Journal of King Saud University - Science 36 (2024) 103471

Contents lists available at ScienceDirect

Journal of King Saud University - Science

journal homepage: www.sciencedirect.com

Full Length Article

Comparing how compost and manure affect soil organic matter using a complete factorial design

Imane Mehdaoui [a,*], Rachid Mahmoud [a], Zineb Majbar [a], Sanae Berrada [a,b], Mohammed Ben Abbou [c,d], Mohamed S. Elshikh [e], M. Ajmal Ali [e], Tse-Wei Chen [f], Mustapha Taleb [a], Zakia Rais [a]

[a] *Laboratory of Electrochemistry, Modelization and Environment Engineering, Faculty of Sciences Dhar El Mahraz, Sidi Mohamed Ben Abdallah University, Fez 30000, Morocco*
[b] *Biotechnology, Environment, agro-food and Health Laboratory, Faculty of Science Dhar El Mahraz, Sidi Mohamed Ben Abdellah University, Fez, Morocco*
[c] *Higher Institute of Nursing Professions and Health Techniques of Fez (Annex Taza), Morocco*
[d] *Laboratory of Natural Resources and Environment, Polydisciplinary Faculty of Taza, PO Box 1223, Taza Gare, Morocco*
[e] *Department of Botany and Microbiology, College of Science, King Saud University, P.O. 2455, Riyadh 11451, Saudi Arabia*
[f] *Department of Materials, Imperial College London, London SW7 2AZ, United Kingdom*

ARTICLE INFO

Keywords:
Full factorial design
Compost
Manure
Soil fertility
Pareto chart
ANOVA

ABSTRACT

Background: The aim of this study was to determine the influence of physico-chemical factors on soil organic matter by comparing two types of soil improver: one produced from olive mill waste cake residues (CRPM) and the other from manure (CF). This was achieved using Full Factorial Design, the main objective of which is to measure precisely the impact of each factor on a given response, to analyze the interactions between the various factors and to identify the optimum conditions for achieving a specific objective or improving the performance of a process.
Methods: Four independent factors were studied: pH, electrical conductivity, humidity and carbon/nitrogen (C/N) ratio. Using design, based on their significance, coefficient of determination, analysis of variance and Pareto charts, the interactions between these variables were assessed to identify those with the most positive impact on soil fertility.
Results: The results show that, for CRPM compost, the most positive interaction is between pH and ratio C/N. For manure, the interaction between pH and moisture has the greatest beneficial effect. These findings underline the importance of controlling all three factors – pH, moisture and ratio C/N to optimize soil fertility.
Conclusions: The analysis confirmed the reliability of the models used, with p-values below 0.05 and coefficients of determination (R^2 and adjusted R^2) close to 1, indicating the robustness of the models. Pareto diagrams were used to precisely identify the most relevant interactions for improving soil amendment management.

1. Introduction

The preservation and management of soils are of paramount importance to contemporary societies, as soils represent a natural resource that is both fragile and non-renewable on a human timescale (Meraj et al., 2021; Rubio et al., 2024). Given the increasing pressures from human activities, there is a critical need for rigorous scientific understanding of soil quality. This requires a thorough clarification of the concept of soil quality to identify reliable and relevant indicators for its assessment (Sánchez-Ortiz et al., 2020; Raymond et al., 2020).

Historically, soil quality has been primarily linked to fertility, defined as the ability of soil to provide a favorable environment for biomass growth, particularly plants (Alkharabsheh et al., 2021; Maurya et al., 2020). However, various anthropogenic factors, such as excessive waste disposal and intensive use of chemical fertilizers, can severely degrade soil structure and function. Therefore, it is essential to adopt sustainable alternatives that not only maintain but also enhance soil fertility while preserving its ecological balance (Asghar et al., 2022; Zilio et al., 2022).

Among these alternatives, the use of organic amendments offers

---

* Corresponding author.
E-mail address: imane.mehdaoui@usmba.ac.ma (I. Mehdaoui).

https://doi.org/10.1016/j.jksus.2024.103471
Received 1 June 2024; Received in revised form 5 September 2024; Accepted 26 September 2024
Available online 30 September 2024

numerous potential benefits, including preserving soil organic matter, maintaining adequate water retention, optimal structure, appropriate pH, and balanced concentrations of essential nutrients in forms that are readily available to plants (Furey and Tilman. 2021; Singh et al., 2020). Recent studies highlight the positive effects of organic amendments on soil quality, leading to higher and better-quality agricultural yields.

In this context, the aim of this study is to deepen our understanding of the effects and interactions of organic amendments on soil quality by analyzing two specific types of compost: one made from olive mill waste pulp and the other from manure. Through a rigorous statistical approach, we examine the influence of four independent variables: pH, moisture, electrical conductivity, and carbon/nitrogen (C/N) ratio on soil organic matter content, a key factor of fertility.

The overall objective of this study is twofold: first, to identify the most significant interactions among these variables to optimize the management of organic amendments; and second, to provide practical recommendations for enhancing soil fertility while minimizing negative environmental impacts. By contributing to a better understanding of the complex mechanisms governing soil quality, this research aims to support more sustainable and resilient agricultural practices in response to current ecological challenges.

2. Materials and methods

2.1. Soil provisioning and characterization

Arid soil of the. the soil was provided by the Ain B'tit region in El-Hajeb. It was characterized by physico-chemical analyses using measurements of pH, electrical conductivity (EC), humidity (%H), dry matter (%DM), kjeldhal nitrogen (%NTK), organic matter (%OM), total organic carbon (TOC) and ratio C/N according to AFNOR standards, and by Horiba Jobin-Yvon Activa model inductively coupled plasma atomic emission spectrometry (ICP-AES) to identify its mineral load in fertilizing elements.

Samples were taken randomly by zigzagging across the field (ISO-18400-102-2017).

2.2. Organic amendment

The study utilized two types of organic amendments: the first was a compost made from residues obtained after extracting residual oil from olive mill waste cake (CRPM), formulated through a mixing plan that included 56.7 % organic and green household waste, 21.7 % olive mill waste cake residues, and 21.7 % poultry droppings (Mehdaoui et al., 2023). The second amendment was manure (CF), which served as a control. Both amendments were characterized using the same physico-chemical analyses as those conducted for the soil.

2.3. Full factorial design

In this work, a full factorial design was used to investigate the effect-interaction of four parameters pH (A), %H (B), C/N (C) and CE(D), on the organic matter content of a compost based on olive mill waste cake residues (CRPM), and a manure (CF). This was described by some form of mathematical equation so that predictions of both models can be made empirically. In addition, the full factorial design was established using Design-Expert software and taking into consideration that there is no secondary constraint on the proportion of components **(Oliveira et al., 2018)**. Eight experiments for each amendment were suggested and conducted in random order to account for any randomized hidden effects (Tables S1 and S2). The boundaries of the mixture components and the geometric location of the experimental points in the mixing design are shown in Tables 1 and 2. Once the modeling is complete, the final stage of the study is optimization, which involves finding the various important interactions between the different factors that have a positive or negative effect on the response. The results are illustrated in Figs. 1 and 2.

