Assessment of organic carbon stock and labile carbon in soils of the Gataaya Oasis, Tunisia Postprint

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Abstract

Oasis soils in Tunisia are characterized by low soil organic carbon (SOC) stocks, primarily due to their coarse texture and intensive irrigation practices. In the Gataaya Oasis, soils receive 3.000 to 4.000 L/m2 annually through submersion irrigation, leading to a rapid decline in SOC stocks. Despite their sandy texture, which promotes good water infiltration, these soils are enriched with clay, dissolved materials, and fertilizers in deeper horizons. This study aimed to assess SOC content in the Gataaya Oasis soils, investigate the transport of labile carbon in drainage water, and clarify the destiny of this transported carbon. Soil samples were collected systematically at three depths (0–10, 10–20, and 20–30 cm), focusing on the top 30 cm depth, which is most affected by amendments. Two sampling points (P1 and P2) were selected, i.e., P1 profile near the trunk of date palms (with manure input) and P2 profile between two adjacent date palms (without manure input). Water samples were collected from drainage systems within the oasis (W1, W2, and W3) and outside the oasis (W4). A laboratory experiment simulating manure application and irrigation was conducted to complement field observations. Physical-chemical analyses revealed a significant decrease in SOC stocks with soil depths. In P1 profile, SOC stocks declined from 17.71 t/hm2 at the 0–10 cm depth to 7.80 t/hm2 at the 20–30 cm depth. In P2 profile, SOC stocks were lower, decreasing from 6.73 t/hm2 at the 0–10 cm depth to 3.57 t/hm2 at the 20–30 cm depth. Labile carbon content in drainage water increased outside the oasis, with chemical oxygen demand (COD) values rising from 73 mg/L in W1 water sample to 290 mg/L in W4 water sample, indicating cumulative leaching effects from surrounding oases. The laboratory experiment confirmed field observations, showing a decline in soil organic matter (SOM) content from 3.27% to 2.62% after 12 irrigations, highlighting the vulnerability of SOC stocks to intensive irrigation. This study underscores the low SOC stocks in the Gataaya Oasis soils and their rapid depletion under successive irrigations. The findings provide insights into the dynamics of labile carbon transport and its contribution to regional carbon cycling, offering valuable information for sustainable soil management and ecological protection in arid ecosystems.

Full Text

Preamble

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Assessment of organic carbon stock and labile carbon in soils of the Gataaya Oasis, Tunisia

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Abstract: Oasis soils in Tunisia are characterized by low soil organic carbon (SOC) stocks, primarily due to their coarse texture and intensive irrigation practices. In the Gataaya Oasis, soils receive 3,000 to 4,000 L/m^2 annually through submersion irrigation, leading to a rapid decline in SOC stocks. Despite their sandy texture, which promotes good water infiltration, these soils are enriched with clay, dissolved materials, and fertilizers in deeper horizons. This study aimed to assess SOC content in the Gataaya Oasis soils, investigate the transport of labile carbon in drainage water, and clarify the fate of this transported carbon. Soil samples were collected systematically at three depths (0–10, 10–20, and 20–30 cm), focusing on the top 30 cm depth, which is most affected by amendments. Two sampling points (P1 and P2) were selected: P1 profile near the trunk of date palms (with manure input) and P2 profile between two adjacent date palms (without manure input). Water samples were collected from drainage systems within the oasis (W1, W2, and W3) and outside the oasis (W4). A laboratory experiment simulating manure application and irrigation was conducted to complement field observations.

Physical-chemical analyses revealed a significant decrease in SOC stocks with soil depth. In the P1 profile, SOC stocks declined from 17.71 t/hm^2 at the 0–10 cm depth to 7.80 t/hm^2 at the 20–30 cm depth. In the P2 profile, SOC stocks were lower, decreasing from 6.73 t/hm^2 at the 0–10 cm depth to 3.57 t/hm^2 at the 20–30 cm depth. Labile carbon content in drainage water increased outside the oasis, with chemical oxygen demand (COD) values rising from 73 mg/L in the W1 water sample to 290 mg/L in the W4 water sample, indicating cumulative leaching effects from surrounding oases. The laboratory experiment confirmed field observations, showing a decline in soil organic matter (SOM) content from 3.27% to 2.62% after 12 irrigations, highlighting the vulnerability of SOC stocks to intensive irrigation. This study underscores the low SOC stocks in the Gataaya Oasis soils and their rapid depletion under successive irrigations. The findings provide insights into the dynamics of labile carbon transport and its contribution to regional carbon cycling, offering valuable information for sustainable soil management and ecological protection in arid ecosystems.

