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Effects of Compost and Compost Tea on Soil Properties and Nutrient Uptake of the Moroccan Date Palm Cultivar "Mejhoul" under Organic Cultivation

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ABSTRACT

Date palm cultivation in regions such as the Middle East and north Africa plays a crucial role in food security, economic development, and environmental preservation. However, the sustainability of date palm farming is threatened by challenges such as soil degradation and nutrient depletion. To address these issues, organic farming practices, particularly the use of compost and compost tea, offer promising solutions. This study assessed the impact of these organic inputs on soil fertility and nutrient uptake in the "Mejhoul" date palm variety. A field experiment was carried out during two successive seasons of 2022 and 2023 in a pilot field in south-eastern Morocco using a completely randomized experimental design with four treatments: To: farmer's practice (50 kg of compost/tree), T1: To + compost tea at 15 liter/tree/week from April to October; T2: To + compost at 50kg/tree and T3: To + combination of 50 kg/tree of compost and tea compost 15L/tree/week from April to October. Results showed that compost tea (T1) and compost (T2) treatments significantly influenced soil macronutrient and micronutrient levels, as well as chemical properties such as organic matter, cation exchange capacity, electrical conductivity, and pH. Pearson correlation analysis revealed significant relationships among soil properties, with principal component analysis confirming the variability explained by the main plane. Leaf nutrient content analysis demonstrated seasonal variations and treatment effects on phosphorus, potassium, magnesium, nitrogen, copper, manganese, zinc, and iron levels. Correlation analysis of leaf nutrient content highlighted complex interactions between nitrogen, phosphorus, potassium, and micronutrients, reflecting their importance in palm leaf physiology. Overall, this study provides valuable insights into the benefits of organic inputs in date palm farming, supporting sustainable agricultural practices for long-term viability and environmental protection.

Keywords: compost, compost tea, organic farming, plant nutrition, soil fertility, *Phoenix dactylifera* L., Morocco.

INTRODUCTION

Date palms have long been a critical component of the agricultural landscape in many regions, including the middle east and north Africa (Meziani, 2019; Almadini et al., 2021). They are a vital source of food, income, and employment for millions of people, and play a significant role in these regions' social and economic development. Date palm is undoubtedly the fruit tree par excellence of the oasis region. In addition to being the characteristic food of populations in oases, it plays a preponderant role in environmental preservation, especially in the economic development of predominantly oasis regions. In Morocco, the oases are part of the natural wealth. With an area of 77,000 km^2, the Tafilalet region, in the south of the country, is home to the largest oasis in the world (Sedra, 2015; Meziani, 2019; Mazri et al., 2019; Almadini et al., 2021). Today, these islands of greenery lost in the desert are confronted with the impacts of climate change (recurrence of droughts, multiplication of extreme climatic phenomena). Moreover, with the decrease in water resources and soil degradation, agricultural activity is declining in oasis areas (Liu et al., 2018; Shen et al., 2018).

Despite its importance, date palm cultivation faces numerous challenges threatening its long-term viability. One of the main challenges date palm cultivation faces is soil degradation and nutrient depletion. The extensive use of conventional fertilizers has led to soil degradation, negatively affecting date palms' growth and productivity. This soil degradation is also associated with an increased risk of soil erosion, which further exacerbates the problem (Alotaibi et al., 2011; Hadrami et al., 2011; Al-Hinai et al., 2022).

Studies carried out in oases systems (mainly on date palm cultivation) have established the multiple advantages of organic farming practices over conventional ones, especially concerning its potential to assure environmental protection, particularly in ecologically sensitive areas such as oases (Tejada et al., 2009; Ahmed et al., 2013; Benziouche, 2017; Namboothiripad et al., 2021). As oasis agriculture for long remained sustainable only because of the low external input factors, organic farming has become increasingly important in date palm cultivation given the rising number of concerns related to the use of chemical fertilizers and pesticides (Safwat, 2007). Organic inputs, such as compost and compost tea, have improved soil fertility and promoted sustainable agriculture (Omotayo and Chukwuka, 2009; Lazcano and Domínguez, 2011; Scotti et al., 2015; Seleiman and Hafez, 2021). Compost is a well-known organic amendment that has been used for centuries to improve soil fertility. It is made from a mixture of organic materials, including plant residue, manure, and other biodegradable materials, and is rich in nutrients and beneficial microorganisms. Compost tea, on the other hand, is a liquid extract of compost that is rich in nutrients and microorganisms (Gómez-Brandón et al., 2015; Shaban et al., 2015). Both compost and compost tea have been shown to increase the availability of essential nutrients in the soil, such as nitrogen, phosphorus, and potassium, and to improve soil structure and water-holding capacity (Lakhdar et al., 2009; Pane et al., 2014; Scotti et al., 2015; Eudoxie and Martin, 2019; Abdel-Haleem et al., 2022).

Applying organic farming techniques to date palm cultivation can offer farmers the opportunity to increase productivity while better managing natural resources (Mahmoudi et al., 2008; Gomiero et al., 2011). This can be a solid and effective way to ensure long-term viability, protect, and safeguard palm groves. The study aims to assess the impact of organic compost and compost tea on the soil fertility and nutrient uptake of the date palm variety "Majhoul."

The findings of this study offer valuable insights into the advantages of incorporating organic inputs in date palm farming, underscoring the significance of fostering sustainable agricultural practices for the industry's enduring success. By aligning with the broader objective of advocating sustainable and eco-friendly agricultural approaches, the study offers pertinent guidance for farmers and policymakers striving to enhance date palm cultivation.

MATERIALS AND METHODS

Experimental design

The study was conducted during two successive seasons of 2022 and 2023 in a pilot field in southeastern Morocco in the Drâa-Tafilalet region (Fig. 1). The region is characterized by a semi-desert climate with extreme temperatures ranging from 48 °C in the hot summers to -7 °C in the cold winters. Precipitation is highly irregular, averaging between 30 to 40 days per year. Dominant winds include the Chergui from the southeast and Sahel from the southwest, with wind speeds peaking in spring, particularly in April and May. The region experiences low and erratic rainfall, ranging from 90 mm in the south to 200 mm in the north, with localized snowfall above 1800 m. Additionally, strong, dry hot winds are common, contributing to intense evaporation levels ranging from 1345 mm to 1385 mm per year (Bouhlassa and Paré, 2006). The experimental design was a randomized complete block, with eight plants per experimental unit and three replications per treatment (Fig. 2). Each elementary plot has four lines with a spacing of 9 × 9, i.e. a density of 123 trees per hectare. Six drippers with a flow rate of 8 l/hour irrigate each tree. Borders (untreated palm trees) delimit the blocks to avoid all sources of heterogeneity. The following treatments were tested: To: farmer's practice (50 kg of compost/tree), T1: To + compost tea at 15 liter/tree/week from April to October; T2: To + compost at 50 kg/tree and T3: To + combination

