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Soil quality and eggplant productivity in response to different mulching strategies under conservation tillage in organic greenhouse production

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Introduction: Mulching is a key practice in sustainable agriculture that improves soil quality, conserves resources, and enhances crop performance. However, comparative assessments of different mulch types under organic greenhouse conditions remain limited, particularly in semi-arid environments.

Methods: A field experiment was conducted in an unheated greenhouse using a randomized complete block design with three replications. Five treatments were tested: black polyethylene mulch (BM), white polyethylene mulch (WM), straw mulch (SM), compost mulch (CM), and a bare soil control (CK). The study evaluated the impact of these treatments on soil physicochemical properties, microbial communities, and eggplant (*Solanum melongena* L.) growth and yield under organic farming conditions.

Results: White mulch significantly increased soil pH, while CK resulted in the highest soil electrical conductivity. BM maintained the highest soil temperature and water content across all dates. CM significantly enhanced soil organic matter (+0.32 g kg⁻¹), available phosphorus (+41 mg kg⁻¹), potassium (+302 mg kg⁻¹), and total nitrogen (+5.33 mg kg⁻¹) compared to CK. SM promoted the greatest microbial abundance, including bacteria, mesophilic and thermophilic fungi. The Soil Quality Index (SQI) ranged from 0.34 to 0.58, with BM recording the highest value and CK the lowest. BM also led to significant improvements in plant growth metrics and yield, with a 29.5 t ha⁻¹ increase over the other treatments.

Discussion: Plastic mulch, particularly black polyethylene, proved to be the most effective in enhancing soil conditions, microbial activity, and eggplant productivity in the short term. These results highlight its potential as a cost-

effective strategy for improving crop performance and soil resilience in semi-arid organic greenhouse systems. Nonetheless, further long-term studies across diverse environments and soil types are necessary to confirm the broader applicability of these findings

KEYWORDS

plastic film mulch, plasticulture, organic mulches, microbial community, soil quality index, crop growth, nutrient availability

1 Introduction

One of the most crucial steps toward global sustainable agriculture is organic farming, which is a sustainable alternative to conventional agriculture, aiming to preserve environmental quality, enhance biodiversity, and produce healthy food without synthetic inputs (Aulakh et al., 2022). Experiments with organic farming over a long period of time have demonstrated that the organic approach enhanced soil quality. Both the nutrient and soil organic carbon (SOC) concentrations were considerably greater than in traditional systems (Chataut et al., 2023). The potential for organic farming to capture SOC has made it a significant step in reducing greenhouse gas emissions (Chataut et al., 2023). Greenhouses leads to the decline of soil quality due to high cropping index, large agrochemical input, and closed environment (Tong et al., 2022). Due to the controlled modification of temperature, humidity, and light, greenhouse agriculture has gained popularity around the world as a crop production technology that improves yields.

Eggplant (*Solanum melongena* L.) eggplant is an herbaceous plant belonging to the Solanaceae family and is among the top 40 vegetable species produced worldwide with 54 million tons produced annually covering ca. 1 million ha (Organization, 2019). Despite having relatively few calories, eggplant is regarded as one of the healthiest vegetables due to its high concentration of bioactive compounds, vitamins, and minerals (Nyasapoh et al., 2024). However, eggplant is one of the plants most affected by climate change (Vasava et al., 2023) and farmers in North Africa often cannot afford the expense of chemical inputs, resulting in the long-term deterioration of soil quality and the subsequent pollution of aquatic ecosystems (Amami et al., 2021). Therefore, the scientific community faces two key problems to ensure sustainable agricultural production in North Africa: protecting the environment while guaranteeing food security (Bolou-Bi et al., 2023).

One potential approach to solve this problem is to increase agricultural output using the principles of organic farming. The overarching aim of organic production systems is twofold: to protect and improve the natural environment, and to tackle the socioeconomic challenges currently facing farmers (Shaik et al., 2023).

