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Effect of different date palm (*Phoenix dactylifera*) compost modalities on soil parameters in the Algerian Semi-Arid Zone

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Abstract. In the vast regions of eastern Algeria, the calcareous soils are characterised by low fertility. Moreover, these soils frequently lack organic matter and essential nutrients, limiting sustainable yield potential. This study aimed to assess the impact of using locally sourced date palm compost with mineral fertilisers on the improvement of soil fertility in a cereal-based system. A field experiment was arranged in a randomised complete block design (RCBD) with 11 treatments: date palm compost applied at three rates (C1: 30 t ha^{-1}, C2: 50 t ha^{-1}, C3: 70 t ha^{-1}), either alone or combined with monoammonium phosphate (C1M, C2M, C3M: 100 kg ha^{-1} MAP) or urea (C1U, C2U, C3U: 50 kg ha^{-1} urea), one treatment with sheep manure at 45 t ha^{-1}, and an untreated control.. The study evaluated the effects of varying rates of date palm compost and mineral fertilisers on soil chemical characteristics at two depths (0–20 cm and 20–40 cm). Results indicated that elevated compost rates, whether applied alone or combined with mineral fertilisers, significantly improved organic matter content, nutrient availability, and soil chemical balance at both depths. Combined treatments C3U (70 t ha^{-1} compost + 50 kg ha^{-1} urea) and C3M (70 t ha^{-1} compost + 100 kg ha^{-1} MAP) showed the greatest improvements, with C3M identified as the optimal treatment. Integrated date palm compost fertilisation is well-suited to the region's calcareous soils, enhancing nutrient availability, improving soil fertility, and efficiently utilising a locally available resource. These findings suggest that integrating date palm compost with mineral fertilisers is a sustainable approche to improving soil fertility in semi-arid mediterranean systems.

Key words: calcareous soils, compost, date palm, integrated fertilisation, semi-arid zone, soil fertility.

INTRODUCTION

In the semi-arid regions of eastern Algeria, cereal production is severely constrained by climate variability and limited soil fertility. The prevailing climatic conditions, marked by insufficient and erratic rainfall, significantly reduce agricultural productivity and grain yield (Smadhi et al., 2017; Amirouche et al., 2021). These areas are dominated by calcareous and alkaline soils with low organic matter, weak cation exchange capacity, and poor availability of nitrogen and phosphorus (Benabderrahim et al., 2017; Kavvadias et al., 2024). Moreover, inadequate irrigation often aggravates water salinisation, leading to further degradation of agroecological productivity (Devkota et al., 2022).

To counteract these constraints, intensive fertilisation with monoammonium phosphate (MAP) and urea (46% N) is frequently applied. However, calcareous soils exhibit reduced fertiliser efficiency due to nitrogen volatilisation losses (Adnan et al., 2025), resulting in structural decline and organic matter depletion (Brownrigg et al., 2022; Bontpart et al., 2024). Integrated fertilisation combining mineral and organic sources has therefore been recognised as a promising option to restore soil fertility and enhance productivity (Saber et al., 2024; Ejigu et al., 2025).

Organic fertilisers such as compost and sheep manure improve both physical and chemical soil properties (Lanno et al., 2020; Šařec et al., 2020) by enhancing water retention, microbial activity, and carbon sequestration (Al-Suhaibani et al., 2020; Bayu, 2020). Mixing organic materials with mineral fertilisers increases nutrient efficiency while reducing volatilisation and leaching losses, thus lowering dependence on synthetic products (Manzoor, 2024). Among locally available residues, date palm (*Phoenix dactylifera* L.), a keystone of oasis agriculture–generates large volumes of unused biomass such as dry fronds and spadices (Abid & Ammar, 2022; Arroussi et al., 2022; Habchi et al., 2022; Kavvadias et al., 2024).

The growing accumulation and burning of palm residues highlight an important need for their valorisation as part of sustainable agricultural transitions (Bhatia & Sindhu, 2024). Composting these by-products offers a promising route, improving soil fertility while supporting a circular bioeconomy (Benabderrahim et al., 2017; Faiad et al., 2022; El Janati et al., 2023; Kavvadias et al., 2024). Blending date palm compost with organic (e.g., sheep manure) and mineral (e.g., MAP) fertilisers enhances crop growth, nutrient availability (Badawi, 2022; Hakimi et al., 2024; Kavvadias et al., 2024), and disease control (Istifadah et al., 2020).

For soil fertility conservation, these composts help maintain soil organic matter, stabilise pH, and mitigate toxic accumulations (Ghouili et al., 2022). They also improve plant tolerance to water stress by promoting root growth and hormonal balance (Ding et al., 2020; Siebielec et al., 2020; El-Aziz et al., 2025; Li et al., 2025). This is highly beneficial as it contributes to reducing pollution from burning, greenhouse gas (GHG) emissions, and valorisation of agriculturally useful waste (Al-Suhaibani et al., 2020; Saber et al., 2024). Combining date palm fronds with organic sources (e.g., manure or olive pomace) or mineral inputs (rock phosphate) produces high-quality composts suited to dryland soils (El Janati et al., 2023; Kavvadias et al., 2024). The present study aims to assess the effects of varying application rates of palm compost and integrated fertilisation strategies on calcareous soil properties in cereal systems, contributing to sustainable soil management in semi-arid environments (Gomez-Muñoz et al., 2012; Ameziane et al., 2020; Badagliacca et al., 2024; Kavvadias et al., 2024).

MATERIALS AND METHODS

Site description and climate

The field trial was carried out under a semi-arid climate, implemented at the farm of Abdessamed Salah (Timgad) (35°31'12.1"N 6°29'24.7"E) at an altitude of 1,100 m (Fig. 1) during the 2021–2022 growing season.

Figure 1. Location of the experimental site within Batna province (Algeria).

Climatic conditions were very unfavourable for crop growth in the Timgad region (Batna) during the 2021–2022 agricultural season (Fig. 2). Cumulative annual rainfall reached approximately 105 mm, which is significantly below the average recorded over the last twenty years.

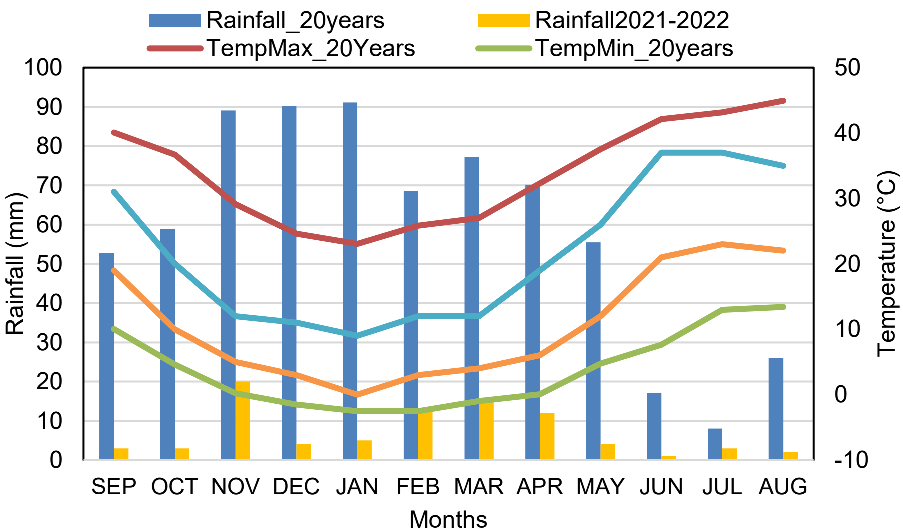


Figure 2. Monthly distribution of rainfall and minimum and maximum temperature during the growing season (2021/2022) and averaged over a 20 years period (DSA-Batna, 2023) and (NASA POWER, 2025).