Keywords: arid soil; carbon cycling; irrigation; leaching; soil physical-chemical characteristics

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1 Introduction

Tunisian oases can be broadly classified into two main types: traditional and modern. Traditional oases are complex, multi-layered agroecosystems that have evolved through centuries of indigenous knowledge and sustainable management practices. These systems are typically organized into a three-tiered vertical structure: the upper canopy is dominated by date palms that provide essential shade, reduce soil temperature, and significantly limit water evaporation; beneath the palms, an intermediate layer consists of fruit trees such as pomegranates, figs, apricots, and olives that benefit from the moderated microclimate and wind protection; and the ground layer is occupied by vegetables, cereals, and fodder crops that thrive in the cooler, shaded soil environment (Hayes-Rich et al., 2023). This vertical stratification optimizes resource use, as each layer captures sunlight, water, and soil nutrients differently, reducing interspecies competition and enhancing system efficiency. Additionally, traditional oases promote microclimate regulation, soil fertility maintenance, and biodiversity conservation, serving as refuges for numerous plant and animal species in the harsh desert landscape (Santoro, 2023). The constant input of organic matter from plant residues and manure contributes to the improvement of soil structure, nutrient availability, and moisture retention, reinforcing the long-term sustainability of these ecosystems (Hayes-Rich et al., 2023). Moreover, the polycultural design of traditional oases enhances their resilience to climatic variability, pests, and diseases, thus ensuring food security and socioeconomic stability for local communities.

In contrast, modern oases often rely on simplified agricultural systems, mainly based on date palm monoculture, coupled with mechanized irrigation and frequent use of chemical fertilizers and pesticides (Dhaouadi et al., 2021). These practices can increase short-term productivity, but they are frequently associated with excessive water consumption, soil salinization, biodiversity decline, and growing risks of long-term ecological degradation (Hayes-Rich et al., 2023). Consequently, the traditional oasis system remains a model of sustainable land use and integrated resource management in arid environments, offering valuable pathways for the preservation and future development of oasis agriculture. Modern oases, however, tend to prioritize monoculture systems, particularly focusing on date palm cultivars, which are highly valued in international markets and central to Tunisia' s export-driven agricultural strategy. This shift toward intensification has undoubtedly increased economic returns and boosted productivity, but it also introduces substantial ecological risks and sustainability challenges. Monoculture-based systems inherently reduce agrobiodiversity, which weakens the ecosystem' s natural defenses against pests and diseases and diminishes functional diversity that supports soil health and nutrient cycling. The simplification of crop structure limits the capacity of modern oases to regulate microclimates and exacerbates the vulnerability of these systems to climatic extremes. Moreover, these systems are heavily dependent on intensive irrigation using scarce groundwater resources, increasing the risk of aquifer depletion and contributing to soil salinization, especially in arid and hyper-arid areas where evaporation rates are high (Buerkert et al., 2021). The dominance of monocultures also accelerates nutrient depletion and soil organic matter (SOM) decline, as continuous cropping without adequate organic amendments reduces soil fertility and long-term productivity. As a result, modern oases are often less resilient to environmental stress, including drought, salinity, and nutrient imbalances, which can threaten their sustainability and long-term viability. This trade-off between short-term economic gains and long-term ecological stability raises critical concerns for the future of oasis agriculture and highlights the urgent need to integrate more sustainable, diversified, and climate-adaptive practices within these systems.