Table 1
Factors of the full factorial design and its limits for the CRPM.

Factors	Name	Unity	Type	Coded Low	Coded High
A	pH	–	EI	+0 ↔ 0,1	6 ↔ 8,5
B	(H)	%	EI	+0 ↔ 0,1	12 ↔ 37
C	(C/N)	–	EI	+0 ↔ 0,1	0 ↔ 13
D	(CE)	mS/cm	EI	+0 ↔ 0,1	0,6 ↔ 600

Table 2
Factors of the full factorial design and its limits for the manure.

Factors	Name	Unity	Type	Coded Low	Coded High
A	pH	–	EI	+0 ↔ 0,1	6 ↔ 8,5
B	Humidity (H)	%	EI	+0 ↔ 0,1	12 ↔ 37
C	Ratio C/N (C/N)	–	EI	+0 ↔ 0,1	0 ↔ 13
D	Electrical Conductivity (CE)	mS/cm	EI	+0 ↔ 0,1	0,6 ↔ 900

H: Humidity.
C/N: Ratio C/N.
CE: Electrical Conductivity.

In our case, the numerical optimization method was applied using the desirability function (D). This choice is taken into consideration in view of the possibility of modifying the weight and importance for both mixture components, and responses (Candioti et al., 2014).

2.4. Modelling and analysis of the statistical properties of the full factorial design

The full factorial design was established using the optimal criterion, and was used to describe the relationship of the responses of interest in terms of the interactions between the selected factors, according to the criteria specified in Tables 1 and 2. The various interactions were detected using Pareto diagrams and interaction figures. The quality of the CRPM and Manure models was tested using analysis of variance (ANOVA) with Fischer test (F-value) and probability value (p-value), and the significance of lack of fit. However, the predictive quality of the models was checked using the multilinear regression coefficients (R^2), the predicted coefficient ($R^2_{predicted}$) and the adjusted coefficient ($R^2_{adjusted}$). In addition, the plot of normal and predicted residual values against normal values was used to assess the distribution and normality of the residuals.

2.5. Organic matter content

To calculate the organic matter content of soil, several methods exist, but one of the most commonly used is the Loss on Ignition (LOI) method (LOI Standard, 2024). This method is based on the mass loss of a soil sample after combustion, attributed to the organic matter. The steps to determine the organic matter content using this method are as follows: First, a representative soil sample (approximately 5–10 g) is collected and dried in an oven at 105 °C for 24 h to remove any free water present in the soil; then, the dried sample is weighed to obtain the initial weight (Wsec). Next, the dried sample is placed in a muffle furnace and heated at a temperature of 400–550 °C for 4–6 h, burning the organic matter, which evaporates as carbon dioxide. After combustion, the sample is allowed to cool in a desiccator to prevent any moisture absorption, and then it is weighed again to obtain the final weight (Wcomb). The weight loss of the sample corresponds to the amount of organic matter that has been burned, and the organic matter content is calculated as follows:

$$\textbf{Organic Matter}(\%) = \frac{\boldsymbol{Wsec - Wcomb}}{\boldsymbol{Wsec}} * 100$$

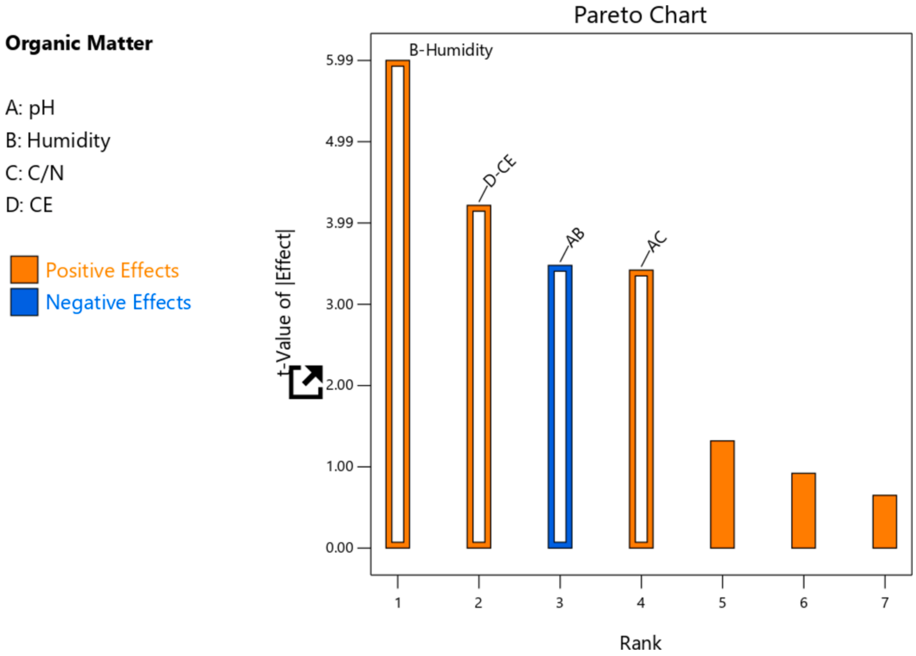

Fig. 1. Pareto diagram for the CRPM.