Monthly rainfall was also very low throughout the year, not exceeding 18 mm, with particularly marked deficits in autumn and winter, which are generally wetter periods.

Maximum temperatures, which were above seasonal averages, reached 40 °C in June and July. Minimum temperatures, particularly from May to August, also exceeded historical averages, with values in July approaching 20 °C, compared to a usual average of around 15 °C over the last twenty years. This persistent water deficit, combined with abnormally high maximum and minimum temperatures, reflects the severe climatic stress experienced by the Timgad region during this growing season.

Experimental design and treatments

The treatment was a randomised complete block design (RCBD) with four replications. It was implemented on land allocated for planting durum wheat. Each block or replication was sub-divided into 11 sub-plots (each corresponding to a fertilisation treatment and covering an area of 31 m²). The total area of the experimental plot was 527 m², including inter-block (1 m²) and inter-plot (1m²) spacing. There were forty-four sub-plots in total (11 treatments × 4 blocks) (Fig. 3).

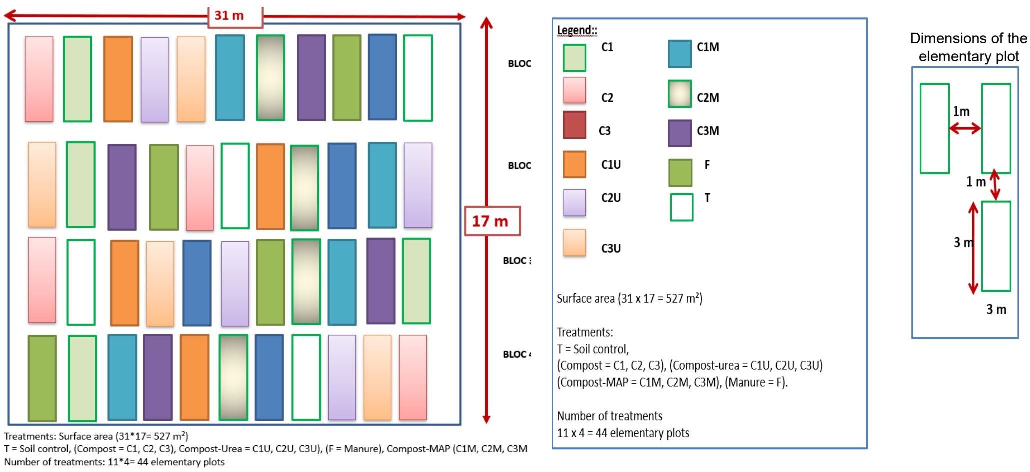


Figure 3. Experimental design.

The 11 fertilisation and organic amendment treatments are shown in Table 1. The selected treatments in this study were chosen based on the mineral fertilisers available, particularly urea (46%) and monoammonium phosphate (MAP), which are readily available on the Algerian market for cereal production. These mineral fertilisers were combined with organic amendments derived from date palm residues as compost, with the aim of increasing soil fertility.

The date palm (*Phoenix dactylifera* L.), is a dioecious monocotyledonous plant widely cultivated in arid and semi-arid regions, primarily for its edible fruit known as dates. It commonly propagates through offshoots or lateral shoots, a method that allows the faithful preservation of the mother plant's genetic traits. Renowned for its remarkable adaptability to harsh climatic conditions such as drought and high temperatures, the date palm plays a vital role as both a food source and an economic resource in dryland areas (Ashraf & Hamidi-Esfahani., 2011; Sharma et al., 2025).

The composting of date palm waste involves several key steps. First, the preparation and mixing of raw materials include collecting the main wastes such as dry leaves, stems, trunks, and sometimes fruit residues. These materials are shredded to hasten decomposition and often mixed with other organic materials like animal manure or green waste to balance the carbon-to-nitrogen (C/N) ratio, which is essential for effective composting. The mixtures are then piled into windrows or heaps to allow adequate aeration. During the thermophilic phase, temperatures rapidly rise up to approximately 45.7 °C before gradually falling back to ambient levels around 21 °C, indicating maturation. Maintaining moisture content between 50 and 60% and regular turning of the piles ensures oxygen supply and prevents anaerobic fermentation. Throughout the process, physico-chemical parameters such as pH, electrical conductivity, and organic carbon loss (typically 8.9 to 10.5%) are monitored to gauge microbial activity and organic matter breakdown. The matured compost has a natural earthy smell and uniform brown colour, with spectroscopic analyses (UV-visible, FTIR) confirming the transformation of organic compounds. A final C/N ratio below 20 indicates the compost has reached maturity and is suitable for use as an organic soil amendment (Habchi et al., 2020; Aydi et al., 2023).

Table 1. Treatments of organic and commercial fertilisation rate

Treatment	Control (T)	Sheep manure (F)	Compost (C) t ha^{-1}	MAP (M) kg ha^{-1}	Urea (U) kg ha^{-1}
T	0	0	0	0	0
F	0	45	0	0	0
C1	0	0	30	0	0
C2	0	0	50	0	0
C3	0	0	70	0	0
C1M	0	0	30	100	0
C2M	0	0	50	100	0
C3M	0	0	70	100	0
C1U	0	0	30	0	50
C2U	0	0	50	0	50
C3U	0	0	70	0	50

Legend: t (Control: Soil without amendment) – F (Sheep manure). Compost rate (C1-C2-C3). Compost-MAP combinations (C1M-C2M-C3M). Compost-Urea 46% combinations (C1U-C2U-C3U). Mineral fertilizer: MAP. Mono Ammonium Phosphate: ($NH_4H_2PO_4$): commercial fertilizer with 12% N and 52% P. U: Urea 46%.

Table 2. Physicochemical characteristics of compost

Settings (units)	Values
Organic C (%)	33.72
OM (%)	58
N total (%)	3 .18
C/N	10.60
Ph	7.47
K exchangeable (ppm)	164.1
K total (%)	0.41
Available phosphorus (ppm)	20.85
Total phosphorus (%)	0.27
EC (ms/cm)	5.22

Legend: OM = Organic Matter; TN = Total Nitrogen; TP = Total Phosphorus; AP = Available Phosphorus; TK = Total Potassium; EK = Exchangeable Potassium; OC = Organic Carbon; CEC = Cation Exchange Capacity; R = C/N Ratio; EC = Electrical Conductivity.

The compost is produced from date palm residues by a private company called PALM COMPOST. This company is located in Biskra, in a typical oasis environment of south-eastern Algeria., Physicochemical characteristics of compost were presented in Table 2.

The EC of compost from date palm fronds is 5.22 mS/cm, which implies a considerable degree of salinity. This value indicates a significant amount of soluble salts which may have effects on the physical, chemical and biological characteristics when applied to soil. Abundant high salinity could raise the content of Na^+ and Cl^- which would directly cause particles dispersion, soil structure impairment, acceleration for the water retention losses and sodicity. These alterations lead to impaired water and nutrient acquisition of plants, resulting in reduced growth and yields, as well as ionic imbalance and toxicity effects. In addition, high salt leads to reduced diversity and activity of soil microorganisms, which slows down the mineralisation of organic matter and decreases availability of essential nutrients, and eventually impacts on soil health and plant resistance to environmental stress conditions.

