, H.S.; Turan, M. Improving organic grape production: The effects of soil management and organic fertilizers on biogenic amine levels in *Vitis vinifera* cv., 'Royal' grapes. *Chem. Biol. Technol. Agric.* **2024**, *11*, 38. [CrossRef]
56. Kaya, O. Harmony in the vineyard: Exploring the ecochemical interplay of Bozcaada Çavuşu (*Vitis vinifera* L.) grape cultivar and pollinator varieties on some phytochemicals. *Eur. Food Res. Technol.* **2024**, *250*, 1327–1339. [CrossRef]
57. Liebhard, G.; Winter, S.; Zaller, J.G.; Bauer, T.; Fantappiè, M.; Strauss, P. Effects of vineyard inter-row management on soil physical properties and organic carbon in Central European vineyards. *Soil Use Manag.* **2024**, *40*, e13101. [CrossRef]
58. Dhaliwal, S.S.; Shukla, A.K.; Behera, S.K.; Dubey, S.K.; Sharma, S.; Kaur Randhawa, M.; Kaur, G.; Singh Walia, S.; Singh Toor, A. Impact of fertilization and tillage practices on transformations of carbon, essential plant nutrients and microbial biota composition in soils: A review. *Technol. Agron.* **2024**, *4*, e003. [CrossRef]
59. Ministry of Agriculture, Institute of Soil, Fertilizerity & Climate: Soil Study of the Rombola Zone. Available online: https://www.minagric.gr/en/ (accessed on 4 May 2025). (In Greek).
60. Ministry of Rural Development and Food, Product Specification "Technical File of "Robola Kefalonia"—Protocol Number: PDO-GRA1240. Available online: https://www.minagric.gr/en/farmer-menu-2/pdo-pgi-tsgproducts-menu/440-listpdoproducts-cat (accessed on 30 March 2025).
61. Stavrakakis, M.N. *Ampelography*; Embryo Publications: Athens, Greece, 2021.
62. McLean, E. Soil pH and lime requirement. In *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; Agronomy Monograph; ASA; SSSA: Madison, WI, USA, 1982; pp. 199–224. [CrossRef]
63. Nelson, D.W.; Sommers, L.E. Total carbon, organic carbon and organic matter. In *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; Agronomy Monograph; ASA; SSSA: Madison, WI, USA, 1982; pp. 539–547. [CrossRef]
64. Hood-Nowotny, R.; Umana, N.H.N.; Inselbacher, E.; Oswald-Lachouani, P.; Wanek, W. Alternative methods for measuring inorganic, organic, and total dissolved nitrogen. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1018–1027. [CrossRef]
65. Olsen, S.; Sommers, L. Phosphorus. In *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; Agronomy Monograph; ASA; SSSA: Madison, WI, USA, 1982; pp. 403–430. [CrossRef]
66. Thomas, G.W. Exchangeable cations methods of soil analysis. In *Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties*; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; Agronomy Monograph; ASA; SSSA: Madison, WI, USA, 1982; pp. 159–166. [CrossRef]
67. Wolf, B. The determination of boron in soil extracts, plant materials, composts, manures, water and nutrient solutions. *Commun. Soil Sci. Plant Anal.* **1971**, *2*, 363–374. [CrossRef]
68. Hansen, T.H.; De Bang, T.C.; Laursen, K.H.; Pedas, P.; Husted, S.; Schjoerring, J.K. Multielement plant tissue analysis using ICP spectrometry. In *Plant Mineral Nutrients. Methods in Molecular Biology (Methods and Protocols)*; Maathuis, F., Ed.; Humana Press: Totowa, NJ, USA, 2013; Volume 953, pp. 121–141. [CrossRef]