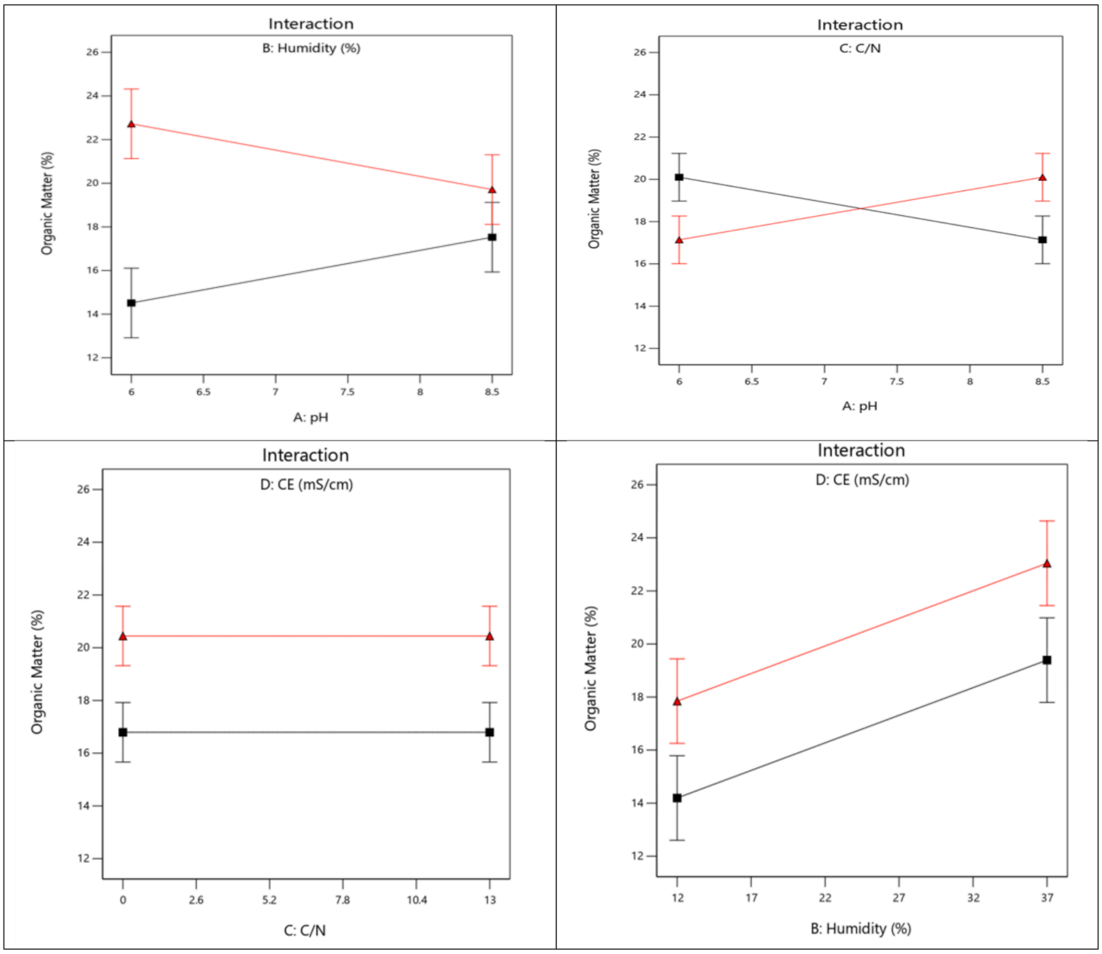

Fig. 2. Different interactions for CRPM.

Where:

- Wsec = Weight of the dried sample (at 105 °C).
- Wcomb = Weight of the sample after combustion (at 400–550 °C).

3. Results

3.1. Physicochemical characterization of amendments

The physico-chemical characterization of the soil improvers, the content of fertilizing elements and heavy metals is presented in Table 3.

The results obtained suggest that the compost's composition in terms of mineral elements and ratios C/N complies with the standard (NFU44-051), which aims to ensure that organic soil improvers (such as composts) are safe for the environment and human and animal health, while being effective in improving soil structure and fertility. However, in terms of fertilizing elements, the compost is endowed with high doses of magnesium, potassium, calcium, iron, phosphorus and sodium. On the other hand, for manure, certain elements are not consistent with the standard, such as p H (8.57) and organic matter (74.68 %).

3.2. Physicochemical characterization of the soil before amendment

The physicochemical characterization of the soil before amendment, the content of fertilizing elements and heavy metals are presented in Tables 4 and 5 respectively.

The soil studied is neutral, rich in calcium, which explains the absence of brown, yellowish patches on the leaves of the plants. Its salinity is optimum for salinity-sensitive crops, its pH is neutral, and it has a low organic matter content, indicating its low fertility.

3.3. Compost model based on olive mill waste cake residues (CRPM)

3.3.1. Pareto chart and interactions

The Pareto diagram and the various interactions obtained using the CRPM are shown in Figs. 1 and 2.

The Pareto diagram shows that humidity and electrical conductivity have a positive effect on the soil organic matter content under study, as does the interaction between pH and ratio C/N. Whereas the pH-humidity interaction has a negative effect. The interaction diagrams for all the factors studied agree with the results of the Pareto diagram.

Table 3
Physicochemical characterization of the two amendments (CRPM and Manure).

Parametres	CRPM	Manure	NFU44-051 Standard (limit values) (Norme-NFU.44-051.)
H %	38	20	40 % < H<65 %
pH	7,42	8,57	5 < pH<8
% KTN	1,53	2,97	–
OM (%)	42,89	74,68	40 < OM<70
RatioC/N	16,37	12,7	10 < C/N<15
Polyphenols	0,0837	0	–
Mineral elements and fertilizers (mg/L)			
P	4,1783	2,39	–
K	15,940	85,460	–
Mg	3,622	3,16	–
Ca	18,868	6,71	–
Fe	3,162	–	–
Na	14,571	10,485	–
Se	<0.01	–	12
Other mineral elements (mg/L)			
As	<0.01	–	18
Al	1,744	1,11	–
Cd	–	0,085	3
Ni	<0.01	–	2
Cr	<0.01	0,34	12

EC (µS\cm): Electrical conductivity.
H %: Humidity.
OM %: Organic Matter.
KTN %: kjeldhal Total Nitrogen.
C/N: Carbon- Nitrogen Ratio.

The final equation of the CRPM model is presented in equation (1).

$$\%\boldsymbol{OM} = +18.62 + 2.60\boldsymbol{B} + 1.83\boldsymbol{D} - 1.51\boldsymbol{AB} + 1.48\boldsymbol{AC} \tag{1}$$

Concerning the validity of the model, the distribution of points in the model is correct, reflected in the distribution of points around the straight line in the normal plot (Fig. 3(a)) because it is homogeneous and the actual values are distributed uniformly from the diagonal in the predicted plot compared to the actual values (Fig. 3(b)).

The relationship between the selected factors (pH, %H, CE and C/N) was established via the 3D and 2D response surface plots (Fig. 3). In fact, the organic matter content may vary according to the type of soil improver used. In our case, the optimum organic matter content was 24.27 % in the region of 8.5, 37 %, 13 and 600 mS/cm for variables A, B, C and D respectively.

According to the ANOVA results, the p-value of the model is 0.0176, i.e. significant. The predicted R^2 of 0.7345 and the adjusted R^2 (0.9129), with an R^2 coefficient of 0.9627, indicate a good fit of the model to the experimental data. Furthermore, the *P-values* of the interaction values between the factors show that they have a statistically significant effect, since the value is less than 0.05. Moreover, these interactions show positive effects for the model by significant coefficients; 18.15 for AB and 17.55 for AC. Parameter B recorded the highest coefficient, at 54.03, followed by parameter D at 26.68.

3.4. Manure model

3.4.1. Pareto diagram and interactions

The Pareto diagram and the various interactions obtained using manure as a soil improver are shown in Figs. 4 and 5.

The Pareto diagram reveals that pH has a positive effect on response, as does pH-humidity interaction. Whereas humidity, electrical conductivity and the pH-CE interaction have a negative effect. These results corroborate those found by the interaction diagrams between all variables.

The experimental values of the mixing design of the Manure experiments presented in Table 2 were used to adjust his model. Indeed, the ANOVA of the Manure model presented in the table shows that the Manure regression is highly significant, with an F-value of 450.76 and a *P-value* of 0.0360.

Furthermore, the R^2 coefficient of the predicted model is 0.9996, confirming the correlation and good fit between experimental and calculated data. This is also evidenced by the difference between the adjusted R^2 (0.9974) and the predicted R^2 (0.9763), which is reasonable given that it is less than 0.2.

The ANOVA analysis for the interaction terms shows that variables C and D are not significant because the *p-values* are equal to 0.5972 and 0.1638 respectively (greater than 0.05). On the other hand, all the others are statically significant, with *p-values* of 0.0247 and 0.0429 for A and B respectively.

In addition, the *p-values* of the interactions between p H and humidity (0.0185) and the interaction between p H and electrical conductivity (0.0255) are also less than 0.05, proving that they are statistically significant.