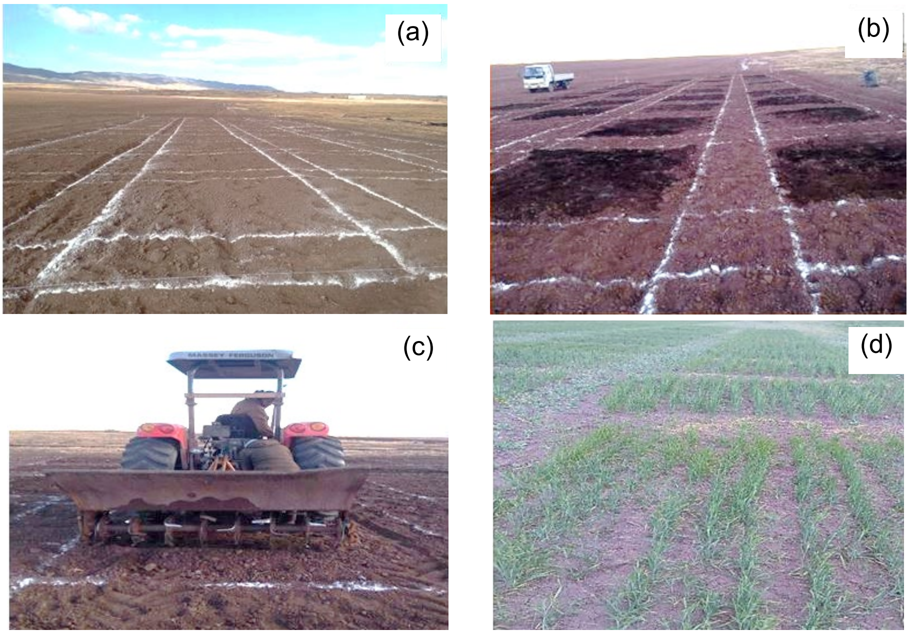


Figure 4. Different stages of experimental setup implementation: (a) Monitoring of the trial (b) Compost application, (c) Compost mixture (d) The wheat crop.

All fertilisation/organic amendments were applied before sowing on 8 January 2022 and mixed mechanically into the top 20 cm using a rotary tiller (Fig. 4).

On 18 December 2021, an initial soil sample (Fig. 5, a) was taken at a depth of 20 cm for an initial soil characterisation analysis (Table 3).

Figure 5. Soil sampling: (a) before sowing (b) after harvest (c) sampling location.

Physicochemical analysis of the soil reveals a loamy texture characterised by 47.82% silt, 30.43% sand and 21.75% clay, giving the soil good water retention capacity but making it susceptible to compaction (Rabot et al., 2018). The organic matter content is 1.83%, which is considered low according to European agronomic standards (Dignac et al., 2017), with a C/N ratio of 6.10 indicating rapid mineralisation of organic matter (Moinet et al., 2020). The total nitrogen content is 0.18%, which is in the average range, while the assimilable phosphorus content is very high at 54.34 ppm, well above the optimal thresholds of 15–30 ppm (Withers et al., 2019). Exchangeable potassium (0.51 meq/100 g) remains at an average level, and the cation exchange capacity (CEC) of 19.02 meq/100 g reflects good nutrient retention capacity (Mattila & Rajala, 2021).

The alkaline pH of 8.04 is explained by exceptionally high levels of total limestone (46.88%) and active limestone (21.44%), which are characteristic of Mediterranean calcareous soils and can lead to micronutrient deficiencies, particularly iron and zinc (Marschner & Rengel, 2023). The electrical conductivity of 1.45 dS/m indicates slight salinity, with a sodium content of 0.90 meq/100 g exceeding the critical threshold of 0.5 meq/100 g, suggesting a potential risk of sodisation (Qadir et al., 2014). The exchangeable cations show a dominance of calcium (12.14 meq/100 g) and an average level of magnesium (2.99 meq/100 g), reflecting the influence of the calcareous parent material on the chemical composition of the soil (Tucker, 1954).

Table 3. Initial soil characterisation analysis (before sowing)

Settings (units)	Values
Texture	Silty
Sand (%)	30.43
Silt (%)	47.82
Clay (%)	21.75
OM (%)	1.83
TN (%)	0.18
P (ppm)	54.34
K (meq/100 g)	0.51
OC (%)	0.79
CEC (meq/100 g)	19.02
R(C/N)	6.10
Ph	8.04
CT (%)	46.88
CA (%)	21.44
EC (dS/m)	1.45
Ca (meq/100 g)	12.14
Mg (meq/100 g)	2.99
Na (meq/100 g)	0.90

Legend: OM = Organic Matter; TN = Total Nitrogen; P = Available Phosphorus; K = Exchangeable Potassium; OC = Organic Carbon; CEC = Cation Exchange Capacity; R = C/N Ratio; Total $CaCO_3$ Active $CaCO_3$; EC = Electrical Conductivity; Ca = Exchangeable Calcium; Mg = Exchangeable Magnesium; Na = Exchangeable Sodium.

After the wheat crop was harvested, a new soil sampling as (Fig. 5, b) carried out at the centre of each elementary plot (Fig. 5, c), at two different horizons: 0–20 cm and 20–40 cm. Each elementary plot measured 3 m × 3 m, and the distance between plots was 1 meter.

Thus, the distance between two adjacent sampling points (center to center) is 4 meters (3 m plot width + 1 m spacing). The samples taken were dried in the open air and then sieved using a 2 mm sieve to obtain a homogeneous fraction suitable for chemical characterisation analyses (Tables 5 and 6).

Statistical analysis

In the RStudio/2025.05.01+513 environment, the collected data were subjected to rigorous statistical analysis to identify significant differences between groups. Analysis of variance (ANOVA) was employed to test these differences, followed by post-hoc comparisons to specify pairwise contrasts. Tukey's honestly significant difference (HSD) test at a 5% significance level, implemented via the **agricolae** package. Relationships among variables were explored through correlation matrices using the **FactoMineR** and **corrplot** packages. Additionally, treatments were characterised using principal component analysis (PCA) and hierarchical clustering (HCA). Finally, simple linear regressions were conducted to determine the most influential explanatory variables for the parameters studied using a program in Matlab (version 2017).

RESULTS AND DISCUSSION

The opposite effects of treatments on nutrient availability and soil chemical properties are evident in analytical results. Treatment effects were assessed by analysis of physical and chemical parameters from two soil depths (0–20 cm, 20–40 cm) (Tables 4 and 5) after six months of applying organic and commercial fertilisers.

Table 4. Soil analysis methods

Measured parameters	Methods used	References
pH	pH meter with a soil/water ratio of 1/2.5	Mathieu & Pieltain, 2003
EC	Conductivity meter with a soil/water ratio of 1/5 is expressed in dS/m at 25 °C).	Estefan et al., 2013
Total CaCO3	Bernard Method	Estefan et al., 2013
Active CaCO3	Drouineau-Galet Method	Estefan et al., 2013
Organic matter OM	Walkley-Black Method	Estefan et al., 2013.
Organic carbon OC	Walkley-Black Method	Estefan et al., 2013
Total nitrogen	Kjeldahl Method	Estefan et al., 2013
Exchangeable Potassium	Extraction (pH 8.2) with ammonium acetate	Mathieu & Pieltain, 2003
Exchangeable calcium	Extraction (pH 8.2) with ammonium acetate	Mathieu & Pieltain, 2003
Exchangeable magnesium	Extraction (pH 8.2) with ammonium acetate	Mathieu & Pieltain, 2003
Exchangeable sodium	Extraction (pH 8.2) with ammonium acetate	Mathieu & Pieltain, 2003
available phosphorus	Olsen Method	Estefan et al., 2013
CEC	Extraction (pH 8.2) with ammonium acetate	Mathieu & Pieltain, 2003

Legend: OM = Organic Matter; TN = Total Nitrogen; P = Available Phosphorus; K = Exchangeable Potassium; OC = Organic Carbon CEC = Cation Exchange Capacity; Total CaCO3 C/N Ratio; Active Total CaCO3 EC = Electrical Conductivity; Ca = Exchangeable Calcium; Mg = Exchangeable Magnesium; Na = Exchangeable Sodium.