Southern Tunisia is characterized by a hyper-arid climate, with annual precipitation typically below 100.0 mm, extremely high evapotranspiration rates, and severely limited freshwater resources. In these challenging environmental conditions, the sustainability of oasis agriculture is critically dependent on both soil quality and efficient water management practices. However, one of the most alarming issues facing modern oases is the continued reliance on flood irrigation, a traditional technique still widely used but increasingly unsustainable in the current context of water scarcity and agricultural intensification. This irrigation method, which often employs saline or brackish groundwater due to limited availability of fresh water, significantly contributes to secondary salinization and soil alkalization. As saline water percolates and subsequently evaporates, this process leaves behind concentrated salts in the upper soil depths, progressively degrading the soil structure and impairing plant growth. Furthermore, the repetitive application of high-sodium water exacerbates soil dispersion and compaction, reducing infiltration rates and increasing the risk of surface crusting and poor drainage. These processes collectively lead to physical soil degradation, which not only limits crop productivity but also threatens the long-term viability of the oasis system. The persistence of these practices, particularly in a context of climate change and growing water scarcity, highlights the urgent need to adopt more water-efficient irrigation techniques, such as drip irrigation, and integrate soil and water management strategies to preserve oasis agriculture in the face of these constraints (Hachicha et al., 2023).

The soils in southern Tunisia, particularly in the Nefzaoua region, are predominantly gypsiferous, saline, and weakly developed, reflecting the harsh pedoclimatic conditions of these hyper-arid landscapes. According to the World Reference Base for Soil Resources of the Food and Agriculture Organization (FAO, 2020), the most common soil types in these areas include Gypsisols, Solonchaks, and Regosols, which are universally recognized as fragile and highly sensitive to degradation when subjected to unsustainable agricultural practices. Gypsisols are notably rich in calcium sulfate (gypsum), while Solonchaks are characterized by high soluble salt content, and Regosols are typically shallow and poorly structured soils with limited horizon development. These soil types are inherently low in fertility and display weak structural stability, making them extremely susceptible to erosion, compaction, and salinization. One of the major physical constraints in gypsiferous soils is the formation of hard surface and sub-surface gypsum crusts, which significantly hinder root penetration, reduce soil aeration, and impede the infiltration of water and nutrients. These crusts not only create mechanical barriers for plant growth but also contribute to surface runoff and soil sealing, further aggravating water scarcity and nutrient accessibility (Al-Kayssi and Mustafa, 2016).

In addition to their physical limitations, these soils face severe chemical and biological degradation, particularly the rapid decline of SOM and soil organic carbon (SOC). Losses of SOC are primarily driven by leaching, accelerated mineralization under high temperatures, and the repeated use of flood irrigation, which often exacerbates drainage problems and promotes organic matter decomposition. This process is further intensified by the poor retention capacity of sandy or weakly aggregated soils, which accelerates nutrient loss and diminishes microbial biomass essential for soil fertility (Lal, 2024). The depletion of SOM compromises soil structure, reduces cation exchange capacity, and limits the soil' s ability to store water and nutrients, ultimately threatening crop productivity and long-term soil health. Beyond local agricultural concerns, the continued decline of SOC in oasis soils also represents a loss of carbon sequestration potential, reducing the ability of these systems to contribute to climate change mitigation and undermining broader ecosystem services such as climate regulation, biodiversity support, and environmental resilience (Tang et al., 2024).

Beyond agricultural production, oasis systems deliver a wide range of ecosystem services that are essential for both environmental sustainability and the well-being of local communities. These services include food and fodder production, habitat provision for endemic and migratory species, microclimate regulation, and carbon sequestration. The unique microclimates created by oases can lower ambient temperatures by 3.0°C–5.0°C compared with surrounding desert areas, offering critical thermal refuges for plant, animal, and human populations (Santoro, 2023). Additionally, oasis soils contribute to soil carbon storage, playing a modest but valuable role in local carbon dynamics. However, these ecosystem services are increasingly at risk due to the overexploitation of groundwater resources, a widespread practice driven by the intensification of irrigated agriculture. The unsustainable extraction of water, often exceeding natural recharge rates, has led to alarming declines in groundwater levels, with drops of up to 1–2 m per year reported in some oases (Lal, 2024). This groundwater depletion not only threatens the long-term viability of agricultural systems but also contributes to the desiccation of surface soils, salinization, and the collapse of oasis vegetation (Masoud et al., 2018).