Consequently, only the effects of significant terms were considered in equation (2) in terms of factors determining soil organic matter content to predict the Manure model

$$\%\boldsymbol{OM} = +15.04 + 0.9650\boldsymbol{A} - 0.5550\boldsymbol{B} - 0.0275\boldsymbol{C} - 0.1425\boldsymbol{D} + 1.29\boldsymbol{AB} - 0.9375\boldsymbol{AD} \tag{2}$$

Table 4
Physicochemical characterization of soil before amendment.

Parameters	pH	EC (µS\cm)	H (%)	DM (%)	OM (%)	MM (%)	TOC (%)	KTN (%)	C/N
Values	8,71	644	14.04	85.96	17.81	82.19	10.33	0	0

Table 5
Soil fertilizer content of soil before amendment.

Elements	Al	Ca	Cu	Fe	K	Mg	Mn	Na	P	Zn
Concentration (mg/L)	1.7719	36.211	0.0878	6.3947	2.9159	3.6216	<0.01	14.641	0.2425	0.0374

EC (µS\cm): Electrical conductivity.
H %: Humidity.
DM %: Dry Matter.
MM %: Mineral Matter.
OM %: Organic Matter.
TOC%: Total Organic Carbon
KTN %: kjeldhal Total Nitrogen.
C/N: Carbon- Nitrogen Ratio.

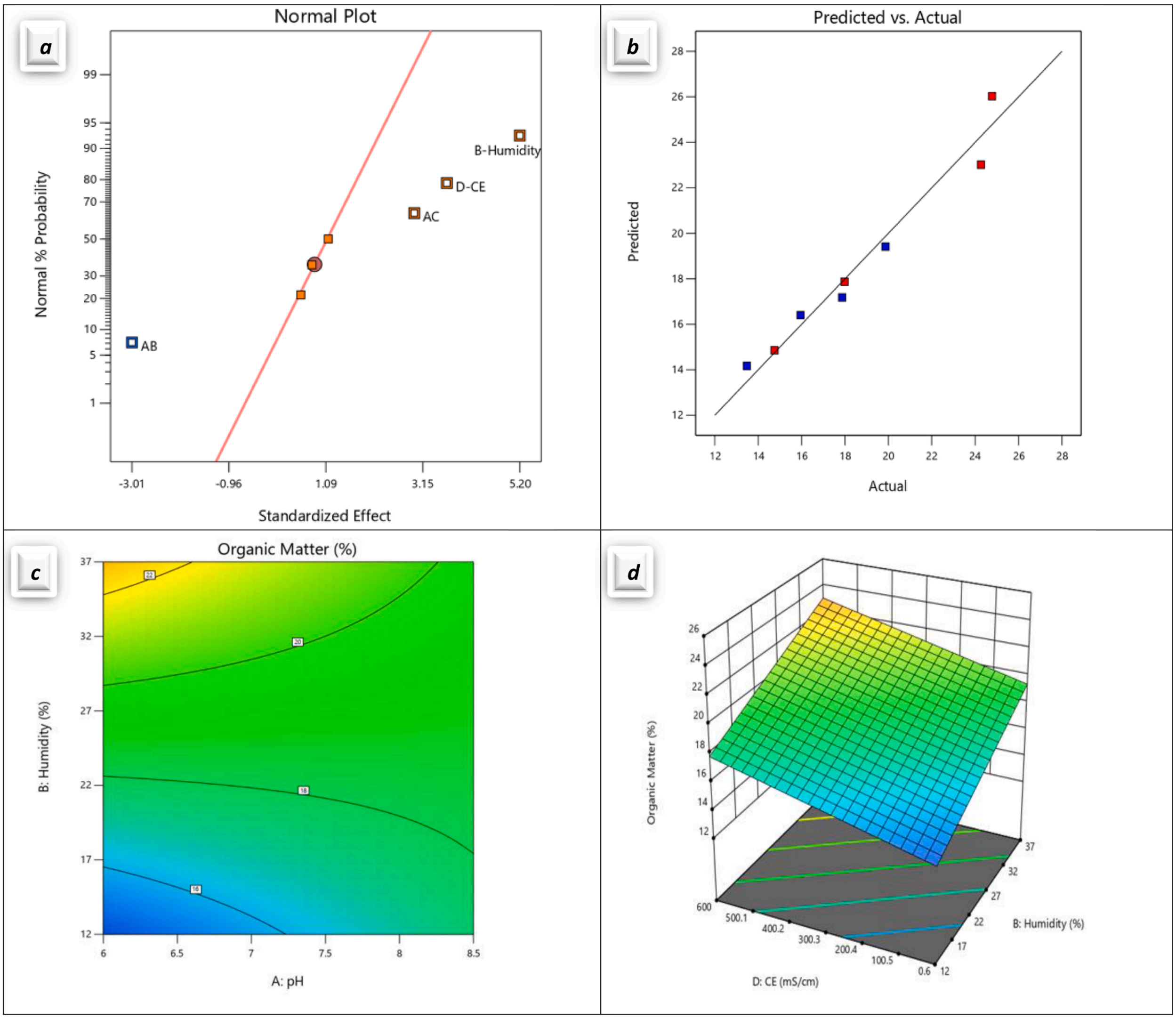

Fig. 3. (a) Normal plot. (b) Predict versus actual plot. (c) Contour plot and (d) 3D surface plot of the effect and interaction of CRPM.

According to the equation, interactions between AB parameters have a positive effect, while those between AD have a negative effect on organic matter, with negative coefficients of 1.29 and −0.9375, respectively.

In the same vein, the normal residue plot shown in Fig. 1(a) indicates that the distribution of residue points correctly follows the straight line, meaning that the distribution is homogeneous (Fig. 6).

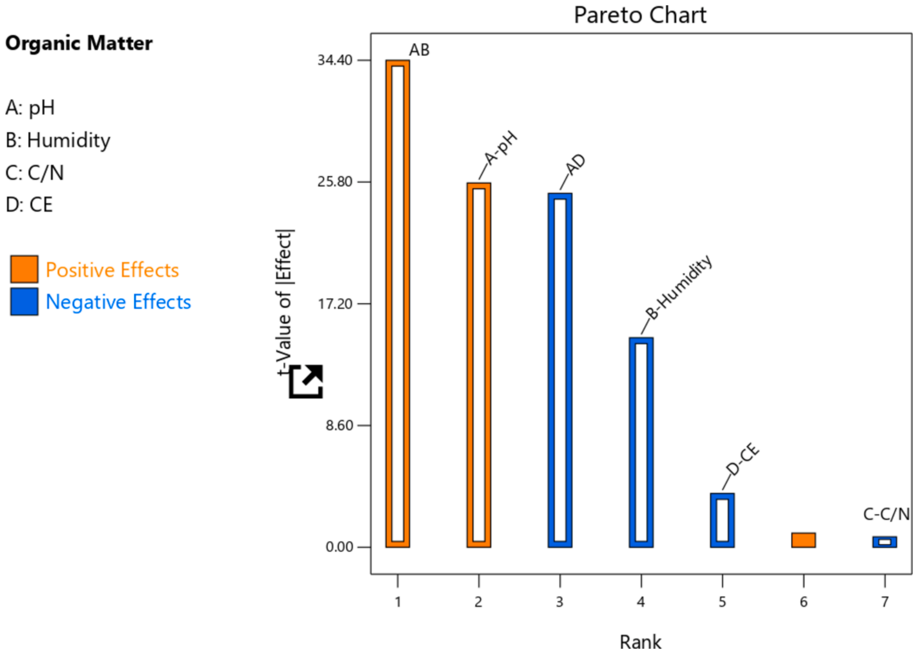

Fig. 4. Pareto diagram for manure.