Effect of different date palm compost modalities on soil fertility

The findings in Tables 5(a) and 5(b) reveal several important trends. First, the combined application of date palm compost and mineral fertilisers significantly increased organic matter content, with the highest values observed in treatment C2M (3.79%) in the surface soil (0–20 cm) and in treatment C3U (4.00%) in the subsurface soil (20–40 cm). This finding is consistent with recent reports by Kumari & Purakayastha (2020), who demonstrated that combined organic inputs are highly effective in building organic matter stocks in semi-arid calcareous soils.

Table 5. (a) and 5(b). Results of the ANOVA for the Effect of different date palm compost modalities on soil fertility two depths: 0–20 cm and 20–40 cm

Table 5(a)

Treatments	OM (%)	OC (%)	CEC (meq/100 g)	C/N (ratio)	pH	EC (dS/m)
T	2.43 ± 0.26 abc	1.06 ± 0.11 abc	21.04 ± 3.52 a	5.81 ± 5.48 a	8.04 ± 0.30 a	1.32 ± 1.20 a
F	3.13 ± 0.36 abc	1.36 ± 0.16 abc	24.24 ± 3.60 a	2.52 ± 0.65 a	7.98 ± 0.13 a	1.47 ± 1.03 a
C1	1.86 ± 0.46 c	0.81 ± 0.20 c	18.77 ± 5.58 a	2.17 ± 1.32 a	7.91 ± 0.14 a	1.69 ± 1.18 a
C2	2.95 ± 0.47 abc	1.28 ± 0.20 abc	19.30± 2.36 a	2.05 ± 0.56 a	7.90 ± 0.09 a	1.51 ± 0.72 a
C3	3.40 ± 0.23 ab	1.48 ± 0.10 ab	19.71 ± 0.51 a	1.66 ± 0.75 a	7.94 ± 0.21 a	1.49 ± 1.00 a
C1M	2.93 ± 0.46 abc	1.27 ± 0.20 abc	21.11 ± 4.67 a	3.23 ± 1.54 a	7.91 ± 0.08 a	1.62 ± 0.90 a
C2M	3.79 ± 0.31 a	1.65 ± 0.34 a	22.90 ± 4.70 a	6.29 ± 1.86 a	7.80 ± 0.10 a	1.36 ± 0.07 a
C3M	3.22 ± 1.56 abc	1.40 ± 0.68 abc	22.37 ± 3.06 a	2.88 ± 2.55 a	7.90 ± 0.18 a	1.71 ± 1.05 a
C1U	2.49 ± 0.42 bc	0.97 ± 0.18 bc	22.11 ± 4.67 a	1.91 ± 0.95 a	7.83 ± 0.06 a	2.35 ± 0.17 a
C2U	2.72 ± 0.30 abc	1.18 ± 0.13 abc	21.70 ± 1.79 a	1.58 ± 0.38 a	7.80 ± 0.10 a	2.45 ± 0.44 a
C3U	3.38 ± 0.52 ab	1.47 ± 0.23 ab	22.37 ± 1.33 a	2.25 ± 0.68 a	7.90 ± 0.06 a	2.65 ± 0.31 a
TEST F/P	3.53 0.00291 **	3.54 0.00291 **	0.96 0.48* ns	2.45 0.0256 *	1.45 0.203 ns	1.098 0.392 ns

Table 5(b)

Treatments	OM (%)	OC (%)	CEC (meq/100 g)	C/N (ratio)	pH	EC (dS/m)
T	0.61 ± 0.39 d	0.56 ± 0.69 a	19.31 ± 0.66 a	0.76 ± 0.48 b	7.85 ± 0.089a	2.32 ± 0.22 a
F	2.36 ± 0.46 b	1.03 ± 0.19 ac	22.50 ± 2.06 bc	2.06 ± 1.65 ab	7.91 ± 0.62 a	1.40 ± 0.80 a
C1	2.62 ± 0.08 ab	1.12 ± 0.03 ab	20.24 ± 2.19 ab	0.92 ± 0.07 ab	7.88± 0.23a	1.14 ± 0.56 a
C2	3.08 ± 0.32 bc	1.34 ± 0.14 bc	22.24 ± 4.19 a	1.30 ± 0.45 ab	7.94 ± 0.13 a	1.20 ± 0.64 a
C3	2.73 ± 0.25 ab	1.22 ± 0.10 ab	21.30 ± 2.24 b	2.51 ± 2.31 ab	8.16 ± 0.47 a	0.58 ± 0.10 a
C1M	2.56 ± 0.21 ab	1.11 ± 0.09 ab	20.11 ± 1.15 bc	2.59 ± 2.06 ac	8.06 ± 0.33 a	1.73 ± 1.33a
C2M	3.12 ± 0.51 bc	1.35 ± 0.22 bc	18.90 ± 3.78 b	3.27 ± 1.32 bc	7.79 ± 0.10 a	1.62 ± 1.08 a
C3M	3.57 ± 0.87 ac	1.55 ± 0.38 bc	22.64 ± 3.30 ab	2.77 ± 0.77 bc	7.95 ± 0.28 a	1.52 ± 1.12 a
C1U	3.36 ± 0.38 bc	1.46 ± 0.16 bc	21.30 ± 4.77ab	4.14 ± 1.58 bc	7.94 ± 0.19 a	1.55 ± 1.00 a
C2U	3.22 ± 0.39 bc	1.40 ± 0.17 bc	23.17 ± 2.32 ab	4.66 ± 1.58 bc	7.98 ± 0.31 a	1.59 ± 1.04 a
C3U	4.00 ± 0.22 c	1.74 ± 0.09 b	26.90 ± 3.30 a	4.22 ± 2.79 bc	8.04 ± 0.30 a	1.47 ± 0.99 a
TEST F/P	17.16 0.0000***	5.180.00015***	2.23 0.0406 *	2.98 0.00882 **	0.664 0.74 ns	0.91 0.536 ns

Legend: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; n.s = no significant. Means followed by the same letter in a column do not differ significantly according to the *test* Tuckey ($p > 0.05$). OM: organic matter; OC: organic carbon; CEC; cation exchange capacity; C/N: the carbon/nitrogen ratio; pH: hydrogen potential; EC = electrical conductivity.

Table 6. (a) and (b). Results of the ANOVA for the Effect of different date palm compost modalities on Soil chemical properties two depths: 0–20 cm and 20–40 cm

Table 6(a)