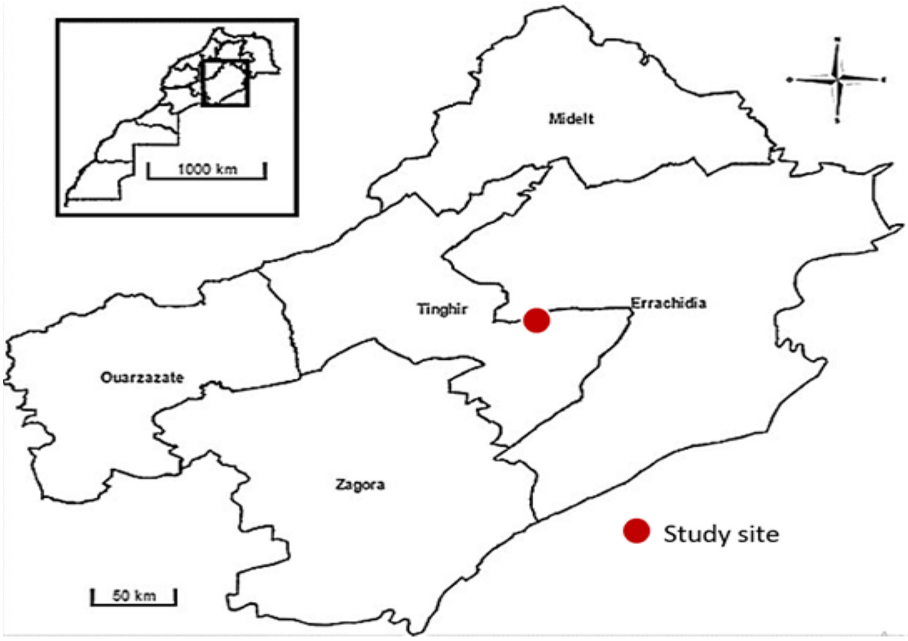

Figure 1. The geographic location of the study site

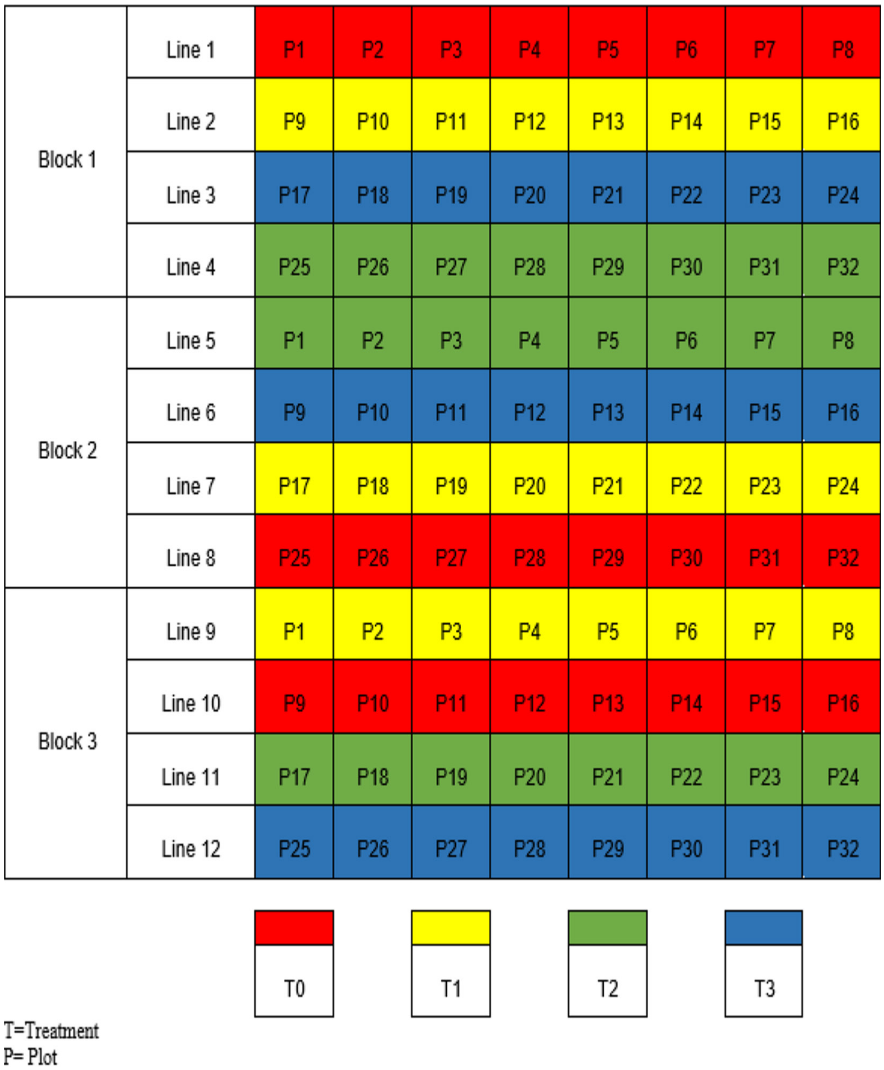

Figure 2. Field experimental layout in a randomized complete block design (RCBD)

of 50 kg/tree of compost and tea compost 15 L/tree/week from April to October. The dosages and application schedules were determined based on a thorough review of existing literature and previous studies (Ou-Zine et al., 2021; Ou-Zine et al., 2023).

Preparation of compost and compost tea

The compost used in this study was made from a mixture of organic materials, including plant residues, and animal manure. The compost tea was made by brewing the organic compost in water for 48 hours and then applying it to the soil. A ratio of 1/30 was adopted (27 kg of compost for 800 L of water) (Table 1). The study was conducted throughout the production cycle to assess the long-term effects of the treatments.

Assessment of soil parameters and nutrient uptake

Soil parameters were assessed both before and after the application of various treatments, encompassing parameters such as available phosphorus, potassium, magnesium, copper, zinc, and organic matter, among others, as detailed in Table 2. Furthermore, the nutrient composition of the date palm leaves was analyzed. The resulting data was systematically collected and subjected to statistical analysis to gauge the influence of these treatments on soil fertility and nutrient uptake.