Recent studies have also highlighted the critical vulnerability of SOM pools in oasis environments, particularly under modern agricultural practices. The extensive use of flood irrigation accelerates the leaching of dissolved organic carbon (DOC), rapidly depleting organic reserves and promoting nutrient losses from the soil profile. Moreover, saline conditions and chemical imbalances related to salt accumulation and nutrient leaching because of poor irrigation management significantly reduce microbial activity, thereby slowing the natural processes of SOM formation, stabilization, and nutrient cycling (Al-Quraishi, 2024). These trends are contributing to a progressive deterioration in soil quality, undermining both the fertility and the carbon sequestration capacity of oasis soils. Addressing these challenges requires a transition toward more sustainable soil and water management practices. Among the most promising solutions are the incorporation of organic amendments such as compost, manure, and biochar, which have been shown to enhance SOM stability, improve soil structure, increase nutrient retention, and support microbial activity (Lal, 2024). Additionally, replacing flood irrigation with drip irrigation systems can significantly reduce water consumption, minimize DOC leaching, and improve water use efficiency, thereby preserving both SOM and water resources essential for the long-term sustainability of oasis agriculture (Lu et al., 2025).

This study focuses on the Gataaya Oasis, a representative example of modern desert oasis agriculture in southern Tunisia. The objectives are: (1) to quantify SOC stock losses under traditional flood irrigation systems; (2) to evaluate the impacts of organic amendments (manure) on SOM retention and soil physical-chemical properties; and (3) to explore alternatives such as improved irrigation techniques for minimizing SOM depletion. By addressing these objectives, the results might contribute to the development of sustainable soil management practices, not only for Tunisian oases but also for arid agroecosystems worldwide, and offer critical insights for policy recommendations and climate-resilient agriculture in environments facing increasing water scarcity, soil degradation, and climate uncertainty.

2.1 Study Area and Soil Sampling

The modern continental oasis of Guettaya lies approximately 8 km southwest of Kebili Town in the Nefzaoua region, Tunisia (33°40 45 N, 08°52 28 E), covering an area of 57 hm^2. According to Institute for Numerical Mathematics (INM) climate data, the summer of 2022 was the second hottest observed in Tunisia since 1950, with a temperature deviation of $±$2.0°C from the normal average (27.8°C) for 1991-2020. However, the summer of 2021 remains the hottest ever recorded, with a temperature anomaly of $±$2.2°C. In terms of precipitation, the cumulative seasonal total from 27 main stations was 167.4 mm, representing a 75.00% reduction from the seasonal normal (681.4 mm), making it the second driest summer after 1993. According to unpublished technical reports from the Institute of Arid Regions, Tunisia, annual evapotranspiration under date palm plantations in the Nefzaoua region can reach 1200.0–1500.0 mm/a.

The Nefzaoua region comprises sedimentary series dating from the Cretaceous to the Quaternary, dominated by limestone, marl, clay, and sand, with the latter three often containing gypsum. The study area, whose relief is based on a vast Mio-Pliocene formation, is bounded to the north and northeast by the Djebel Tebaga Mountain, which marks its northern limit. Chott El Jerid Basin is the largest salt flat or sebkha in Tunisia, covering approximately 5 km^2 (Abbas et al., 2018). The salt lake extends approximately 100 km east-west through Chott El Fejaj, spanning southern Tunisia between the Gulf of Gabes and the Algerian border (Kraiem et al., 2025). Geomorphologically, it occupies a synclinal depression between mountain ranges and the Saharan platform at 15–20 m elevation (Heckmann et al., 2022).

Two sampling points were selected: P1 profile near the trunk of date palms (with manure input) and P2 profile between two adjacent date palms (without manure input). Water samples were collected from drainage systems within the oasis (W1, W2, and W3) and outside the oasis (W4; Fig. 1 [Figure 1: see original paper]).

Fig. 1 Location of the study area and sampling sites. P1, profile near the trunk of date palms (with manure inputs); P2, profile between two adjacent date palms (without manure input); W1, W2, and W3 are water sample sites within the oasis; W4 is water sample site (a drainage station) outside the oasis.