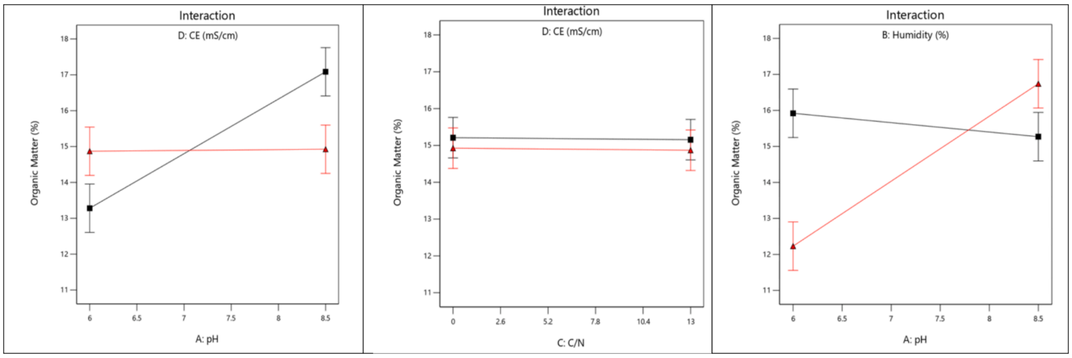

Fig. 5. Different interactions for manure.

Furthermore, the significance of the experimental values was verified by plotting the predicted versus actual graph presented in Fig. 6(b), which shows that all the values were distributed closely around the diagonal line, confirming the accuracy and validity of the predicted model.

The 2D and 3D response surface curves illustrate the effect of the chosen parameters on the response. The results show that the percentage of organic matter reached its maximum (17.81) in the zone containing 8.5 pH, 37 % humidity, 0 ratio C/N and 0.6 m S/cm electrical conductivity.

4. Discussion

The statistical tools employed in the full factorial design have revealed that certain factors significantly impact the organic matter content of the soil in the Ain B'tit region when using compost derived from olive mill waste cake residues. Specifically, soil moisture, electrical conductivity, and the interaction between pH and the ratio C/N have been shown to positively influence the organic matter content. This suggests that appropriate levels of moisture and conductivity, as well as a balanced carbon-to-nitrogen ratio, enhance soil enrichment. However, the interaction between pH and moisture has exhibited a negative effect, indicating that certain combinations of these variables may limit the compost's effectiveness. These findings underscore the importance of understanding and optimizing these factors and their interactions to maximize the benefits of compost in improving soil quality. Careful management of moisture, electrical conductivity, and pH, along with a thorough analysis of their combined effects, is essential to achieve the best results in terms of soil organic matter content.

4.1. *Positive influence of factors and interactions*

4.1.1. *Humidity*

Humidity is a critical factor in soil fertility, influencing various aspects that determine a soil's ability to support plant growth. Water is essential for photosynthesis, nutrient transport, and cell hydration, and soil humidity determines water availability for plants; while dry or arid conditions can impede growth, well-moistened soil promotes development. Additionally, water facilitates the solubilization of nutrients such as nitrogen, phosphorus, and potassium, allowing plant roots to absorb these essential elements. Soil microorganisms, including bacteria and fungi, rely on appropriate humidity for their metabolic activity, and extreme dryness or wetness can disrupt their functions, affecting soil fertility. The balance of moisture also impacts soil structure, where optimal humidity maintains an aerated structure conducive to air and root circulation, whereas excessive moisture can cause compaction and

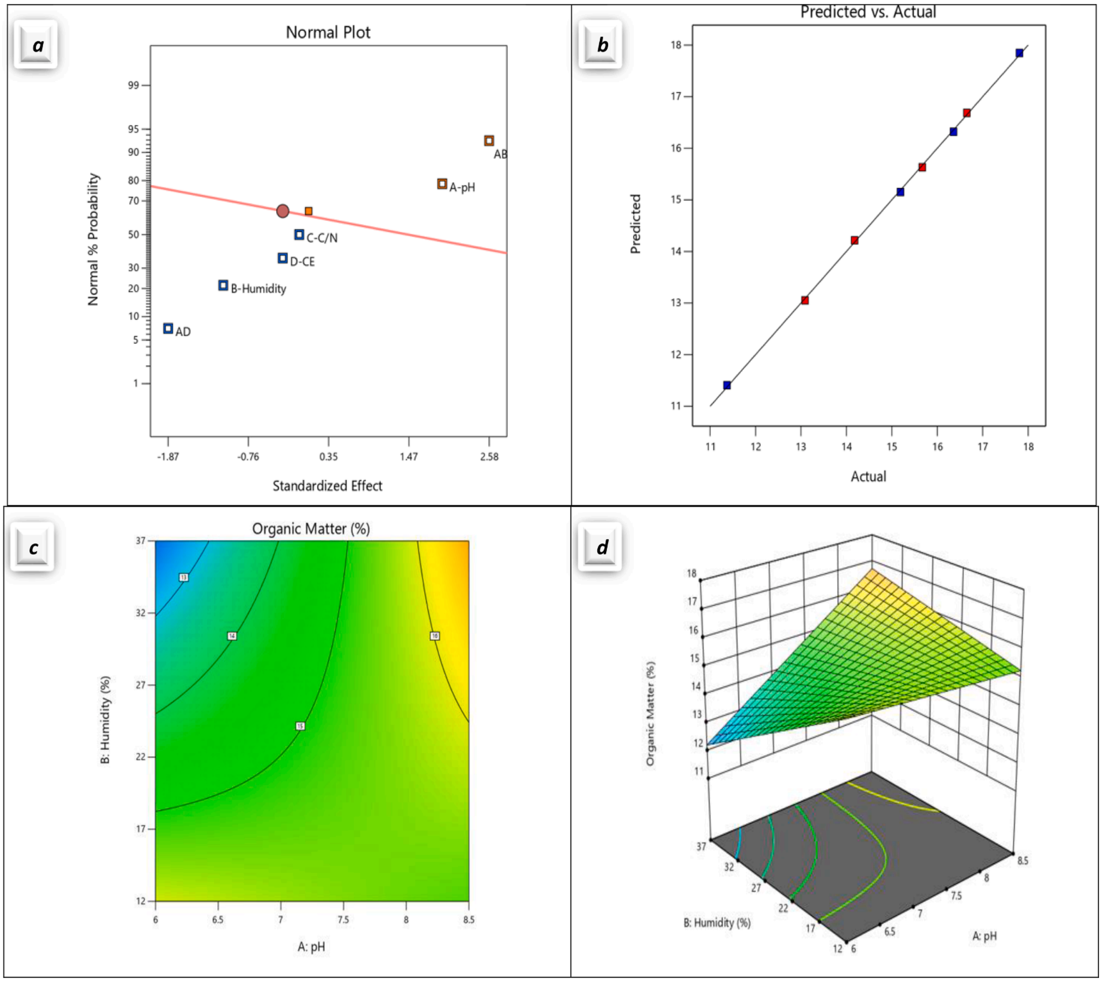

Fig. 6. (a) Normal plot. (b) Predict versus actual plot. (c) Contour plot and (d) 3D surface plot of the effect and interaction of CRPM.

insufficient moisture can lead to cracking and structural degradation. High humidity can result in soil erosion, which depletes essential nutrients and reduces fertility. Conversely, insufficient humidity can lead to salt accumulation due to evaporation, negatively impacting soil fertility by impairing the plants' ability to absorb water and nutrients. Thus, managing soil humidity is crucial for maintaining optimal soil conditions and ensuring healthy plant growth.