Statistical analysis

Statistical analyses were conducted using the R programming language (R Core Team, Vienna, Austria, 2021), ensuring the accuracy and reliability of the findings. The dataset underwent thorough rigorous statistical analysis, beginning with a one-way ANOVA followed by the Duncan grouping test to determine statistical significance at a p-value threshold of ≤ 0.05. Pearson's correlation matrix was utilized to examine the strength of the linear relationship between the investigated parameters, with values ranging from −1 (indicating perfect negative correlation) to 1 (indicating perfect positive correlation), and 0 representing no linear correlation. The graphical representation of the correlation matrix was generated using the corrplot package. Additionally, principal component analysis (PCA) was employed to explore the correlation between the studied parameters and assess the impact of factors on the identified correlation patterns. PCA was conducted using the "FactomineR" and "Factoextra" packages, with factors projected as supplementary qualitative variables.

RESULTS AND DISCUSSION

Soil fertility promotion effects of compost and compost tea

Macronutrient contents in soil as affected by various treatments

The Table 3 illustrates the effects of various treatments (T0, T1, T2, T3) on soil nutrient concentrations (P_2O_5, K_2O, MgO) across the growing seasons of 2021–2022 and 2022–2023, including initial soil nutrient levels for reference. The results reveal no significant differences between treatments within the same growing season (a), but uppercase letters (A, B) indicate significant

Table 1. Properties and composition of the applied compost and compost tea

Specyfication	N	OM	C	C/N	P	K	Cu	Fe	Mn	Zn	B
Compost	1.06****	46***	27***	25	1168*	12322*	15*	1837*	92*	59*	28*
Compost tea	9.24***	0.02***	0***	0	0.68**	31.65**	0.01**	0.51**	0.05**	0.16**	0.15**

Note: N, total nitrogen; OM, organic matter; OC, organic carbon C, total carbon; P, extractable phosphorus; K, available potassium; Cu, copper; Fe, iron; Mn, manganese; Zn, zinc; B, boron. *mg/kg, **mg/l, ***% dry matter, ****%.

Table 2. Properties and composition of the experimental soil

NH_4^+	NO_3^-	P	K	Mg	Ca	Na	B	Cu	Mn	Zn	Fe	pH	E.C.	CEC	OM	OC
0.82*	62*	31.15*	167*	279*	6.88***	116*	0.37*	0.59*	3.56*	0.6*	1.5*	9.02	235****	1.73*****	0.9**	0.7**

Note: NH_4^+, nitrogen ammonium; NO_3^-, nitrogen nitrate; P, extractable phosphorus; K, available potassium; Mg, magnesium; Ca, calcium; Na, sodium; B, boron; Cu, copper; Mn, manganese; Zn, zinc; Fe, iron; E.C., electrical conductivity; CEC, cationic exchangeable capacity; OM, organic matter; C, organic carbon. *mg/kg, **%, ***g/kg, ****µS/cm, *****meq /100g.

differences ($p < 0.05$) between the two seasons, 2021–2022 and 2022–2023, particularly for P_2O_5 and K_2O elements. The data suggest that treatments led to variable levels of P_2O_5, K_2O, and MgO in the soil. In 2021–2022, treatment T1 displayed the highest average values for P_2O_5 (54.7 ± 35.9a), K_2O (204.3 ± 6.8a), and MgO (387.5 ± 36.7a), while treatment T2 exhibited the lowest values. Conversely, during the 2022–2023 growing season, treatment T1 had the highest average values for P_2O_5 (122.2 ± 76.7a), K_2O (481.4 ± 160.4a), and MgO (360.2 ± 51 a), with treatment T2 recording the lowest values. Overall, soil nutrient levels for P_2O_5, K_2O, and MgO were higher in the 2022–2023 growing season compared to 2021–2022 (Table 3). This trend aligns with previous studies that have reported enhanced soil fertility and nutrient availability following the application of compost and compost tea (Eudoxie and Martin, 2019; Abdel-Haleem et al., 2022; Luo et al., 2022).

Soil micronutrient levels as affected by different treatments

The Table 4 presents the levels of micronutrients (Cu, Mn, Zn, Fe) in the soil influenced by different treatments over two growing seasons (2021–2022 and 2022–2023). The treatments (T0, T1, T2, T3) were applied, and the average values are provided for each micronutrient. Lowercase letters (a) denote no significant difference between treatments within the same growing season, while uppercase letters (A, B) represent significant differences between the two growing seasons for each micronutrient. The initial soil levels of each micronutrient are also included for reference. During the 2021–2022 growing season, variations in copper concentrations

Table 3. Effect of different treatments on macronutrient contents in soil across the two growing seasons 2021–2022 and 2022–2023

Growing season	Treatment	P_2O_5 (mg·kg^{-1})	K_2O (mg·kg^{-1})	MgO (mg·kg^{-1})
2021–2022	T0	41.9 ± 12.7a	160.6 ± 38.6a	322 ± 15.6a
	T1	54.7 ± 35.9a	204.3 ± 6.8a	387.5 ± 36.7a
	T2	31.7 ± 10.3a	168.1 ± 27.2a	319.1 ± 28.2a
	T3	53.8 ± 29.6a	235.8 ± 74.9a	349.2 ± 35.6a
	Average	45.5 ± 26.4B	192.2 ± 53.7B	344.4 ± 40.9A
2022–2023	T0	111.3 ± 44.5a	476.1 ± 57.8a	381.5 ± 24.8a
	T1	122.2 ± 76.7a	481.4 ± 160.4a	360.2 ± 51a
	T2	62.5 ± 27.2a	306.4 ± 96.4a	348.2 ± 57.9a
	T3	96 ± 59.2a	385.3 ± 180.2a	338.8 ± 39.2a
	Average	98 ± 59.4A	412.3 ± 151.3A	357.2 ± 47.8A
Initial soil level		31.15	167.00	279.00

Table 4. Effect of different treatments on micronutrient contents in soil across the two growing seasons 2021–2022 and 2022–2023