2.2 Analysis of Soil Characteristics

To determine soil physical-chemical properties, we employed various methods and analytical techniques. Bulk density (BD) was measured using the cylindrical core method. Chemical oxygen demand (COD) and biological oxygen demand (BOD) were determined using a spectrophotometer. SOC content was quantified using the method of Aubert (1978). Soil pH was measured in a 1.0:2.5 soil-water suspension, while electrical conductivity (EC) was analyzed in a saturated soil paste and for water samples (AFNOR, 1994). Particle size distribution, including coarse sand, fine sand, coarse silt, fine silt, and clay, was determined according to AFNOR (2003) standards. Limestone content ($CaCO_3$) was determined using the Bernard method (AFNOR, 1995).

SOC stocks in the upper 50 cm depth were calculated by summing SOC stocks of individual soil layers (Brahim et al., 2014). SOC stock (g/m^2) for each depth was computed using the following equation:

$$\text{SOC stock} = \text{OC} \times \text{BD} \times D \times 10$$

where OC is the organic carbon content (%), BD is the bulk density (g/cm^3), and D is the sample depth (cm). Additionally, sodium adsorption ratio (SAR) was calculated to assess soil sodicity, which is a critical indicator of soil structure and infiltration capacity and is widely used to evaluate the risk of soil infiltration issues and particle dispersion caused by excessive sodium levels (Ayers and Westcot, 1985; Weiner, 2008). SAR was determined using the following equation:

$$\text{SAR} = \frac{\text{Na}^+}{\sqrt{(\text{Ca}^{2+} + \text{Mg}^{2+})/2}}$$

where Na^+, Ca^{2+}, and Mg^{2+} are the concentrations of sodium, calcium, and magnesium ions, respectively (mmol/L).

2.3 Statistical Analysis

Statistical significance of differences between groups was determined using analysis of variance (ANOVA). All statistical analyses were performed using MaxStat Pro v.3.6 software and Past software. Statistical significance was identified if the P-value tested was less than 0.050, 0.010, or 0.001. When pairwise multiple comparisons were performed, the Bonferroni correction was used to adjust the significance level.

2.4 Ex-situ Experiment

The experiment aimed to simulate the reality of what happens in oasis soil after manure addition and the subsequent evolution of SOM after each irrigation for one year (12 irrigations). Pots were used for the experiment. On the same soil and the same manure, an equivalent quantity of irrigation water was added, i.e., each pot was irrigated with a quantity of water equal to that added each month.

After each irrigation, the infiltrated water was collected and soil samples were taken for analysis. At the end of the experiment, soil samples taken from the pots and the soil leaching solutions were analyzed (Table 1 ; Fig. 2 [Figure 2: see original paper]).

Table 1 Physical-chemical properties of fresh goat and sheep manure

Origin	SOC (g/kg)	TN (g/kg)	TP (mg/kg)	EC (mS/cm)
Goat and sheep fresh manure	401.0	31.0	4500.0	8.79

Note: SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; EC, electrical conductivity.

Fig. 2 Experimental design of this study

3.1 Soil Physical-Chemical Properties

Analysis of soil characteristics revealed that the sandy fraction dominated across all samples, ranging from 66.63% to 88.65%, while the clay fraction was minimal, ranging from 0.33% to 1.18% (Table 2). Soil textures were similar for all samples, with some variations between sandy, silty-sandy, and sandy-silty textures. Therefore, we can conclude that soil texture is sandy-loamy. Texture changed as depth increased: the proportion of fine particles decreased while the proportion of coarse particles increased. Generally, soils in the Gataaya Oasis are sandy-loamy. It is well known that sandy soils have low water reserves due to their permeability and filtering properties. Sandy texture indicates a well-aerated soil; however, sandy soils are poor in nutrients and have low cation exchange capacity (CEC).