In summary, soil humidity, is a key factor in fertility, as it affects water availability, nutrient solubility, microbial activity, soil structure, erosion and salinity. An appropriate humidity, balance is essential to support plant growth and maintain soil fertility (Ahmed and Al-Mutairi, 2022; Purwanto and Alam, 2020).

4.1.2. Electrical conductivity

Electrical conductivity (EC) is a crucial indicator of soil fertility as it reflects soil salinity, which impacts plant growth in various ways. EC measures the soil's ability to conduct electricity, influenced by ions such as sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-). Higher ion concentrations result in increased EC, indicating soil salinity. High EC, often due to excessive salinity, can be detrimental to plants by causing root damage, disrupting nutrient absorption, and inducing water stress due to osmotic pressure. Additionally, high EC can affect nutrient availability, as excessive ions may compete with essential nutrients like nitrogen, phosphorus, potassium, and calcium. Therefore, EC is commonly used to gauge soil fertility, with normal levels indicating adequate nutrient concentration and low salinity, whereas high EC suggests salinity issues that need to be managed to enhance soil fertility.

To maintain or improve soil fertility, it is important to monitor electrical conductivity and take steps to manage salinity if it is too high. This can include proper irrigation, selection of salt-tolerant plants, soil amendment to reduce salinity and other appropriate management practices. Judicious salinity management helps to maintain an optimal growing environment for plants, thus promoting soil fertility (Boudjabi and Chenchouni, 2022; Javed et al., 2022).

4.1.3. pH- ratio C/N interaction

The interaction between soil pH and the carbon-to-nitrogen (C/N) ratio significantly impacts soil fertility. Soil pH affects the availability of nutrients like nitrogen and phosphorus by influencing the soil's ability to release these elements to plants. Similarly, the ratio C/N plays a role in nitrogen availability by affecting the decomposition of organic matter, which provides nitrogen. Additionally, the ratio C/N affects microbial activity, as a balanced ratio promotes efficient decomposition and nutrient release. Soil pH also influences microbial community composition, which can further affect the decomposition process and nutrient availability.

In summary, the interaction between soil pH and ratio C/N is crucial to understanding soil fertility. An appropriate pH and balanced ratio C/N promote adequate nutrient availability and efficient microbial activity, which is essential for plant growth. It is important to adjust these factors to the specific needs of the crops you wish to grow to optimize soil fertility (Xu et al., 2020; Xu et al., 2021; Zhou et al., 2020).

4.2. Negative influence of factors and interactions

4.2.1. pH-humidity interaction

The interaction between soil pH and soil humidity can significantly impact soil fertility, with effects varying based on soil type, crops grown, and farming practices. Negative consequences of this interaction include soil acidification, where excessive humidity in acidic soils can worsen acidity, reducing the availability of essential nutrients like calcium, magnesium, and phosphorus, and impairing soil fertility. Acidic, moist soils can also lead to increased solubility of heavy metals such as lead, cadmium, and aluminum, which can be toxic to plants. Additionally, nutrient leaching can occur in highly acidic and moist conditions, causing the loss of vital nutrients like nitrogen, potassium, and calcium, and potentially altering soil structure and increasing erosion risk. On the positive side, increased humidity can sometimes reduce undesirable elements like ferrous iron and manganese, improving soil quality for certain crops. Furthermore, consistent humidity can help maintain a stable soil pH, which benefits plants that require a steady pH for optimal growth.

Indeed, statistical studies have been carried out on soil quality in the Araban plain, Turkey, using Principal Component Analysis (PCA), Hierarchical Analytical Process (HAP) and Expert Opinion (EO) to identify the most effective method for assessing soil quality and recommending protective practices.

In summary, the interaction between soil pH and soil humidity can have complex effects on soil fertility. It is essential to take these factors into account during farm management to ensure that the soil remains fertile and that crops develop optimally. It is also recommended to carry out regular soil tests to monitor pH and other soil characteristics, and adjust management practices accordingly **(**Silveira and Kohmann, 2020; Nguemezi et al., 2020**)**.

Notwithstanding, for Manure, the plan obtained showed that its use has a positive effect on pH, pH-humidity interaction; thus it noted negative effects on the response studied for the electrical conductivity factor and pH-CE interaction.

4.2.2. pH

Soil pH, a measure of acidity or alkalinity, has a significant impact on soil fertility. Proper soil pH is essential for plant growth and nutrient availability. In general, a neutral soil pH (pH 7) is considered ideal for most crops, although slight variations are tolerated depending on specific plant needs.

Soil pH can positively affect fertility in several ways. It influences the solubility of essential plant nutrients such as nitrogen, phosphorus, and potassium, making them more available to plants at a neutral pH, which promotes their growth. Additionally, soil microorganisms like bacteria and fungi, which are crucial for breaking down organic matter and transforming nutrients, generally function optimally at near-neutral pH. This right pH level stimulates microbial activity, aiding in the decomposition of organic matter and the release of nutrients. Proper pH also ensures that plant roots can effectively absorb nutrients; an inadequate pH can hinder nutrient uptake, particularly of trace elements like iron, manganese, and zinc, leading to deficiencies. Furthermore, appropriate pH levels help prevent the increased solubility of heavy metals, which can be toxic to plants and negatively impact their growth.

To optimize soil fertility, it is important to monitor pH and adjust if necessary. Soil amendment with substances such as lime can be used to raise the pH (correct acidity), while the addition of organic matter can help lower the pH (correct alkalinity) in soils that are too basic. Adjusting soil pH to the specific needs of your crops will enhance their growth and yield **(**Butterly et al., 2022**)**.

4.2.3. pH-humidity interaction

The interaction between soil pH and soil humidity can positively affect soil fertility in dry conditions, though this depends on various factors. Proper soil humidity helps maintain pH at an optimal level for plant growth, ensuring that the chemical reactions necessary for nutrient availability are not impaired. Effective soil management is crucial to maintaining this optimal pH-humidity interaction. This can involve adding organic matter to enhance water retention and pH regulation, as well as using soil amendments to adjust soil pH as needed.