Treatments	TN (%)	P (ppm)	K (meq/100 g)	Ca (meq/100 g)	Mg (meq/100 g)	Na (meq/100 g)	CT (%)	CA (%)
T	0.29 ± 0.18	57.67 ± 16.46	0.75 ± 0.08 c	15.64±3.00	2.65 ± 1.31 ab	0.87 ± 0.08 b	34.69 ± 0.80 ac	15.34 ± 0.40 ac
F	0.57 ± 0.18	70.00 ± 28.11	1.30 ± 0.40 abc	13.75 ± 3.55	2.31 ± 1.40 ab	1.48 ± 0.28 bd	34.75 ± 1.34 ab	15.38 ± 0.69 ab
C1	0.59 ± 0.53	55.75 ± 9.81	0.93 ± 0.15 bc	12.62 ± 0.57	2.08 ± 1.25 ab	1.04 ± 0.32ab	35.09 ± 0.22 ab	15.54 ± 0.11 ab
C2	0.66 ± 0.20	78.09 ± 11.77	0.94 ± 0.11 bc	14.07± 1.42	2.47 ± 1.16 ab	1.79 ± 0.24 acd	35.02 ± 0.96 ab	15.51 ± 0.48 ab
C3	1.04 ± 0.44	85.17± 23.77	1.01± 0.20 bc	14.30 ±2.53	1.76 ± 1.00 ab	1.79 ± 0.06 acd	34.02 ± 0.76 a	15.01 ± 0.38 a
C1M	0.48 ± 0.26	78.34 ± 20.32	0.93 ± 0.18 bc	12.96 ±1.19	1.66 ± 1.36 ab	1.14 ± 0.32 bc	35.76 ± 0.35 bc	15.88 ± 0.17 bc
C2M	0.28 ± 0.08	76.92 ± 6.99	1.25 ± 0.40 abc	12.94 ± 138	3.38± 1.05 bc	0.92 ± 0.67 b	36.43 ± 0.22 b	16.21 ± 0.11 b
C3M	0.71 ± 0.62	79.80 ± 18.87	1.47 ± 0.66 abc	12.51 ±0.40	3.78 ± 1.05 bc	2.23 ± 0.28 d	36.09 ± 0.34 bc	16.05 ± 0.85 bc
C1U	0.61 ± 0.29	70.17 ± 8.91	0.76 ± 0.14 c	12.97± 1.20	6.06 ± 1.18 c	1.38 ± 0.32 bc	35.75 ± 0.15 bc	15.88 ± 0.07 bc
C2U	0.78 ± 0.20	87.21 ± 20.99	1.83 ± 0.14 ab	11.97 ± 0.54	4.22 ± 0.38 ac	1.86 ± 0.25 cd	35.76 ± 0.35 bc	15.88 ± 0.17 bc
C3U	0.71 ± 0.27	55.38 ± 39.39	1.96 ± 0.84 a	13.50±0.33	1.43 ± 0.87 b	1.82 ± 0.15 cd	36.23 ± 1.06 bc	16.11 ± 0.52 bc
TEST F/P	1.641 0.138 ns	1.79 0.101 ns	4.61 0.00039***	1.316 0.263 ns	5.96 0.000***	8.260.000 ***	4.52 0.0000 ***	4.52 0.0000 ***

Table 6(b)

Treatments	TN (%)	P (ppm)	K (meq/100 g)	Ca (meq/100 g)	Mg (meq/100 g)	Na (meq/100 g)	CT (%)	CA (%)
T	0.36 ± 0.06 b	53.25 ± 5.97	0.25 ± 0.02 a	12.34 ± 0.34 ab	4.97 ± 1.17 ab	2.15 ±0.41 b	46.11 ± 0.60 ab	21.05 ± 0.29 ab
F	0.71 ± 0.44 ab	86.83 ± 23.79	0.69 ± 0.16 ab	14.26 ± 0.35 b	2.04 ± 1.38 ab	1.72 ± 0.29 b	45.17 ± 0.80 ab	21.60 ± 0.38 ab
C1	1.24 ± 0.07 a	78.58 ± 13.63	0.66 ± 0.04 ab	13.29 ± 0.45 ab	3.44 ± 1.35 ab	0.89± 0.23 a	46.79 ± 1.22 ab	21.39 ± 0.61 ab
C2	1.13 ± 0.41 a	80.62 ± 23.58	0.73 ± 0.22 ad	10.83 ± 0.53 a	5.65 ± 1.45 ab	1.77 ± 0.24 b	45.17 ± 0.90 ab	20.58 ± 0.45 ab
C3	0.74 ± 0.43 ab	89.46 ± 8.56	0.63 ± 0.13 ab	12.47 ± 0.20 ab	1.08 ± 0.81 ab	2.13 ± 0.51 b	43.89 ± 0.58 bc	19.94 ± 0.29 bc
C1M	0.68 ± 0.45 ab	79.96 ± 18.33	0.58 ± 0.21 ac	11.22 ± 0.47 a	3.58 ± 2.02 ab	1.63 ± 0.21 b	41.76 ± 3.39 c	18.88 ± 1.70 c
C2M	0.50 ± 0.30 ab	75.17 ± 9.88	0.72 ± 0.23 ab	13.02 ± 1.26 ab	2.16 ± 1.18 ab	1.53 ± 0.09 b	44.57 ± 1.16 bc	20.28 ± 0.58 bc
C3M	0.57 ± 0.14 ab	89.71 ± 17.45	1.31 ± 0.37 d	14.03 ± 2.61 b	2.08 ± 0.45 ab	1.94 ± 0.36 b	48.41 ± 1.86 a	22.20 ± 0.93 a
C1U	0.37 ± 0.11 b	73.42 ± 19.25	0.98 ± 0.18 bcd	12.24 ± 1.89 ab	2.45 ± 1.06 ab	1.96 ± 0.16 b	45.59 ± 1.05 ab	20.79 ± 0.52 ab
C2U	0.32 ± 0.08 b	74.04 ± 18.31	1.21 ± 0.40 bd	13.44 ± 0.68 ab	1.53 ± 0.65 ab	1.77 ± 0.16 b	45.17 ± 0.44 ab	20.58 ± 0.22 ab
C3U	0.60 ± 0.38 ab	72.55 ± 17.58	1.19 ± 0.32 bd	11.86 ± 0.91 ab	1.73 ± 1.09 a	1.50± 0.23 ab	44.92 ± 0.32 bc	20.46 ± 0.16 bc
TEST F/P	3.78 0.00182**	1.45 0.204 ns	7.175 0.0000***	3.67 0.00226**	6.89 0.0000***	5.87 0.00000***	5.72 0.0000***	5.72 0.0000 ***

Legend: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = no significant. Means followed by the same letter in a column do not differ significantly according to the test. ($p > 0.05$). TN: total nitrogen; P: available phosphorus; K: exchangeable potassium; Ca: exchangeable calcium; Mg: Exchangeable magnesium; Na: exchangeable sodium; CT: Total Calcium Carbonate; CA: active Calcium Carbonate.

Organic carbon (OC) followed a similar pattern, with the highest concentrations recorded under treatment C2M (1.65 ± 0.34%) and C3U (1.74 ± 0.09%) These results confirm the important role of compost in enhancing soil structure and promoting soil carbon sequestration, which is in good agreement with findings reported by Ameziane et al. (2019), Spaccini & Piccolo (2020), Chen et al. (2023), and Li et al. (2023).

The CEC values reached 18.77 ± 5.58 meq/100 g in the surface layer (0–20 cm) under treatment C1 and 26.90 ± 3.30 meq/100 g in the subsurface layer (20–40 cm) under treatment C3U. These results indicate enhanced cation retention capacity in the subsurface soil, which improves the soil's ability to retain essential nutrients and reduce leaching losses, thereby maintaining nutrients available for crop uptake. These findings are consistent with observations reported by Asaye et al. (2022).

The C/N ratio (carbon/nitrogen) ultimately varies greatly between treatments (from 6.29, C2M to 1.58, C2U) representing a balance between organic matter build-up and N-enrichment necessary to support the subsequent gradual mineralisation (Smith et al., 2024). These results underline the importance of the balanced management of the applied organic nutrients and mineral fertiliser in calcareous soils of semi-arid regions to maintain the sustainability of nutrient balance (Krištaponytė., 2005).

Effect of different date palm compost modalities on soil chemical properties

The data from analysis of variance in Table 6(a) and 6(b) the soil chemical properties as in the case of the botanical characteristics of soil, the influence of the combined effects of the fertilisation date palm compost, mineral+fertilisers varies greatly. The cation exchangeable ions (Na, Mg and K) also reveal a highly significant change (K no amendments (0.25 ± 0.02 meq/100 g). The improvement in cations availability observed in the present study can chiefly be attributed to the results reported by Singh et al. (2021), who shows the importance of organic amendments in nutrient mobilization in semi-arid calcareous soils. The highest concentration of total N is reported in the only-compost treatment (C1: 1.24 ± 0.07%; C2: 1.13 ± 0.41%) while the presence of urea exerted a lesser effect (C1U: 0.37 ± 0.11%; C2U: 0.32 ± 0.08%), due to possible interaction between mineral and organic sources in the deep N process (Marzi et al., 2020).