Growing season	Treatment	Cu (mg·kg^{-1})	Mn (mg·kg^{-1})	Zn (mg·kg^{-1})	Fe (mg·kg^{-1})
2021–2022	T0	0.42 ± 0.1a	3.63 ± 0.35a	2.46 ± 1.16a	2.85 ± 0.67a
	T1	0.56 ± 0.17a	6.86 ± 2.41a	1.89 ± 0.71a	3.05 ± 1.4a
	T2	0.53 ± 0.2a	3.47 ± 1.56a	1.42 ± 0.61a	1.69 ± 0.23a
	T3	0.7 ± 0.21a	4.5 ± 1.71a	0.91 ± 0.21a	2.25 ± 0.84a
	Average	0.55 ± 0.2A	4.62 ± 2.16A	1.67 ± 0.95A	2.46 ± 1.04A
2022–2023	T0	0.15 ± 0.04a	0.41 ± 0.08a	0.24 ± 0.05a	1.35 ± 0.24a
	T1	0.2 ± 0.05a	0.44 ± 0.14a	0.31 ± 0.09a	1.61 ± 0.45a
	T2	0.22 ± 0.12a	0.29 ± 0.03a	0.21 ± 0.02a	1.21 ± 0.12a
	T3	0.18 ± 0.08a	0.36 ± 0.02a	0.35 ± 0.06a	1.6 ± 0.48a
	Average	0.19 ± 0.08B	0.38 ± 0.1B	0.28 ± 0.08B	1.44 ± 0.39B
Initial soil level		0.59	3.56	0.60	1.50

were observed among different treatments. Specifically, treatment T3 exhibited the highest Cu concentration at 0.7 ± 0.21a, while treatment T0 showed the lowest concentration at 0.42 ± 0.1a. However, in the subsequent growing season of 2022–2023, Cu concentrations decreased across all treatments compared to the previous season. Among the treatments, T2 recorded the highest Cu concentration at 0.22 ± 0.12a, while T0 displayed the lowest at 0.15 ± 0.04a. On average, the Cu concentration was notably higher in the 2021–2022 season, with a mean value of 0.55 ± 0.2A, compared to the 2022–2023 season, where it decreased to 0.19 ± 0.08B.

In both the 2021–2022 and 2022–2023 growing seasons, treatment T1 consistently exhibited the highest manganese concentration levels. Specifically, during the 2021–2022 season, treatment T1 recorded a Mn concentration of 6.86 ± 2.41a, while in the subsequent 2022–2023 season, it registered a concentration of 0.44 ± 0.14a. Despite the variability between the two seasons, the overall average Mn concentration remained slightly higher in the 2021–2022 season, with a value of 4.62 ± 2.16A, in comparison to the 2022–2023 season, where it was measured at 0.38 ± 0.1B. These findings underscore the significance of treatment T1 in influencing Mn levels in the soil.

The concentrations of zinc remained consistent across all treatments throughout both growing seasons, with no significant variation observed. Despite this consistency, the average Zn concentration was slightly higher during the 2022–2023 season, measuring at 0.28 ± 0.08B, compared to the 2021–2022 season, where it recorded a concentration of 1.67 ± 0.95A. These findings suggest that while treatment effects did not significantly impact Zn levels, slight seasonal variations were evident.

Similarly, iron concentrations exhibited consistency across treatments in both the 2021–2022 and 2022–2023 growing seasons, with treatment T1 consistently showing slightly higher values. Overall, the average Fe concentration was marginally higher during the 2021–2022 season, measuring at 2.46 ± 1.04A, compared to the subsequent 2022–2023 season, where it was recorded at 1.44 ± 0.39B. Despite the subtle differences, treatment T1 consistently appeared to influence Fe levels, indicating its potential role in influencing soil fertility dynamics across the two seasons.

Previous studies have consistently shown that the application of compost and compost tea can significantly influence micronutrient levels in the soil (Fouda and Niel, 2021; Luo et al., 2022). Micronutrients play a crucial role in various physiological processes in plants, including enzyme activation, photosynthesis, and nutrient uptake (Bhat et al., 2020; Rahman et al., 2020; Cakmak et al., 2023). Therefore, variations in soil micronutrient concentrations induced by changes in micronutrient contents can have profound implications for plant growth and productivity (Graham, 2008; Hajiboland, 2012).

Some chemical soil properties as affected by various treatments

The Table 5 displays soil properties including OM, CEC, EC, and pH, influenced by different treatments over two growing seasons (2021–2022 and 2022–2023). Lowercase letters (a) indicate no significant difference between treatments within

Table 5. Effect of various treatments on soil chemical properties across two growing seasons: 2021–2022 and 2022–2023

Growing season	Treatment	OM (% DM)	CEC (meq·100g^{-1})	EC (µS·cm^{-1})	pH
2021–2022	T0	1.89 ± 0.64a	1.71 ± 0.23a	242.5 ± 9.6a	9 ± 0.07a
	T1	1.6 ± 0.43a	2.76 ± 1.02a	256.1 ± 29.9a	9.02 ± 0.06a
	T2	1.83 ± 0.58a	1.59 ± 0.42a	357.8 ± 190.9a	9.12 ± 0.02a
	T3	2.37 ± 1.08a	2.46 ± 0.6a	251.5 ± 16.6a	9.12 ± 0.1a
	Average	1.92 ± 0.78A	2.13 ± 0.81B	277 ± 107.8A	9.06 ± 0.09A
2022–2023	T0	2.13 ± 0.22a	5.44 ± 0.18a	375 ± 36a	8.77 ± 0.12a
	T1	2.21 ± 0.07a	5.37 ± 0.79a	388.7 ± 137.5a	8.87 ± 0.09a
	T2	1.89 ± 0.18a	4.82 ± 0.23a	258 ± 23a	8.9 ± 0.08a
	T3	1.62 ± 0.4a	6.07 ± 0.68a	299.3 ± 113.7a	8.93 ± 0.05a
	Average	1.96 ± 0.34A	5.42 ± 0.7A	330.3 ± 106.3A	8.87 ± 0.11B
Initial soil level		0.90	1.73	235.0	9.02

the same growing season, while uppercase letters (A, B) represent significant differences between the two growing seasons for each parameter. The initial soil levels of each parameter are also included for reference. During the 2021–2022 growing season, the treatments showed variability in organic matter content, with treatment T3 having the highest concentration (2.37 ± 1.08a) and treatment T1 the lowest (1.6 ± 0.43a). Conversely, in the 2022–2023 season, organic matter content was more consistent across treatments. On average, the organic matter content was slightly higher in the 2021–2022 season (1.92 ± 0.78 A) compared to the 2022–2023 season (1.96 ± 0.34A). For cation exchange capacity, treatment T1 exhibited the highest values in both seasons, while treatment T2 showed the lowest. The average CEC values were slightly higher in the 2022–2023 season (5.42 ± 0.7A) compared to the 2021–2022 season (2.13 ± 0.81B).