Soil EC showed contrasting trends between profiles. In profile P1, EC was lowest at the surface (1.93 mS/cm) and increased with depth, reaching 2.04 mS/cm at the 20–30 cm depth. Conversely, in profile P2, EC decreased from 2.78 mS/cm at the surface to 2.26 mS/cm at the 20–30 cm depth. Although these patterns suggest profile-dependent variations, the correlation between EC and depth was not statistically significant ($P>0.050$). Soil pH was generally alkaline, ranging narrowly between 7.11 and 7.21. Total calcium carbonate ($CaCO_3$) content varied from 1.83% to 0.00%, with no significant correlation observed between $CaCO_3$ and EC ($P=0.173$) or pH ($P=0.246$). However, a significant negative correlation was detected between $CaCO_3$ and BD ($P=0.015$), indicating that higher $CaCO_3$ contents may be associated with lower soil compaction. Overall, BD values were relatively low across both profiles, ranging from 0.70 to 1.19 g/cm^3.

3.2 SOC Stock Variation

Profile P1, located adjacent to the palm tree where manure is regularly applied, exhibited the highest SOC and SOM contents compared with profile P2, which is situated between two date palms and farther from organic inputs. In profile P1, SOC significantly decreased with depth, from 2.53% at the 0-10 cm depth to 1.28% at the 20-30 cm depth. Similarly, in profile P2, SOC declined from 0.59% to 0.23%. Table 3 illustrates the variation in SOM and SOC contents with depth across both profiles. A statistically significant decrease in both SOC and SOM was observed with increasing depth ($P<0.001$). In profile P1, SOM ranged from 4.37% at the surface to 2.21% at the 20-30 cm depth, whereas in profile P2, SOM remained consistently low, below 1.00% throughout the profile. Furthermore, estimations of SOC stocks confirmed this trend. In profile P1, SOC stocks decreased markedly from 17.72 t/hm^2 at the surface to 7.81 t/hm^2 at the 20-30 cm depth. Similarly, SOC stocks in profile P2 dropped from 6.73 to 3.57 t/hm^2. These changes were strongly correlated with both SOC and BD contents, as shown by highly significant correlation coefficients (Fig. 3 [Figure 3: see original paper]).

3.3 Chemical Analysis of Drainage Water

As shown in Table 4 , pH of the water samples was consistently alkaline, with values ranging from 7.58 to 7.85. This alkalinity is typical for water in arid and semi-arid areas, where high evaporation rates and limited leaching contribute to the accumulation of basic ions. However, the correlation between pH and sampling site was not statistically significant ($P=0.670$). EC, an indicator of water salinity, exhibited a clear spatial trend, increasing towards the oasis. Notably, water from drains W2 and W3 displayed exceptionally high EC values, reflecting elevated salt concentrations. A significant decrease in EC was observed at the drainage station (W4), suggesting potential dilution or removal of salts at this site. This highly saline water had an EC that rose from 8.58 mS/cm in the oasis (W1) to 75.23 mS/cm (W4). Despite this trend, the correlation between EC and site was also not statistically significant ($P=0.274$). All samples had EC values well above 4.00 mS/cm, indicating a severe risk of salinity. SAR values for samples W1 and W4 were 1.72 and 1.14, respectively, both below 3.00, indicating no sodicity risk and no restrictions on water use. However, SAR was very high at W2 (9.77) and moderately high at W3 (7.50), posing a sodicity hazard. The SAR value at W3 fell into a moderate-risk category (3.00-9.00). Still, the overall SAR variation across sites was not statistically significant ($P=0.879$).

COD and BOD values increased from W1 to W4 sites. COD rose from 73.0 (W1) to 290.0 mg/L (W4), while BOD increased from 32.5 to 64.5 mg/L. However, their variations with sampling sites were not statistically significant ($P=0.202$ for COD, and $P=0.183$ for BOD, respectively). High COD relative to BOD suggested a predominance of non-biodegradable organic matter. The COD:BOD ratio ranged from 2.24 to 4.50 at samples W1-W3, indicating moderate biodegradability, but exceeded 4.00 at the W4 sample, making the water at this site difficult to biodegrade, though this trend was also not statistically significant (P=0.251).