There were no significant differences in available phosphorus between treatments ($p > 0.05$), with values ranging from 53.25 ± 5.97 ppm (control) to 89.71 ± 17.45 ppm (C3M). This lack of response to phosphorus reflects the specific constraints of calcareous soils, where precipitation with calcium limits phosphorus availability (Leytem & Mikkelsen, 2005).

Relationships analysis of the effects of date palm compost

Correlation matrix analysis, Principal Component Analysis (PCA), Ascending Hierarchical Classification (AHC) and linear regression, made it possible to carry out an overall study, synthesis, grouping and modelling of the complex effects of various applications of date palm compost on soil parameters.

The advantages of integrated fertilisation can be explained by the complementary nature of the two sources: compost improves soil structure and biological activity by increasing organic matter (Ameziane et al., 2019) while mineral fertiliser quickly meets crop needs through the immediate release of nitrogen or phosphorus (Saini et al., 2025).

This combination makes it possible to circumvent certain classic limitations of calcareous soils, in particular the low natural availability of phosphorus due to precipitation with calcium (Teng et al., 2020; Jalali & Jalali, 2022).

The correlation matrices (Fig. 2) corroborate these observations, showing a strong relationship (r = 1.00) between organic matter and organic carbon, and notable positive correlations between potassium, C/N and organic matter, both at shallow depths (0–20 cm) and deep depths (20–40 cm). Research has been carried out in Morocco and the Mediterranean Basin, showing the positive effects of the application of compost from date palm on organic matter, organic carbon and K+ exchangeability in calcareous soils, thus confirming the good conjunction of organic fertility and mineral nutrition (Ou-Zine et al., 2021; Badawi, 2022; Kavvadias et al., 2024).

The integrated treatments (C1M, C2M) showed a clear advantage in terms of root nutrition and subsurface fertility, where the effects are particularly marked for potassium, magnesium, electrical conductivity and organic matter at a depth of 20–40 cm.

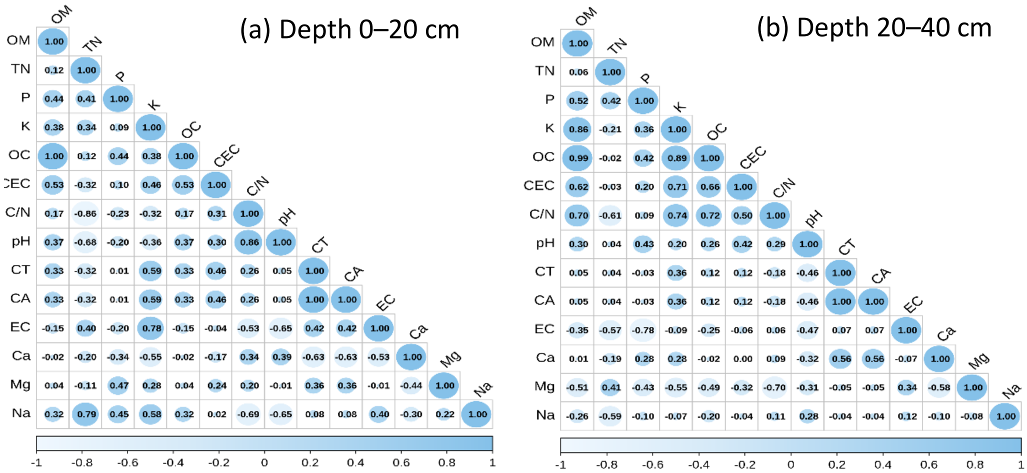
The compost has C/N ratio close to equitability (12.54, Table 2) compared to uncomposted residues, which biases towards the high mineralization rates (Lazicki et al., 2020). However, the strong negative relationship between total nitrogen (NT) and pH (r = −0.64) alters the traditional model of nitrogen limitation in alkaline soils in which calcareous soils normally impose a 30–40% decrease mineralisation efficiency (Zarabi & Jalali, 2013).

The high organic matter (58% OM) contained in the compost affects the relationship K–organic matter (r = 0.89) at depth (20–40 cm) suggesting the potential of stable organo-mineral complexes due to phenolic compounds that occur in date palm tissues (Abid et al., 2020).

Detailed analysis of the correlation matrix, obtained by merging depths (0–20 cm) and (20–40 cm) (Fig. 6) and calculating averages per treatment, reveals strong statistical links between most of the major soil fertility parameters. Correlation coefficients frequently exceed 0.90 between organic matter (OM), total nitrogen (TN), organic carbon (OC), potassium (K), cation exchange capacity (CEC), calcium (Ca), magnesium (Mg) and the R(C/N) ratio. This means that an increase in organic matter, obtained through the addition of organic residues, compost or sheep manure, is systematically accompanied by an improvement in the availability of major nutrients and the soil's ability to retain them. For example, the OM–TN correlation (r = 0.96) shows that enriching the soil with organic matter directly increases total nitrogen, while the OM–OC correlation (r = 0.98) illustrates the structural relationship between these two components.

The strong correlations between CEC, calcium, magnesium and the soil R(C/N) ratio (CEC–Ca r = 0.93; Mg–Ca r = 0.97) indicate that improving soil exchange capacity, promoted by organic inputs, enhances the availability of essential cations and soil structural stability. Phosphorus (P) also shows high correlations with CEC and organic matter (P–CEC r = 0.71; P–OM r = 0.70), suggesting that integrated fertilisation, combining organic matter and mineral fertilisers, improves phosphorus availability while enhancing overall fertility.

Sodium (Na) and pH show weaker or insignificant correlations with other parameters, indicating that they evolve relatively independently and require specific monitoring, particularly to prevent the risks of salinisation or acidification.



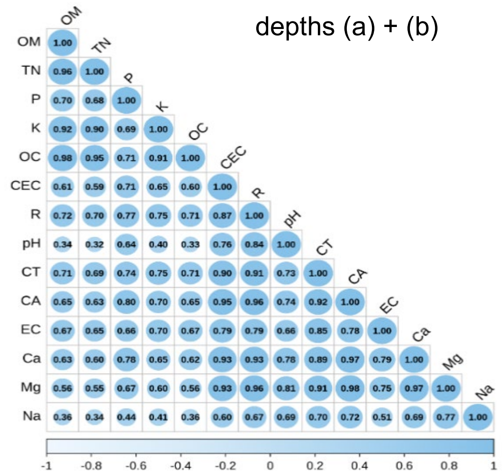


Figure 6. Correlation matrix depths (0–20 cm) and (20–40 cm), depth (a), depth (b) and depth (a+b).

Research rigorously confirms that integrated fertilisation, combining organic and mineral inputs, simultaneously and consistently improves most soil chemical properties, particularly in semi-arid regions (Wang et al., 2025). The increase in organic matter plays a central role, promoting the retention and availability of essential nutrients, while improving organic carbon, total nitrogen, available phosphorus, cation exchange capacity and soil pH (Ejigu et al., 2021).

This combined management not only sustainably increases soil productivity and resilience, but also limits the risks of sodium-related imbalances or acidification by buffering pH variations and improving soil structure (Wang et al., 2025).

The beneficial effects of integrated fertilisation are observed on various types of soil (tropical, clayey, sandy, degraded, etc.) and in different climatic contexts, confirming its universal effectiveness for sustainable and productive agriculture, even in areas with severe environmental constraints (Urmi et al., 2022).

Principal component analysis (Fig. 7, a) reveals a clear discrimination between fertilisation treatments, with 50.9% of variance explained (PC1: 31%, PC2: 19.9%).

With respect to the C3, C3M, and C3U treatments showing segregations in the optimal quadrant of the factorial space, we believe they exhibit quite stable relationships with the major fertility components: electrical conductivity (EC), total calcium carbonate (TCC), total nitrogen (TN) and organic matter (OM). They are clearly highly efficient for improving the fertility of alkaline soils (Urmi et al., 2022).