Electrical conductivity values remained relatively consistent across treatments within each season. The average EC value was higher in the 2022–2023 season (330.3 ± 106.3A) compared to the 2021–2022 season (277 ± 107.8A). pH values also showed consistency across treatments within each season, with no significant variation observed. The average pH value was marginally higher in the 2021–2022 season (9.06 ± 0.09A) compared to the 2022–2023 season (8.87 ± 0.11B).

These findings are consistent with prior research conducted by Bayoumy et al. (2019) and Abdel-Haleem et al. (2022), which have similarly reported variations in soil properties in response to the application of compost and compost tea. Both studies registered changes in soil organic matter, cation exchange capacity, electrical conductivity, and pH following the implementation of compost and compost tea treatments, supporting the notion that organic amendments can influence soil fertility and physicochemical characteristics. While organic amendments such as compost and compost tea generally have positive effects on soil health and plant productivity in both the short and long term, improper long-term application may potentially lead to some negative effects. These could include nutrient imbalances, buildup of certain elements, changes in soil pH, and alterations in microbial community composition (Gani et al., 2020; Ye et al., 2022). Therefore, it's essential to monitor these factors carefully over time to ensure sustainable agricultural practices. Additionally, it is crucial to use compost in moderation and regularly test soil to prevent excessive nutrient application, which can have adverse effects on plants and the environment (Goldan et al., 2023).

Correlations between different soil properties and principal component analysis

The correlation matrix shows the Pearson correlation coefficients between different soil properties. A correlation coefficient close to 1 indicates a strong positive linear relationship between two variables, while a coefficient close to -1 indicates a strong negative linear relationship. A coefficient close to 0 suggests no linear relationship between the variables. Blue, positive correlation; red, negative correlation. *, **, *** indicate the significance of the correlation coefficient at $p < 0.05$, 0.01, and 0.001, respectively (Fig. 3).

According to results, P_2O_5 exhibits a highly significant positive correlation with K_2O (r = 0.73) and MgO (r = 0.64), as well as a significant positive correlation with pH (r = -0.56) and CEC (r = 0.58).

K_2O also showed a highly significant positive correlation with CEC (r = 0.69), a significant negative correlation with pH (r = -0.56) and a significant positive correlation with MgO (r = 0.58), as well as a significant negative correlation with Mn, Zn, and Cu with respective values of r = -0.49, r = -0.49, and r = -0.47. MgO is significantly correlated with pH (r = -0.41). pH exhibits a highly significant correlation with CEC (r = -0.62) and Cu (r = 0.52), as well as a significant positive correlation with Mn (r = 0.41). However, OM is not correlated with any of the studied parameters. CEC was found to be highly significantly correlated with Mn (r = -0.74), Zn (r = -0.7), and Cu (r = -0.71), and significantly correlated with Fe (r=-0.51). Mn exhibits a highly significant positive correlation with Cu (r = 0.86) and Fe (r = 0.67), as well as a significant positive correlation with Zn (r = 0.61). Zn is significantly correlated with Cu (r = 0.49), and Fe exhibits a significant positive correlation with Cu (r = 0.52). The observed correlations among soil properties in our study align with findings from previous research by Sanyal and Majumdar (2009) and Shiel (2010), underscoring the interconnectedness and complexity of soil nutrient dynamics. Soil systems are inherently intricate, with various physical, chemical, and biological factors influencing nutrient availability and interactions (Vogel et al., 2018). The first two axis of the PCA expressed 69.7% of the total dataset inertia (Fig. 4). This value

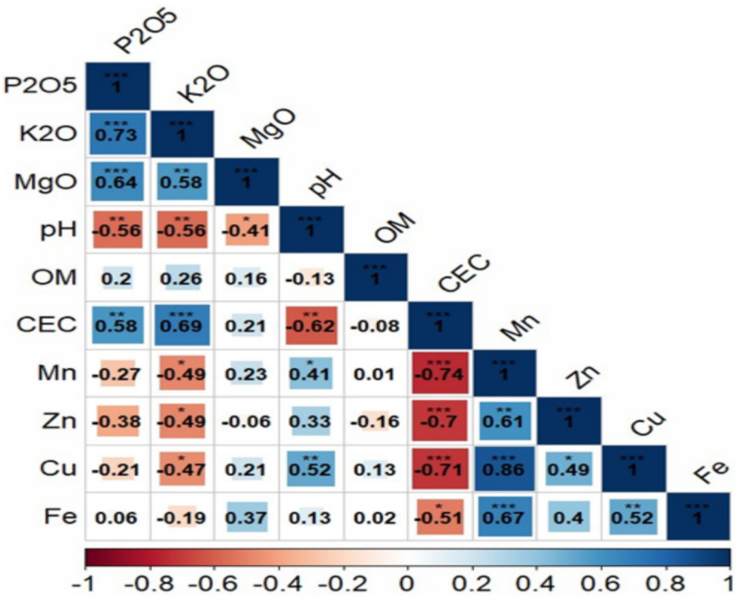

Figure 3. Pearson's correlation matrix between various soil properties. Values in the matrix represent Pearson's correlation coefficient. *, **, *** indicate the significance of the correlation coefficient at $p < 0.05$, 0.01, and 0.001, respectively. The matrix graphical representation was carried out using the corrplot package of R programming language.

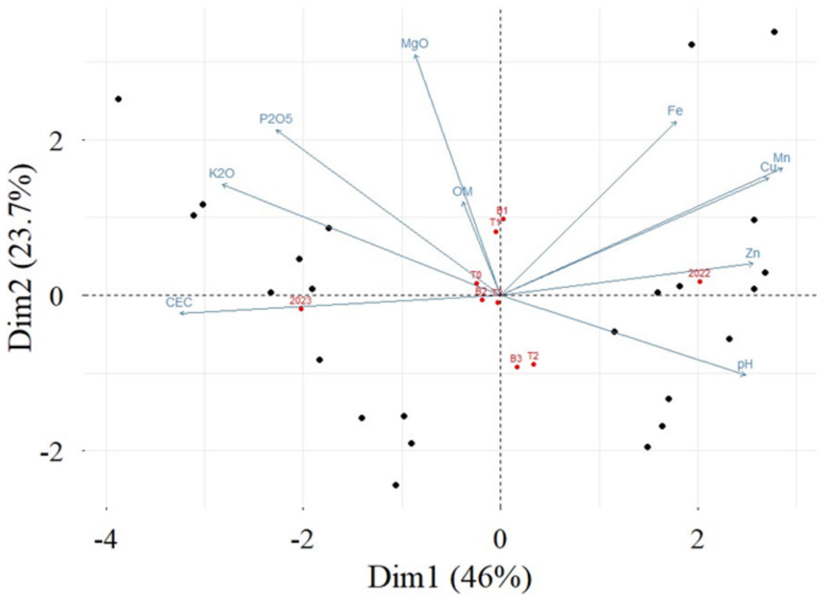

Figure 4. PCA – biplot projection of individuals (black points), factors (red points), and variables (blue arrows) on the main plan for the investigated parameters. 2022: First growing season. 2023: Second growing season. The plot was designed with "Factoextra" package of R programming language.