69. Chapman, H.D.; Pratt, P.F. *Methods of Analysis for Soils, Plants and Waters*; University of California Division of Agricultural Sciences, Office of Agricultural Publications: Riverside, CA, USA, 1961; p. 309. [CrossRef]
70. Dunjó, G.; Pardini, G.; Gispert, M. Land use change effects on abandoned terraced soils in a Mediterranean catchment, NE Spain. *Catena* **2003**, *52*, 23–37. [CrossRef]
71. Damatto Júnior, E.R.; Villas Bôas, R.L.; Leonel, S.; Fernandes, D.M. Alterações em propriedades de solo adubado com doses de composto orgânico sob cultivo de bananeira. *Rev. Bras. Frutic.* **2006**, *28*, 546–549. [CrossRef]
72. Neugschwandtner, R.; Liebhard, P.; Kaul, H.; Wagentristl, H. Soil chemical properties as affected by tillage and crop rotation in a long-term field experiment. *Plant Soil Environ.* **2014**, *60*, 57–62. [CrossRef]
73. Ruiz-Colmenero, M.; Bienes, R.; Eldridge, D.J.; Marques, M.J. Vegetation cover reduces erosion and enhances soil organic carbon in a vineyard in the central Spain. *Catena* **2013**, *104*, 153–160. [CrossRef]
74. Schreck, E.; Gontier, L.; Dumat, C.; Geret, F. Ecological and physiological effects of soil management practices on earthworm communities in French vineyards. *Eur. J. Soil Biol.* **2012**, *52*, 8–15. [CrossRef]

75. Junior, C.C.; Corbeels, M.; Bernoux, M.; Piccolo, M.D.C.; Neto, M.S.; Feigl, B.J.; Cerri, C.E.P.; Cerri, C.C.; Scopel, E.; Lalet, R. Assessing soil carbon storage rates under no-tillage: Comparing the synchronic and diachronic approaches. *Soil Till. Res.* **2013**, *134*, 207–212. [CrossRef]
76. Bonifacio, E.; Said-Pullicino, D.; Stanchi, S.; Potenza, M.; Belmonte, S.A.; Celi, L. Soil and management effects on aggregation and organic matter dynamics in vineyards. *Soil Till. Res.* **2024**, *240*, 106077. [CrossRef]
77. Fageria, N.; Baligar, V.; Clark, R. Micronutrients in crop production. *Adv. Agron.* **2002**, *77*, 185–268. [CrossRef]
78. Rahman, M.M.; Alam, M.S.; Kamal, M.Z.U.; Rahman, G.M. Organic sources and tillage practices for soil management. In *Resources Use Efficiency in Agriculture*; Kumar, S., Meena, R.S., Jhariya, M.K., Eds.; Springer: Singapore, 2020; pp. 283–328. [CrossRef]
79. Kavvadias, V.; Alifragis, D.; Tsiontsis, A.; Brofas, G.; Stamatellos, G. Litterfall, litter accumulation and litter decomposition rates in four forest ecosystems in northern Greece. *For. Ecol. Manag.* **2001**, *144*, 113–127. [CrossRef]
80. Masunga, R.; Uzokwe, V.N.E.; Mlay, D.P.; Odeh, I.O.A.; Singh, A.; Buchan, D.; De Neve, S. Nitrogen mineralization dynamics of different valuable organic amendments commonly used in agriculture. *Appl. Soil Ecol.* **2016**, *101*, 185–193. [CrossRef]
81. Silva, D.J.; Bassoi, L.H.; Rocha, M.G.; Silva, A.O.; Deon, M.D. Organic and nitrogen fertilization of soil under 'Syrah' grapevine: Effects on soil chemical properties and nitrate concentration. *Rev. Bras. Cienc. Solo.* **2016**, *40*, e0150073. [CrossRef]
82. Mugnai, S.; Mais, E.; Azzarello, E.; Mancuso, S. Influence of long-term application of green waste compost on soil characteristics and growth, yield and quality of grape (*Vitis vinifera* L.). *Compost Sci. Utiliz.* **2012**, *20*, 29–33. [CrossRef]
83. Ibrahim, M.; Alhameid, A.; Kumar, S.; Chintala, R.; Sexton, P.; Malo, D.D.; Schumacher, T.E. Long-term tillage and crop rotation impacts on a Northern great Plainsmollisol. *Adv. Crop Sci. Tech.* **2015**, *3*, 178. [CrossRef]