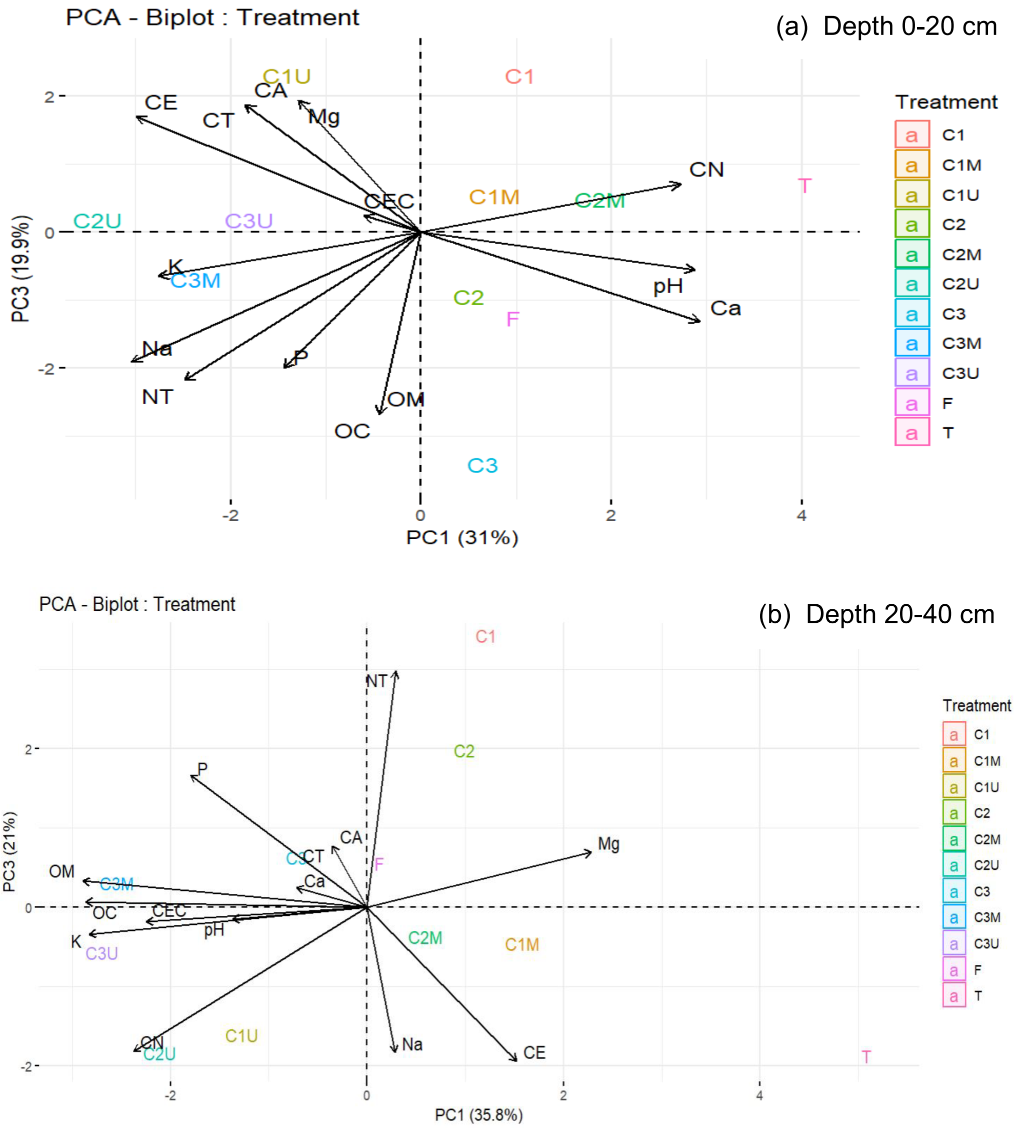


Figure 7. Principal component analysis of depth 0–20 cm(a) and depth 20–40 cm (b).

In contrast, T and F control and manure-only treatments are arranged in a low-productivity area, which provides evidence that adapted fertilisation strategy are necessary. Low rates (C1, C1M, C1U) are not effective at all and intermediate (C2, C2M) rates show intermediate effectiveness.

That potassium is greatly limited in the former soils, is still-better demonstrated by the fact that applications of potassium do not increase yield in the presence of organic matter, even though such practice may facilitate potassium release. Potassium supply is often significantly enhanced when organic matter content exceeds a threshold level, and the supply of potassium is promoted by increasing organic matter, even though to a lesser extent than that observed for N (Zhao et al., 2016). However, low doses and/or single manure application cannot ensure a proper restoration of soil fertility, indicating the need for an intelligent analytical and integrated strategy in soil maintenance.

The principal component analysis of the 20–40 cm depth (Fig. 7, b) shows good discrimination of the fertilisation treatments accounting for 53.4% (PC1 = 35.8% and PC2 = 17.6%) of the variation which is even higher compared to the depth 0–20 cm. The biplot revealed that treatment-C3M, treatment-C3U, treatment-C2U and treatment-C2M stand further apart from the other groups based on their related positions with the soil variables. The treatments C3M and C3U representers the lower left quadrant where a high influence of the C/N and CEC are observed, where CEC and C/N ratio explained the most variation. Treatment C2U, immediately adjacent these groups, also shows significant impact on C/N ratio, which is associated with high potassium concentration. Last, the treatment C2M, which also had a high C/N ratio, is a specific treatment for sodium (Na). It is thus the high C/N ratio, CEC, potassium and sodium value itself in combination, which particularly distinguished these four treatments, and the variation in treatment could largely be attributed to these variables in the multivariate analysis.

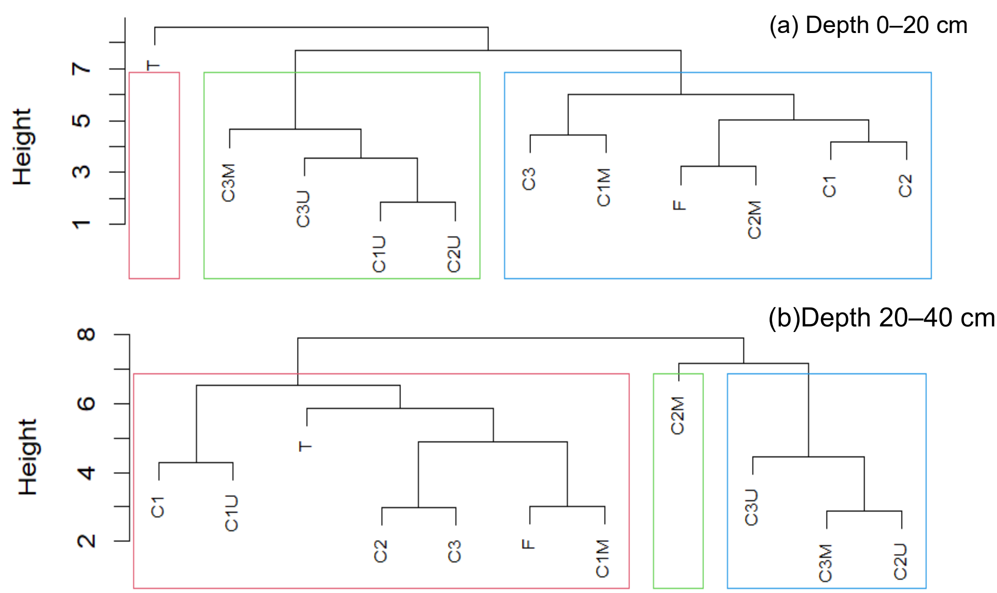
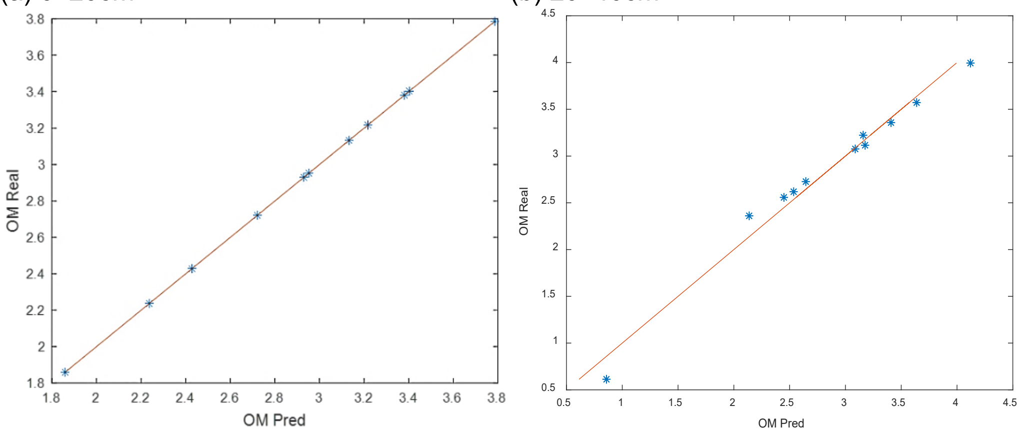