is significantly greater than the reference value of 44% (Husson et al., 2017). Thus, the variability explained by the main plane is highly significant. The soil's CEC and pH as well as its content on Mn, K_2O, Cu, Zn, and P_2O_5 were the main contributors to the construction of the firs dimension of the PCA. This dimension was strongly and positively correlated to the on Zn, Cu, Mn, Fe and the soil's pH. In addition, strong negative correlations were recorded between the first component and the CEC, K_2O, and P_2O_5. Regarding the second PCA component, the MgO, Fe and P_2O_5 contents contributed the most to its construction. Those three variables were all positively and strongly correlated to the second dimension.

Effects of compost and compost tea on leaf nutrient content

Leaf nutrient content as affected by various treatments

The Table 6 presents the nutrient content (phosphorus, potassium, magnesium, and nitrogen) across different treatments and growing seasons. Within each growing season, treatments did not show significant differences in nutrient content, as indicated by the lowercase letters (a). However, uppercase letters (A, B) signify significant differences between the two growing seasons for each nutrient. Through both growing seasons, phosphorus content remained relatively consistent across treatments, with an average value of 0.11 ± 0.03 in the first season and 0.09 ± 0.02 in the second season. Similarly, potassium content did not vary significantly between treatments within each growing season. The average potassium content was 1.38 ± 0.53 in the first season and 0.45 ± 0.09 in the second season. Magnesium content also showed consistency across treatments within each season, with an average value of 0.16 ± 0.04 in the first season and 0.15 ± 0.03 in the second season. Nitrogen content exhibited slight variations across treatments and seasons, with an average value of 1.01 ± 0.17 in the first season and 1.05 ± 0.38 in the second season. Comparing these findings to similar studies (Hu and Barker, 2004; Duong et al., 2012; Marosz, 2012; Khan et al., 2017), it is evident that the effects of compost and compost tea on leaf nutrient content can vary depending on factors such as compost type, application regime, and additional fertilization. For example, in the study by Hu and Barker (2004), leaf nitrogen, potassium, phosphorus, calcium, and magnesium concentrations and accumulations were influenced by different compost media and fertilization regimes. Agricultural-waste compost resulted in the highest leaf K and N and lowest Ca concentration and accumulation, while yard-waste compost had the highest leaf content of Mg. Fertilization further increased N and K concentrations and accumulations in leaves, with significant variations observed across different compost media and regimes. These results suggest that the interaction between compost type, fertilization, and other factors can play a crucial role in determining leaf nutrient content (Adugna, 2016; Agegnehu et al., 2017; Sánchez et al., 2017). Table 7 presents the leaf content of Cu, Mn, Zn, and Fe across different treatments and growing seasons (2021–2022 and 2022–2023). In the 2021–2022 growing season, treatment T2 displayed the highest Cu content (45.27 ± 46.42 a), while treatments T1 and T3 showed relatively higher Mn content (45.25 ± 9.17a and 47.38 ± 13.46a, respectively). For Zn content, treatments T0 and T2 had comparable levels (11.5 ± 2.1a and 11.14 ± 1.79a, respectively), while Fe content remained relatively consistent across treatments. In the 2022–2023 growing season, treatment T1 exhibited the highest Cu content (44.05 ± 77.33a), while treatment T3 showed the highest Mn content (55.47 ± 10.58a). Zn content was highest in treatment T0 (12.08 ± 4.01a), while Fe content was highest in treatment T0 (87.41 ± 39.37a). Overall, the average leaf content of Cu, Mn, and Fe was higher in the 2022–2023 season compared to the 2021–2022 season. These findings align with previous studies reporting seasonal variations in nutrient uptake and allocation by plants (Dubberstein et al, 2016; Cruz et al., 2019; Lu and

Table 6. Effects of different treatments of compost and compost tea on leaf content of P, K, Mg, and N across the 2022 and 2023 growing seasons

Growing season	Treatment	P (% DM)	K (% DM)	Mg (% DM)	N (% DM)
2021–2022	T0	0.11 ± 0.04a	1.29 ± 0.42a	0.17 ± 0.06a	1.04 ± 0.16a
	T1	0.1 ± 0.02a	1.25 ± 0.17a	0.15 ± 0.03a	1.03 ± 0.13a
	T2	0.11 ± 0.03a	1.79 ± 0.8a	0.16 ± 0.02a	1.02 ± 0.18a
	T3	0.1 ± 0.01a	1.21 ± 0.23a	0.17 ± 0.03a	0.94 ± 0.18a
	Average	0.11 ± 0.03A	1.38 ± 0.53A	0.16 ± 0.04A	1.01 ± 0.17A
2022–2023	T0	0.09 ± 0.01a	0.43 ± 0.07a	0.15 ± 0.02a	0.94 ± 0.23a
	T1	0.09 ± 0.02a	0.51 ± 0.1a	0.14 ± 0.01a	1.03 ± 0.37a
	T2	0.1 ± 0.03a	0.47 ± 0.07a	0.16 ± 0.04a	1.1 ± 0.4a
	T3	0.08 ± 0.02a	0.4 ± 0.08a	0.14 ± 0.02a	1.12 ± 0.44a
	Average	0.09 ± 0.02B	0.45 ± 0.09B	0.15 ± 0.03A	1.05 ± 0.38A

Table 7. Effects of different treatments of compost and compost tea on leaf content of Cu, Mn, Zn, and Fe across the 2022 and 2023 growing seasons