84. Wyngaard, N.; Echeverría, H.E.; Rozas, H.R.S.; Divito, G.A. Fertilization and tillage effects on soil properties and maize yield in a Southern Pampas Argiudoll. *Soil Till. Res.* **2012**, *119*, 22–30. [CrossRef]
85. Jiménez Becker, S.; Ebrahimzadeh, A.; Plaza Herrada, B.M.; Lao, M.T. Characterization of compost based on crop residues: Changes in some chemical and physical properties of the soil after applying the compost as organic amendment. *Commun. Soil Sci. Plant Anal.* **2010**, *41*, 696–708. [CrossRef]
86. Bustamante, M.A.; Said-Pullicino, D.; Agulló, E.; Audreu, J.; Paredes, C. Application of winery and distillery waste composts to a Jumilla (SE Spain) vineyard: Effects on the characteristics of a calcareous sandy-loam soil. *Agric. Ecosyst. Environ.* **2011**, *140*, 80–87. [CrossRef]
87. Dorneles, E.P.; Lisboa, B.B.; Abichequer, A.D.; Bissani, C.A.; Meurer, E.J.; Vargaset, L.K. Tillage, fertilization systems and chemical attributes of a Paleudult. *Sci. Agric.* **2015**, *72*, 175–186. [CrossRef]
88. Matowo, P.R.; Pierzynski, G.M.; Whitney, D.; Lamond, R.E. Soil chemical properties as influenced by tillage and nitrogen source, placement, and rates after 10 years of continuous sorghum. *Soil Till. Res.* **1999**, *50*, 11–19. [CrossRef]
89. Gadermaier, F.; Berner, A.; Fließbach, A.; Friedel, J.K.; Mäder, P. Impact of reduced tillage on soil organic carbon and nutrient budgets under organic farming. *Renew. Agric. Food Syst.* **2012**, *27*, 68–80. [CrossRef]
90. Lanyon, D.M.; Cass, A.; Hansen, D. The Effect of Soil Properties on Vine Performance. CSIRO Land and Water Technical Report No. 34/04. 2004, pp. 1–54. Available online: http://www.clw.csiro.au/publications/technical2004/tr34-04.pdf (accessed on 30 March 2025).
91. Holzapfel, B.; Quirk, L.; Hutton, R.; Holland, J. *Winegrape Nutrition and Use of Fertilisers and Other Nutritional Supplements to Sustain Production. Water & Vine—Managing the Challenge. Fact Sheet No. 15*; The Grape and Wine Research and Development Corporation: Adelaide, Australia, 2009.
92. Michopoulos, P.; Solomou, A. Effects of conventional and organic (manure) fertilization on soil, plant tissue nutrients and berry yields in vineyards. The use of the original native soil as a control. *J. Plant Nutr.* **2019**, *42*, 2287–2298. [CrossRef]
93. Reeve, J.R.; Carpenter-Boggs, L.; Reganold, J.P.; York, A.L.; McGourthy, G.; McCloskey, L.P. Soil and winegrape quality in biodynamically and organically managed vineyards. *Am. J. Enol. Vitic.* **2005**, *56*, 367–376. [CrossRef]
94. Feng, Y.; Balkcom, K.S. Nutrient cycling and soil biology in row crop systems under intensive tillage. In *Soil Health and Intensification of Agroecosytems*; Al-Kaisi, M.M., Lowery, B., Eds.; Academic Press: Cambridge, MA, USA, 2017; pp. 231–255. [CrossRef]
95. Ateş, F.; Yağmur, B.; Çakir, E.; Yalçin, H. Effects of different tillage methods on the nutrient contents of organically grown Sultani Çekirdeksiz grape. *J. Agric. Mach. Sci.* **2017**, *13*, 33–38. Available online: https://dergipark.org.tr/en/download/article-file/399373 (accessed on 4 May 2025).

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