It's important to note that soil pH and humidity requirements vary from crop to crop. A soil analysis can help determine the specific requirements for a given crop. In general, maintaining an appropriate soil pH and adequate humidity can contribute significantly to improving dry soil fertility and plant growth **(Hag** Husein et al., 2021; Birhane and Mehari, 2021**)**.

4.2.4. Electrical conductivity

Electrical conductivity can negatively impact soil fertility and organic matter content, depending on various factors. It measures the soil's ability to conduct electrical current, primarily due to dissolved ions in the soil water. High electrical conductivity often indicates excessive soil salinity, with elevated concentrations of soluble ions like sodium, chloride, sulfate, and carbonate. This excess salinity can disrupt plants' water balance and nutrient absorption, leading to osmotic stress that affects growth and fertility. Additionally, high electrical conductivity can reduce the availability of essential nutrients such as nitrogen, phosphorus, and potassium, as excess ions compete with nutrient ions for uptake by plant roots. Excessive salinity can also deteriorate soil structure by causing soil particles to aggregate, which reduces soil porosity and water retention capacity, making it less suitable for plant growth. Moreover, high electrical conductivity can affect soil organic matter by impacting microorganisms responsible for its decomposition, slowing down this process and reducing the soil's organic matter content.

In summary, high electrical conductivity due to excessive salinity can have negative effects on soil fertility by disrupting nutrient uptake by plants, degrading soil structure, and reducing organic matter content. It is important to monitor and manage the electrical conductivity of the soil to maintain its fertility and health. Appropriate management practices, such as adequate irrigation, drainage, reducing salt inputs, and adding organic matter, can help minimise the negative effects of electrical conductivity on the soil **(**Rayne and Aula, 2020**)**.

4.2.5. pH-CE interaction

The interaction between soil pH and electrical conductivity can significantly influence soil fertility. Inadequate soil pH can reduce the availability of essential nutrients such as nitrogen, phosphorus, and potassium, with excessively acidic soils potentially making aluminium toxic to plants. Similarly, high electrical conductivity, often due to increased salinity, can affect nutrient availability by causing competition with saline ions. This elevated conductivity can also lead to ion toxicity, where an accumulation of saline ions like sodium and chlorine interferes with plants' ability to absorb water and nutrients, further impacting their growth and soil fertility.

To maintain soil fertility, it is essential to monitor and adjust pH and electrical conductivity according to the specific needs of the crops grown. This may involve adding organic matter to correct pH or implementing management practices to reduce soil salinity. Regular soil tests are useful for assessing these parameters and taking corrective action if necessary to optimize soil fertility **(**Khadem et al., 2021**)**.

5. Conclusion

This study has provided valuable insights into the complex interactions affecting the organic matter content of arid Moroccan soils through the evaluation of two different organic amendments: CRPM (compost derived from olive mill waste cake residues) and manure. The findings reveal that each type of amendment interacts differently with soil properties, a variation that can be attributed to their distinct initial characteristics and their behavior when integrated into the soil.

For the CRPM amendment, the analysis identified a positive interaction between soil pH and the carbon–nitrogen (C/N) ratio. This suggests that an optimal balance between these two factors can significantly enhance the retention and effectiveness of organic matter in the soil. Specifically, maintaining a favorable pH and ratio C/N can improve the decomposition process and nutrient availability, thereby boosting soil fertility and supporting plant growth. This interaction highlights the importance of carefully managing these parameters to maximize the benefits of CRPM in improving soil quality.

On the other hand, manure exhibited a different set of interactions. The study found that the most beneficial effect on soil organic matter content resulted from the interaction between pH and soil moisture. This indicates that adjusting both pH and moisture levels can create a more favorable environment for the organic matter in manure to contribute effectively to soil fertility. Proper management of these factors is crucial for optimizing the impact of manure and ensuring that its nutrients are utilized efficiently by plants.

The results emphasize that while controlling optimal doses of the studied variables is important for stimulating soil fertility, their interactions can produce varying and sometimes opposing effects. This underscores the necessity of developing comprehensive factorial models that encompass all relevant interactions. By doing so, researchers and practitioners can identify the most effective combinations of variables for enhancing soil fertility and achieving desired agricultural outcomes.

In practical terms, the insights gained from this study are critical for improving agricultural practices in arid regions like Morocco, where soil fertility is a key determinant of agricultural productivity. By leveraging the knowledge of how different amendments and their interactions affect soil quality, farmers can implement more targeted and effective soil management strategies. These improvements not only have the potential to enhance agricultural yields but also to stimulate the country's economy by increasing the productivity and sustainability of its agricultural sector. Therefore, further research should continue to refine these models and explore additional variables and interactions to support sustainable agriculture and economic development in arid environments.

CRediT authorship contribution statement

Imane Mehdaoui: Writing – review & editing, Writing – original draft, Visualization, Resources, Formal analysis, Data curation, Conceptualization. **Rachid Mahmoud:** . **Zineb Majbar:** . **Sanae Berrada:** . **Mohammed Ben Abbou:** . **Mohamed S. Elshikh:** . **M. Ajmal Ali:** Writing – review & editing, Writing – original draft, Funding acquisition. **Tse-Wei Chen:** . **Mustapha Taleb:** . **Zakia Rais:** Writing – review & editing, Writing – original draft.

Declaration of Competing 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.

Acknowledgements

The authors extend their appreciation to the Researchers supporting project number (RSP2024R306), King Saud University, Riyadh, Saudi Arabia.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2024.103471.

References

Ahmed, N., Al-Mutairi, K.A., 2022. Earthworms effect on microbial population and soil fertility as well as their interaction with agriculture practices. Sustainability 14 (13), 7803. https://doi.org/10.3390/su14137803.

Alkharabsheh, H.M., Seleiman, M.F., Battaglia, M.L., Shami, A., Jalal, R.S., Alhammad, B. A., Almutairi, K.F., Al-Saif, A.M., 2021. Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: a review. Agronomy 11 (5), 993. https://doi.org/10.3390/agronomy11050993.

Asghar, Waleed, Muhittin Onur Akça, Hanife Akça, Ommolbanin Jafari Tarf, Ryota Kataoka, et Oğuz Can Turgay. 2022. Chapter 1 - Alternative strategies to synthetic chemical fertilizers: revitalization of soil quality for sustainable agriculture using organic-based approaches. In New and Future Developments in Microbial Biotechnology and Bioengineering, édité par Harikesh Bahadur Singh et Anukool Vaishnav, 1-30. Elsevier. 10.1016/B978-0-323-85581-5.00003-3.

Birhane, Hailu, Hagos, Mehari, 2021. Impacts of soil salinity/sodicity on soil-water relations and plant growth in dry land areas a review. J. Natural Sci. Res., Février. 2021. https://doi.org/10.7176/JNSR/12-3-01.

Boudjabi, Sonia, Haroun Chenchouni, 2022. Soil fertility indicators and soil stoichiometry in semi-arid steppe rangelands. CATENA 210 (mars): 105910. 10.1016/j.catena.2021.105910.

Butterly, C.R., Amado, T.J.C., Tang, C., 2022. In: Soil Acidity and Acidification. In: Subsoil Constraints for Crop Production, Édité Par Teogenes. Springer International Publishing, Cham, pp. 53–81. https://doi.org/10.1007/978-3-031-00317-2_3.