Growing season	Treatment	Cu (mg·kg^{-1})	Mn (mg·kg^{-1})	Zn (mg·kg^{-1})	Fe (mg·kg^{-1})
2021–2022	T0	17.89 ± 7.66a	35.83 ± 5.8a	11.5 ± 2.1a	121.85 ± 8.58a
	T1	19.2 ± 8.55a	45.25 ± 9.17a	8.23 ± 1.87a	122.9 ± 9.75a
	T2	45.27 ± 46.42a	40.64 ± 8.75a	11.14 ± 1.79a	127 ± 17.47a
	T3	30.88 ± 26.67a	47.38 ± 13.46a	9.35 ± 1.85a	115.93 ± 7.15a
	Average	28.31 ± 29.51A	42.27 ± 10.66A	10.05 ± 2.33A	121.92 ± 12.12A
2022–2023	T0	31.89 ± 60.06a	39.97 ± 5.22a	12.08 ± 4.01a	87.41 ± 39.37a
	T1	44.05 ± 77.33a	40.06 ± 11.93a	8.41 ± 4.05a	60.15 ± 11.57a
	T2	7.73 ± 3.78a	51.04 ± 10.96a	5.96 ± 3.37a	63.54 ± 10.39a
	T3	5.17 ± 2.47a	55.47 ± 10.58a	7.19 ± 4.05a	61.12 ± 11.06a
	Average	22.21 ± 51.67A	46.64 ± 12.11A	8.41 ± 4.51A	68.05 ± 24.59B

al., 2024). Conversely, Zn content showed no significant variation between the two seasons. The Table 8 illustrates the N/P (nitrogen to phosphorus), N/K (nitrogen to potassium), and P/K (phosphorus to potassium) ratios across different treatments and growing seasons (2021–2022 and 2022–2023). In the 2021–2022 growing season, treatment T1 exhibited the highest N/P ratio (10 ± 1.27 a), while treatments T0 and T2 showed slightly lower ratios. The N/K ratio remained consistent across all treatments, with an average of 6 ± 0.27 A. For the P/K ratio, treatments T0 and T1 had comparable values (0.08 ± 0.01 a), while treatments T2 and T3 showed slightly lower ratios. In the 2022–2023 growing season, treatment T3 displayed the highest N/P ratio (13.94 ± 2.52 a), whereas treatments T0 and T1 had slightly lower ratios. The N/K ratio remained consistent across treatments, averaging 6 ± 0.82 B. Similarly, the P/K ratio showed no significant variation between treatments, with an average of 0.19 ± 0.04 B. Overall, the N/P and P/K ratios exhibited variability between treatments and growing seasons, while the N/K ratio remained relatively consistent. The observed variability in the N/P and P/K ratios emphasizes the critical role of nitrogen and phosphorus availability in maximizing plant growth and yield potential (Leghari et al., 2016; Islam et al., 2018; Jiang et al., 2019; Mussarat et al., 2021). These ratios serve as indicators of nutrient balance within the plant, influencing crucial metabolic pathways and physiological functions (Zhang et al., 2017; Shrestha et al., 2020).

Correlations between different nutrient contents in leaves and principal component analysis

The correlation matrix displays the Pearson correlation coefficients among various nutrient contents in palm leaves. A coefficient near 1 signifies a strong positive linear relationship between two variables, while a coefficient close to -1 indicates a strong negative linear relationship. A coefficient near 0 suggests no linear relationship between the variables. Blue represents positive correlation, while red represents negative correlation. Significance levels are denoted by *, **, and ***, indicating p-values of less than 0.05, 0.01, and 0.001, respectively (Fig. 5).

The study results reveal that N demonstrates a moderate positive correlation with P (r = 0.4), along with a highly significant positive correlation with N/K and N/P ratios (r = 0.51 and r = 0.57, respectively), corroborating previous research indicating the importance of nitrogen-phosphorus dynamics in plant physiology (Li et al., 2016; peng et al., 2019; Li et al., 2019). This positive correlation suggests that an adequate supply of nitrogen may enhance phosphorus uptake and utilization, contributing to overall plant health and growth (Cloe et al., 1963; Hoffmann et al., 1994). Additionally, the highly significant positive correlations observed between nitrogen and the N/K and N/P ratios underscore the importance of nitrogen balance in relation to potassium and phosphorus levels. These findings align with studies emphasizing the significance of nutrient balance for optimal plant performance and yield (Habte and Boke, 2017; Ma et al., 2019).

Phosphorus is highly significantly positively correlated with potassium (r = 0.52) and exhibits a moderate positive correlation with iron (r = 0.41). The positive correlation between phosphorus and potassium supports existing literature suggesting synergistic effects between these elements in regulating various metabolic processes and plant development (Fageria and Oliveira, 2014; Jiaying et

Table 8. N/P, N/K, and P/K ratios in leaves across different treatments and growing seasons (2021–2022 and 2022–2023)

Growing season	Treatment	N/P	N/K	P/K
2021–2022	T0	11.06 ± 3.27a	6 ± 0.35a	0.08 ± 0.01a
	T1	10 ± 1.27a	6 ± 0.14a	0.08 ± 0.01a
	T2	9.56 ± 0.81a	6 ± 0.25a	0.07 ± 0.03a
	T3	9.5 ± 2.42a	6 ± 0.22a	0.09 ± 0.02a
	Average	10.03 ± 2.26A	24 ± 0.27A	0.08 ± 0.02A
2022–2023	T0	11.25 ± 3.08a	6 ± 0.77a	0.2 ± 0.03a
	T1	12.24 ± 5.02a	6 ± 0.84a	0.18 ± 0.02a
	T2	11.51 ± 2.75a	6 ± 0.7a	0.21 ± 0.05a
	T3	13.94 ± 2.52a	6 ± 0.77a	0.2 ± 0.03a
	Average	12.24 ± 3.64B	24 ± 0.82B	0.19 ± 0.04B

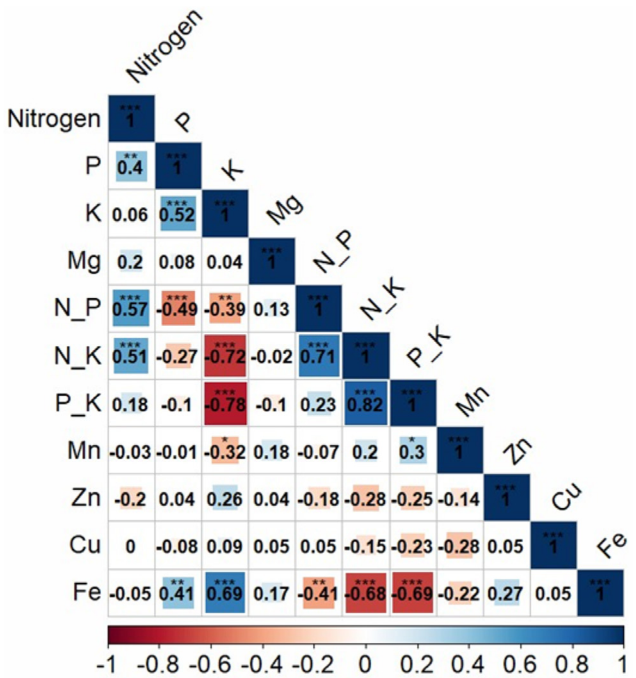

Figure 5. Pearson's correlation matrix between various nutrient contents in leaves. Values in the matrix represent Pearson's correlation coefficient. *, **, *** indicate the significance of the correlation coefficient at $p < 0.05$, 0.01, and 0.001, respectively. The matrix graphical representation was carried out using the corrplot package of R programming language.