3.4.1 Soil Chemical Analysis

Table 5 shows that EC value during the first irrigation was 9.79 mS/cm, indicating highly saline conditions. During the last irrigation, the value was 3.33 mS/cm, indicating slightly saline conditions. A marked reduction in EC was observed from the second irrigation, with EC falling from 9.79 to 4.03 mS/cm. Although the decrease was close to the threshold of statistical significance (P=0.059), salinity risk remained significant for the soil as EC values were above 4.00 mS/cm. Soil pH increased from 7.34 to 7.64 between the first and last irrigations, suggesting that the addition of manure and successive irrigations altered the soil’ s alkalinity and acidity. However, this trend was not statistically significant (P=0.179). SAR results showed little variation across irrigations, ranging from 1.43 to 2.18. Although SAR slightly increased from 1.43 to 1.82 between the first and last irrigations, the correlation with irrigation number was not statistically significant (P=0.386). The SAR values were less than 3.00, indicating no risk of soil sodicity.

COD and BOD values decreased with irrigation. During the initial irrigation, COD value was 61,767 mg/L. During the last irrigation, COD value decreased significantly to 66 mg/L (P=0.049). Similarly, BOD value decreased from 17,800 to 38 mg/L (P=0.057) over the same period. These findings suggest that the amount of oxidizable organic and mineral matter was much higher than that of biodegradable organic matter. The COD:BOD ratio significantly decreased from 3.47 to 1.76 (P=0.006). SOM content varied between 2.62% and 3.27%, falling within the typical range of 1.00%-5.00% for agricultural soils. Similarly, SOC content ranged from 1.52% to 1.90%, with values generally observed between 0.60% and 3.00% in cultivated soils. The results indicate that 0.65% of SOM and 0.38% of SOC were lost through leaching by irrigation water. Based on these results, we can conclude that irrigation water leaching leads to the reduction in SOM over time.

3.4.2 Correlations Between Chemical Parameters and Irrigation Times

SOC content declined from 1.90% to 1.52% over successive irrigations, indicating a progressive loss of SOM. This trend coincided with notable changes in water quality variables. Strong and statistically significant correlations were found between EC, COD, and BOD with irrigation times (r=0.99-1.00, P<0.050; Fig. 4 [Figure 4: see original paper]), suggesting that as irrigation proceeded, organic compounds were mineralized or leached into drainage water, increasing EC and oxygen demand. The tight coupling between EC and BOD (r=0.99, P=0.057) further supports the hypothesis that SOC was mobilized by irrigation. In contrast, SAR showed weak and non-significant correlations with these variables (r=-0.46, P>0.300), implying that sodium displacement was not the main driver of carbon loss. These synergistic variations between SOC, EC, COD, and BOD support the conclusion that irrigation-induced leaching and microbial decomposition contribute significantly to SOC stock depletion in oasis soils under arid conditions. Figure 5 [Figure 5: see original paper] provides a comprehensive overview of the spatiotemporal changes in soil and water properties across the Gataaya Oasis, reflecting the combined effects of irrigation practices, organic amendments, and environmental conditions.

4.1 SOM Dynamics and Agricultural Practices in Oasis Soils

Soils in Tunisian arid areas are characterized by very low SOM content, often as low as 0.80%. However, the high SOM content observed in oasis systems is the result of centuries of human intervention, which has led to the formation of a humus layer. This explains the elevated SOC content in the surface depth of these soils (Brahim et al., 2022). Analyses of the Gataaya Oasis revealed high SOM content, ranging from 1.02% to 4.37% in the surface depths, primarily due to the direct application of manure under the date palm trunks. This practice aligns with traditional oasis management strategies that enhance soil fertility and moisture retention (Mlih et al., 2016). To further understand SOM dynamics in these systems, we conducted an experiment simulating the evolution of SOM over time and with repeated irrigation. The results showed a decline in SOM content from 3.27% to 2.62%, indicating significant losses due to microbial activity, leaching, and mineralization processes (Wichern and Joergensen, 2009). Similarly, COD and BOD values of the soil solutions decreased markedly, from 61,767 to 66 mg/L and from 17,800 to 38 mg/L, respectively. These reductions highlight the leaching of dissolved SOM and the mineralization of labile organic compounds, which are common in irrigated arid soils (Luo et al., 2021).