This agricultural paradigm exploits ecological processes to oversee biological threats, optimize resource utilization and enhance ecosystem services, while simultaneously ensuring minimal environmental disruption and sustainable management of critical non-renewable resources, such as soil and water (Foteinis et al., 2021). One way to enhance soil fertility is to boost soil mesofauna, arbuscular mycorrhizal fungi and nitrogen-fixing bacteria. Another way is to increase the organic matter content of the soil (e.g. by using organic mulching) (Demo and Asefa Bogale, 2024). Crop growth and development are influenced by soil temperature and moisture content. Soil moisture levels and distribution can have a direct impact on soil characteristics, which in turn can affect crop growth (Chen et al., 2020). The temperature of the soil is very important for growing crops. It directly affects how the roots develop, how much water and minerals the plants take in, and various metabolic processes (Jarvi and Burton, 2020). Mulching is a vital component of sustainable soil management, as it significantly improves both the physical and chemical properties of the soil. It enhances moisture retention, moderates soil temperature, suppresses weed growth, and mitigates erosion, thereby contributing to improved soil health and crop productivity (Liu et al., 2021).

A wide range of plant nutrients, including micronutrients that are often absent from commercial fertilizers, can be found in compost. The application of compost in cropping systems brings improvement to soil properties through neutralization of both acidic and alkaline soils, buffering of pH levels to the optimal range for nutrient availability and creation of an ideal environment for plant growth (Perween and Ansari, n.d.). Compost also directly aids in the retention of water and nutrients, particularly in sandy soils which are common in North Africa (Sportelli et al., 2022). Organic mulching may also increase soil fertility by better regulating soil temperature and promoting greater soil biodiversity via provision of carbon (C) and microbial habitat (Shilpa and Singh, 2020; Rahul and Manikandan, 2021). Furthermore, mulches may increase soil water infiltration, which lowers soil erosion and water runoff and increases crop yields (Jia et al., 2024). The reduction of phytopathogens and enhanced soil tolerance to abiotic stress have been associated with greater microbial diversity (Di Miceli et al., 2024).

Soil microorganisms are sensitive to changes in soil physicochemical properties arising from different mulching models (Cong et al., 2020; Wang et al., 2020). Depending on the soil type, climate, and mulch materials used, mulching can have different effects. For example, in comparison to traditional organic compost mulches, plastic film mulch may potentially have a greater impact on regulating soil temperature, water retention and weed control (Naik et al., 2022; Díaz-Pérez, 2023). Conversely, composts and cereal residues may be better at promoting soil C storage and microbial activity. However, few studies have investigated the combined impact of different mulching materials under organic management on soil fertility and eggplant crop output in organic farming, particularly in North Africa. To address this knowledge gap, we investigated the impact of organic (compost and straw) and plastic film mulching (PFM) on soil quality and eggplant production.

Our objective is to support the organic and intense production of eggplant. We hypothesized that (1) Different mulching materials (synthetic vs. organic) will differentially affect soil physicochemical properties, microbial community composition, and nutrient availability, with organic mulches (compost and straw) promoting greater soil biological activity and nutrient enrichment, while synthetic mulches (black and white plastic) will more effectively regulate soil temperature and moisture in organic greenhouse eggplant production; and (2) that black plastic mulch will result in significantly higher eggplant productivity parameters (vegetative growth, flowering, and yield) compared to other mulching materials and no-mulch control due to its superior ability to maintain optimal soil temperature, reduce weed competition, and create favorable conditions for nutrient uptake under Mediterranean semi-arid conditions. The study provides novel insights into the choice of