al., 2022). Moreover, P shows a highly significant negative correlation with the N/P ratio (r = -0.49) indicating potential competition or antagonistic interactions between nitrogen and phosphorus uptake pathways, warranting further investigation into nutrient uptake mechanisms (Teng and Timmer, 1994). Potassium demonstrates a highly significant positive correlation with iron (r = 0.69) and a highly significant negative correlation with N/K and P/K ratios (r = -0.72 and r = -0.78, respectively). emphasizing the intricate balance required among these nutrients for optimal plant growth. These findings are consistent with previous studies highlighting the role of potassium in enhancing iron uptake and utilization, as well as its involvement in nutrient partitioning and homeostasis (Jolley et al., 1988; Szlek et al., 1990). Additionally, K displays a moderate significant negative correlation with the N/P ratio (r = -0.39). Furthermore, the N/P ratio shows a highly significant positive correlation with the N/K ratio (r = 0.71) and a moderate significant negative correlation with Fe (r = -0.41).

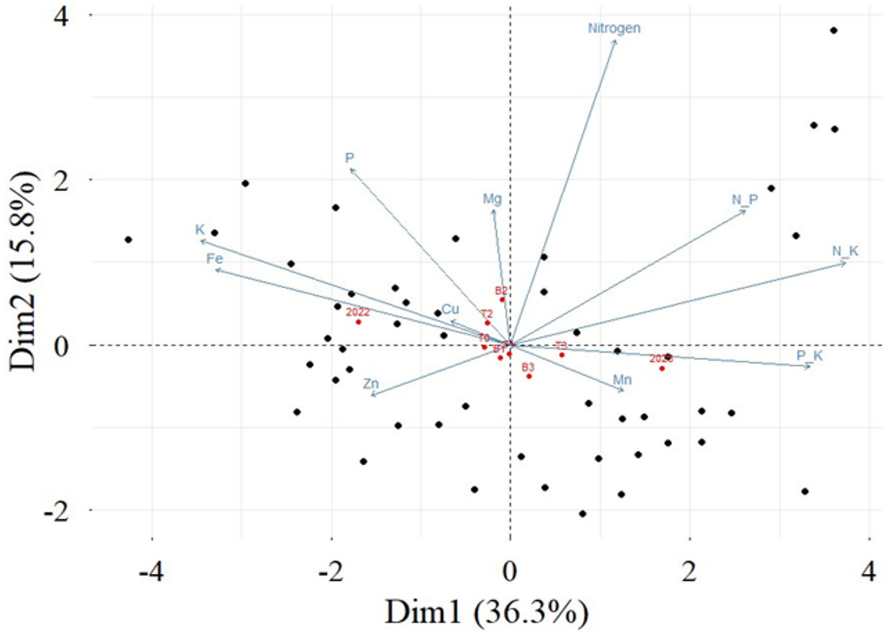

Figure 6. PCA–biplot projection of individuals (black points), factors (red points), and variables (blue arrows) on the main plan for the investigated parameters. 2022: First growing season. 2023: Second growing season. The plot was designed with "Factoextra" package of R programming language.

Alternatively, the N/K ratio exhibits a highly significant positive correlation with the P/K ratio (r = 0.82) and a highly significant negative correlation with Fe (r = -0.68). The P/K ratio exhibits a significant positive correlation with Mn (r = 0.3) as well as a highly significant negative correlation with Fe (r = -0.69). These findings underscore the intricate relationships between N, P, K, and Fe in palm leaf physiology, as discussed in previous studies (Malvi, 2011; Panda et al., 2012). The first two axes of the PCA accounted for 52.1% of the total dataset inertia (Fig. 6), surpassing the reference value of 44% (François Husson et al., 2017, Exploratory Multivariate Analysis by Example Using R), indicating a highly significant variability explained by the main plane. Fe, K, N/P, N/K, and P/K were the main contributors to the construction of the first dimension of the PCA. This dimension was strongly and positively correlated to the N/P, N/K and P/K. Additionally, a strong negative correlation was observed between the first component and Fe and K. Concerning the second PCA component, N, Mg, and P contents were the main contributors to its construction, all exhibiting strong positive correlations with the second dimension.

CONCLUSIONS

The current study underscores the critical importance of organic farming practices, particularly the application of compost and compost tea, in enhancing soil fertility and nutrient uptake in date palm cultivation. Through a comprehensive analysis of soil parameters and leaf nutrient content, the study elucidates the significant positive effects of organic inputs on soil macronutrients, micronutrients, and chemical properties. The findings highlight the efficacy of compost and compost tea treatments in promoting nutrient availability and balance in the soil, thereby contributing to improved plant growth and productivity.

Moreover, the study reveals intricate relationships between various soil properties and leaf nutrient content, as evidenced by the correlation analyses and principal component analysis. These results underscore the complexity of soil-plant interactions and emphasize the importance of nutrient balance for optimal plant performance. By elucidating these relationships, the study provides valuable insights into the underlying mechanisms governing nutrient dynamics in date palm cultivation. However, it is important to note that further research is needed to confirm these results and to explore the potential benefits of organic fertilization in date palm cultivation and potentially in other crops as well. The continued exploration and implementation of organic fertilization practices can contribute to the development of more sustainable and environmentally friendly agricultural systems.

Overall, the findings of this study have significant implications for sustainable agriculture and environmental preservation in oasis regions. By promoting organic farming practices and enhancing soil fertility through compost and compost tea applications, date palm farmers can mitigate the adverse effects of soil degradation and nutrient depletion while ensuring the long-term viability of palm groves. Furthermore, the study contributes to the broader goal of advocating for sustainable and eco-friendly agricultural approaches, aligning with global efforts to address climate change and promote food security. Through continued research and implementation of organic farming techniques, stakeholders can work towards safeguarding the livelihoods of millions of people dependent on date palm cultivation while preserving the ecological integrity of oasis ecosystems.

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