Furey, G.N., Tilman, D., 2021. Plant biodiversity and the regeneration of soil fertility. Proc. Natl. Acad. Sci. 118 (49), e2111321118. https://doi.org/10.1073/pnas.2111321118.

Husein, H., Hussam, B.L., Bäumler, R., Sahwan, W., 2021. A contribution to soil fertility assessment for arid and semi-arid lands. Soil Systems 5 (3), 42. https://doi.org/10.3390/soilsystems5030042.

ISO-18400-102-2017.pdf. s. d. Consulté le 14 mars 2024. https://cdn.standards.iteh.ai/samples/62843/ea8dbe1411f94017ae77a9fca48d2d71/ISO-18400- 102-2017.pdf.

Javed, A., Ali, E., Afzal, K.B., Osman, A., Riaz, D.S., 2022. Soil fertility: factors affecting soil fertility, and biodiversity responsible for soil fertility. Int. J. Plant, Animal Environ. Sci. 12 (1), 21–33.

Khadem, A., Raiesi, F., Besharati, H., Khalaj, M.A., 2021. The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. Biochar 3 (1), 105–116. https://doi.org/10.1007/s42773-020-00076-w.

LOI Standard, 2024. s. d. What Is Loss on Ignition? | LOI. Precisa. Consulté le 5 septembre 2024. https://www.precisa.com/blog/what-is-loss-on-ignition-loi/.

Maurya, S., Abraham, J.S., Somasundaram, S., Toteja, R., Gupta, R., Makhija, S., 2020. Indicators for Assessment of Soil Quality: A Mini-Review. Environ. Monit. Assess. 192 (9), 604. https://doi.org/10.1007/s10661-020-08556-z.

Mehdaoui, Imane, Faical El Ouadrhiri, El Mokhtar Saoudi-Hassani, Rachid Mahmoud, Mohammed Ben Abbou, Amal Lahkimi, Mustapha Taleb, Zakia Rais, 2023. Cocomposting of olive mill waste cake residues (OMWC) and other wastes: Prediction and optimization using an optimal mixture design. Int. J. Recycling Organic Waste Agric. 13 (1). https://ijrowa.isfahan.iau.ir/article_708987.html.

Meraj, G., Kanga, S., Kranjčić, N., Durin, B., Singh, S.K., 2021. Role of natural capital economics for sustainable management of earth resources. Earth 2 (3), 622–634. https://doi.org/10.3390/earth2030036.

Nguemezi, C., Tematio, P., Yemefack, M., Tsozue, D., Silatsa, T.B.F., 2020. Soil quality and soil fertility status in major soil groups at the Tombel Area, South-West Cameroon. Heliyon 6 (2), e03432.

Norme-NFU.44-051-copie.pdf. s. d. Consulté le 28 janvier 2024. http://www.vertcarbone.fr/wp-content/uploads/2021/03/Norme-NFU.44-051-copie.pdf.

Purwanto, B.H., Alam, S., 2020. Impact of intensive agricultural management on carbon and nitrogen dynamics in the humid tropics. Soil Sci. Plant Nutr. 66 (1), 50–59. https://doi.org/10.1080/00380768.2019.1705182.

Raymond, A.J., Tipton, J.R., Kendall, A., DeJong, J.T., 2020. Review of Impact Categories and Environmental Indicators for Life Cycle Assessment of Geotechnical Systems. J. Ind. Ecol. 24 (3), 485–499. https://doi.org/10.1111/jiec.12946.

Rayne, N., Aula, L., 2020. Livestock manure and the impacts on soil health: a review. Soil Systems 4 (4), 64. https://doi.org/10.3390/soilsystems4040064.

Rubio, J.L., Reyes-Sánchez, L.B., Duihu, N., Costantini, E.A.C., Horn, R., Zlatic, M., 2024. Protecting the soil is protecting the climate WASWAC and IUSS position paper on the inter linkages of soil and climate change. Soil Security 14 (mars), 100124. https://doi.org/10.1016/j.soisec.2023.100124.

Sánchez-Ortiz, J., Rodríguez-Cornejo, V., Del Río-Sánchez, R., Valderrama, T., 2020. Indicators to measure efficiency in circular economies. Sustainability 12 (11), 4483. https://doi.org/10.3390/su12114483.

Silveira, Maria Lucia, et Marta Moura Kohmann. 2020. Chapter 3 - Maintaining soil fertility and health for sustainable pastures. In: Management Strategies for Sustainable Cattle Production in Southern Pastures, édité par Monte Rouquette et Glen E. Aiken, 35-58. Academic Press. 10.1016/B978-0-12-814474-9.00003-7.

Singh, Teg Bahadur, Akbar Ali, Mrinalini Prasad, Arti Yadav, Preksha Shrivastav, Deepika Goyal, et Prem Kumar Dantu, 2020. Role of Organic Fertilizers in Improving Soil Fertility. In Contaminants in Agriculture: Sources, Impacts and Management, édité par M. Naeem, Abid Ali Ansari, et Sarvajeet Singh Gill, 61-77. Cham: Springer International Publishing. 10.1007/978-3-030-41552-5_3.

Vera Candioti, Luciana, María M. De Zan, María S. Cámara, and Héctor C. Goicoechea, 2014. Experimental design and multiple response optimization. Using the desirability function in analytical methods development. Talanta 124 (juin), 123-38. 10.1016/j.talanta.2014.01.034.

Xu, Hu, Andong Cai, Dong Wu, Guopeng Liang, Jing Xiao, Minggang Xu, Gilles Colinet, et Wenju Zhang. 2021. Effects of biochar application on crop productivity, soil carbon sequestration, and global warming potential controlled by biochar C:N ratio and soil pH: A global meta-analysis. Soil and Tillage Research 213 (septembre): 105125. 10.1016/j.still.2021.105125.

Xu, Z., Zhang, T., Wang, S., Wang, Z., 2020. Soil pH and C/N ratio determines spatial variations in soil microbial communities and enzymatic activities of the agricultural ecosystems in Northeast China: Jilin Province case. Appl. Soil Ecol. 155 (novembre), 103629. https://doi.org/10.1016/j.apsoil.2020.103629.

Zhou, W., Han, G., Liu, M., Zeng, J., Liang, B., Liu, J., Rui, Qu., 2020. Determining the distribution and interaction of soil organic carbon, nitrogen, pH and Texture in Soil Profiles: a case study in the Lancangjiang River Basin, Southwest China. Forests 11 (5), 532. https://doi.org/10.3390/f11050532.

Zilio, Massimo, Ambrogio Pigoli, Bruno Rizzi, Axel Herrera, Fulvia Tambone, Gabriele Geromel, Erik Meers, Oscar Schoumans, Andrea Giordano, et Fabrizio Adani. 2022. Using highly stabilized digestate and digestate-derived ammonium sulphate to replace synthetic fertilizers: The effects on soil, environment, and crop production. Sci. Total Environ. 815 (avril): 152919. 10.1016/j.scitotenv.2022.152919.