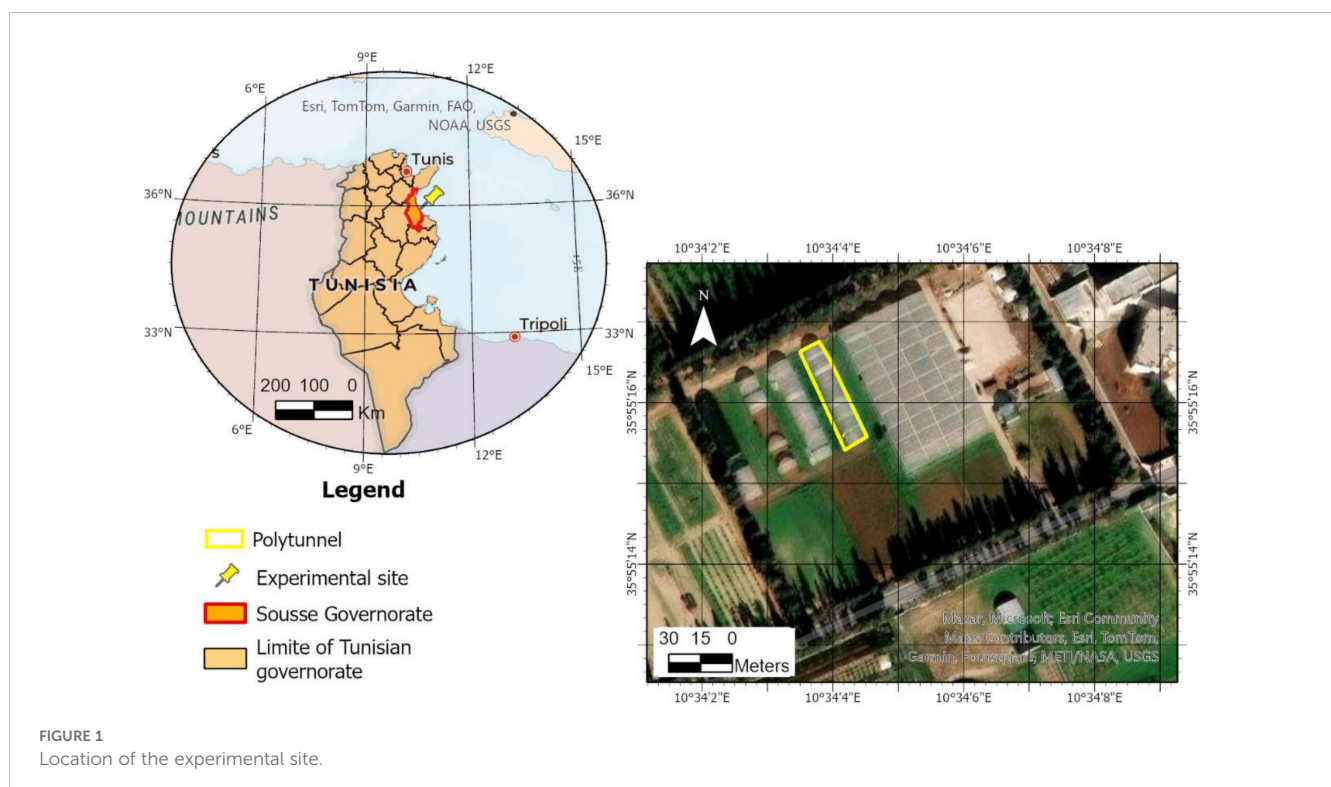
mulches for sustainable organic greenhouse production in climate-vulnerable areas.

2 Materials and methods

2.1 Experimental site and design

The experiment was conducted from November 2022 to May 2023 at the Technical Centre of Organic Farming (TCOF) in Chott Mariem-Sousse (35°54'53"N, 10°34'16"E), Tunisia (Figure 1). The field site is located 12 m a.s.l. and has a temperate Mediterranean climate (annual precipitation 350–400 mm, mean annual temperature 17°C). The experiment was carried out in a polytunnel (7.5 m wide and 40 m long), covering an area of 300 m² which faced north-south and was surrounded by windbreaks on all four sides. The polytunnel was constructed from transparent thermal polyethylene. According to the world reference base for soil resources, the soil of the study site is classified as Fluvisol (IUSS Working Group WRB, 2015). It has a sandy clay loam texture comprising 66.1% sand, 9.7% silt and 24.2% clay. It is characterized by a bulk density of 1.62 g cm⁻³, a water content of 17.2%, total porosity of 37.3%, organic matter content of 3.98%, electrical conductivity (EC) of 3.09 dS m⁻¹ and pH in distilled water of 7.04.