The leaching of soils in the Gataaya Oasis by irrigation water progressively reduces SOM content, especially in subsurface depths. This process results from the downward movement of dissolved or colloidal organic compounds due to excess irrigation, typical in oasis agriculture (Brahim et al., 2022). However, the presence of limestone in the soil, even from the surface, can mitigate this loss by promoting SOM accumulation throughout the soil profile (Védère et al., 2022). In calcareous soils, carbonates enhance the integration and protection of SOM, playing a key role in both humification and mineralization processes by limiting microbial decomposition (Kang et al., 2024). Results from Brahim et al. (2022) confirmed this pattern: SOM and $CaCO_3$ contents decreased with depth. The surface depths showed 1.83% $CaCO_3$ and 4.37% SOM in profile P1, and 0.00% $CaCO_3$ and 1.02% SOM in profile P2, supporting the phenomenon of carbonate-facilitated SOM preservation in the upper horizons (Table 2). Soil pH, a major chemical indicator, strongly affects nutrient availability, microbial dynamics, and cation exchange equilibria. Soil pH is considered a key factor in agronomy due to its influence on three aspects of soil fertility: nutrient bioavailability, biological activity, and soil structural stability (Devau et al., 2009; McCauley et al., 2017; Gao et al., 2024). In the Gataaya Oasis, pH levels decreased with higher SOM content.

4.2 Soil Salinity, pH, and Sodicity in Irrigated Systems

Water samples from drains and the drainage station showed weakly alkaline conditions, with pH ranging from 7.58 to 7.85. The mineralization of organic components elevates soil salinity, impacting EC, which declines with depth alongside SOM. Profile P2, where no manure was applied, exhibited the highest EC values: 2.78 mS/cm at the 0–10 cm depth and 2.26 mS/cm at the 20–30 cm depth. In contrast, values were lower in profile P1, where manure was gradually added (1.93 mS/cm at the 0–10 cm depth and 2.04 mS/cm at the 20–30 cm depth). EC generally decreased with soil depth. The presence of SOM reduces the effect of salinity, which explains the lower values observed in profile P2 (Weil and Brady, 2017). Moving towards the Chott El Jerid Basin (Fig. 5 [Figure 5: see original paper]), EC increased from 8.58 to 75.23 mS/cm, indicating a serious salinity risk. Chemical analyses revealed SAR values of 1.72 and 1.14 for samples W1 and W4, respectively, indicating no risk of sodicity. However, samples W2 and W3 recorded values of 9.77 and 7.50, respectively, indicating significant sodicity damage (Qadir et al., 2023).

4.3 Soil Physical Properties, Clay-Humus Complexes, and SOC Stocks

SOM content is influenced by soil physical properties such as texture and BD (Zhang and Shao, 2014). BD increased with depth; for instance, in profile P2, BD rose from 1.14 to 1.19 g/cm^3. Conversely, SOM and SOC values decreased with depth. The close relationship between BD and SOC stocks underscores the importance of soil physical conditions in carbon storage dynamics.

5 Conclusions

The oasis agroecosystem, shaped by centuries of indigenous knowledge and ongoing human intervention, is increasingly vulnerable to the combined effects of climate change, soil salinity, and dwindling water resources. In the Gataaya Oasis, our findings confirmed that the traditional practice of applying manure under date palm trunks significantly contributed to increased SOC stocks, particularly in surface soils. However, the observed 20.00% decline in SOC stocks during a single year of irrigation highlighted the fragility of these gains and the dynamic nature of SOM in arid environments. These results emphasize the need to maintain a continuous supply of organic matter to offset losses from mineralization, microbial decomposition, and leaching. Furthermore, the elevated levels of EC, SAR, and COD observed near sample W4 suggested the accumulation of leached organic compounds, raising concerns about nutrient redistribution and re-salinization in low-lying areas.

Although this study provides important insights into the interactions between organic amendments, irrigation, and soil properties, its scope is limited by the short observation period and focus on a single oasis system. Future studies should adopt a multi-site and long-term monitoring approach, considering a broader range of soil types, irrigation systems, and organic fertilizers. Furthermore, integrating microbial activity assessment and detailed analysis of clay-SOM interactions would help refine sustainable management strategies. Such efforts are essential to increasing soil resilience and ensuring the long-term viability of oasis agriculture under increasingly challenging environmental conditions.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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