Figure 8. Ascending Hierarchical Classification of depth 0–20cm(a) and depth 20–40cm (b).

The ascending hierarchical classification (Fig. 8) shows that integrated (organic and mineral) fertilisation systems are the best for recovery the fertility of calcareous soils intended for cereal crops. Using this approach, treatments were categorised into three broad groups: (1) high-rate applications (C3M, C3U) – where this achieved the best performance across agronomy parameters; (2) intermediate rates of fertilisation – mainly increasing availability of Mg and deep layer fertility; and (3) control and low-rate applications – where little overall performance was observed on such parameters across all four agronomy response indicators. These groupings corroborate the results of previous research (Zhang et al., 2022; Kumari et al., 2024) highlighting that application of organic amendment in combination with mineral fertilizer allows favourable mineralization scheduling for nutrient release and increased soil fertility (Okhumata, 2022; Oyetunji et al., 2022).

When considering the multivariate approach, linear regression analysis (Fig. 9) in combination disentangled indirect influences between organic matter and the main soil fertility variables. Date palm compost and mineral fertiliser inputs in the depth 0–20 cm exhibited a perfect positive relationship with organic matter for organic carbon ($R^2 = 1.0$). This organic matter increase matches the positive changes in carbon quantity at the depth 0–20 cm, a major driver of soil structure and productivity, as stressed by Ou-Zine et al. (2021), El Janati et al. (2023), and Kumari et al. (2024).

(a) 0–20cm (b) 20–40cm



OM = 2.2987•OC
$R^2 = 1$

OM = –0.4663–0.1392•K + 3.0318•OC – 0.0172•CEC–0.0125•C/N
$R^2 = 0.98$

Figure 9. (a) soil organic matter as a function of organic carbon $R^2 = 1$; (b) organic matter as a function of exchangeable potassium, cation exchange capacity and C/N ratio. $R^2 = 0.98$.

In the depth 20–40 cm, the model showed that carbon amount continues to be a primary determinant of organic matter content, but that its influence on organic matter dynamics is also controlled by other chemical conditions particularly with respect to major cation dynamics (K; CEC) and C/N ratio. Indeed, there is a relationship between CEC and organic matter, which has been demonstrated in the literature (Nouar et al., 2019) These findings suggest that depth 0–20 cm management alone is not enough to improve fertility; proper and reasonable management of the depth 20–40 cm, where root systems developed, is also required as explicitly stated by Li et al. (2023).

This method of modelling provides important advantages for the agricultural and land management community. Adjusting the rates of compost and mineral fertilisers to the soil conditions, for each layer, is important for a sustainable recovery of the organic matter and improving the stability and flexibility of the soil. This is an important factor to sustain cereal systems under a semi-arid environment found by (Zhao et al. (2016).

The results align with recent studies reporting increased soil carbon stocks in calcareous soils of semi-arid regions under Integrated Nutrient Management (INM) (Singh et al., 2021; Li et al., 2023; Kumari et al., 2024). Mixed fertility approaches address environmental constraints by combining organic matter inputs from compost, which improve soil structure, water retention, and stimulate microbial activity, with mineral fertilisers that provide immediate nutrient supply, particularly nitrogen and phosphorus. In calcareous soils, high pH restricts phosphorus availability, reflected by the lack of significant difference in available phosphorus between the 0–20 cm and 20–40 cm soil layers, indicating complex phosphorus dynamics. Phosphorus fixation, mainly through reactions with calcium and magnesium, can reduce plant-available phosphorus by over 80% (Adnan et al., 2025). Precipitation and adsorption processes in these soils diminish the effectiveness of phosphorus amendments from both organic and mineral sources (Hinsinger, 2001). The combined application of date palm compost and monoammonium phosphate (MAP) markedly enhances organic matter content, organic carbon, and cation exchange capacity (CEC) by increasing soil organic matter stocks and promoting the formation of organo-mineral complexes with soil calcium carbonates (Ben Mbarek et al., 2019; Abid et al., 2020; Islam et al., 2022; Kavvadias et al., 2024). Compost also stimulates microbial activity, notably Actinobacteria and saprotrophic fungi, accelerating organic matter decomposition and nutrient release (Islam et al., 2022; Ghouili et al., 2023; Zhao et al., 2025). Microbial biomass is subsequently stabilised through mineral association, enhancing carbon retention and CEC (Islam et al., 2022; Zhao et al., 2025). The increase in organic matter density raises the number of negative charges on soil particle surfaces, improving retention of cations such as Ca^{2+}, Mg^{2+}, and K^{+} (Ben Mbarek et al., 2019; Abid et al., 2020; Kavvadias et al., 2024). Stability of soil organic matter in calcareous contexts results from the formation of organo-mineral complexes, precipitation of organic compounds with calcium, and accumulation of microbial necromass, which slows mineralisation and favours long-term carbon storage (Islam et al., 2022; Zhao et al., 2025). However, phosphorus availability remains limited due to precipitation of MAP-derived phosphorus as poorly soluble calcium phosphates, temporary microbial immobilisation, and the high buffering capacity of calcareous soils that restricts phosphorus solubilisation even in presence of organic acids from compost (Abid et al., 2020; Ghouili et al., 2023; Kavvadias et al., 2024; Zhao et al., 2025).

CONCLUSION

The results of this study indicate that integrated fertilisation practices (C3U, C3M, C2U), involving the application of date palm frond compost combined with mineral fertilisers (urea 46% and MAP) as a basal input for cereals, are both effective and environmentally sustainable for improving the fertility of calcareous soils. Among these treatments, C3M was identified as the most effective, demonstrating that integrated date palm compost fertilisation is particularly well-suited to the region's calcareous soils. This approach significantly enhanced key soil fertility parameters, including organic matter (OM), organic carbon (OC), cation exchange capacity (CEC), the C/N ratio, and particularly potassium (K) content. These findings provide valuable insights into the efficiency of integrated fertilisation under semi-arid calcareous soil conditions.

However, experimental observations were limited to a single agricultural year and one study site, which may not adequately capture spatial and temporal variability. The research was additionally constrained by limited water availability, reducing irrigation capacity and thus influencing crop performance. These conditions reflect the broader challenges typical of semi-arid agroecosystems. Nevertheless, the study incorporated participatory research involving local farmers to ensure practical relevance and the co-production of knowledge. Further multi-annual and multi-site investigations are therefore recommended to validate and enhance the robustness and transferability of these findings.

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