The field experiment was arranged in a randomized complete block design with twelve plots and three replicates. The experimental plots were 12 m long and 1 m wide each (12 m²). The experiments involved different organic and synthetic mulching materials including: (i) wheat straw mulch (SM), (ii) compost mulch (CM), (iii) black polyethylene mulch (BM), (iv) white polyethylene mulch



(WM), and (v) no mulch bare soil used as a control (CK) (Figure 2). The mulch materials were manually placed on the soil 20 d after transplantation, which was carried out on November 2nd, 2022. Details of the crop are presented later. The polytunnel contained six 36-m-long rows, spaced 1 m apart and 0.50 m along each row, with a density of 2 plants m⁻² (72 plants row⁻¹).

2.2 Soil sampling and analysis

Soil samples (0–20 cm) were collected from each plot 144 days after transplantation. The pH was measured in a 1:2.5 soil-to-distilled water suspension. Available phosphorus (P) was determined using the Olsen method (Olsen, 1954), exchangeable potassium (K) was extracted with 1 M ammonium acetate at pH 7 (Jones, 2018). Nitrogen (N) analysis was conducted using the Kjeldahl method (Kirk, 1950).

Soil temperature was measured using an EC Testr 11+ Multi Range sensor and the soil water content (WC) was determined using the gravimetric method by drying wet soil samples at 105°C for 24 h. In this method, the water content (WC, %) was calculated by Equation 1.

$$\text{Water Content (\%)} = \frac{(M_w - M_s)}{M_s \times 100} \quad (1)$$

Where M_w is the mass of wet soil and M_s is the mass of soil dried at 105°C (g).

Soil temperature and soil water content was measured at 6 different dates (19/01/2023; 26/01/2023; 08/02/2023; 15/02/2023; 07/03/2023 and 22/03/2023).

The abundance of bacterial and fungal communities was estimated using the standard serial dilution and plate count method. After serially diluting soil samples in sterile saline solution, aliquots (1 mL) from the proper dilutions were plated in



FIGURE 2

Photograph showing the different mulching materials used in the experiment. BM, black polyethylene mulch; WM, white polyethylene mulch; CM, compost mulch; SM, straw mulch.

triplicate on Potato Dextrose Agar (for fungi) and Nutrient Agar (for bacteria). For bacteria and fungi, plates were incubated at 28°C for 24–48 hours and 25°C for 3–5 days, respectively. On plates with 30–300 colonies, the number of colony-forming units (CFU) was measured. Using the following formula (Equation 2), the microbial population (N, in CFU/g of soil) was determined:

$$N = \frac{\sum a}{V * (n1 + 0.1 * n2) * d} \quad (2)$$

where $\sum a$ is the total number of colonies on all counted plates, V is the plated volume (mL), n1 and n2 are the number of plates at the first and second selected dilutions, and d is the dilution factor of the first selected dilution (Garland et al., 2021).

Lastly, soil total organic carbon (SOC) was determined with colorimeter using the $K_2Cr_2O_7-H_2SO_4$ method (Alovisi et al., 2024). Soil organic matter (SOM) content was calculated as described in Equation 3

$$\text{Soil Organic Matter (\%)} = \text{SOC} \times 1.72 \quad (3)$$

2.3 Plant material and crop management

An early harvesting variety of eggplant (*Solanum melongena* L. cv. Bonica) with large oval shaped fruits and dark violet color was used in the experiment. Uniform seedlings (3 weeks old) were transplanted in the field. Irrigation was managed using a drip system, with a flow rate of 4 L h⁻¹ per dripper at a pressure of 100 kPa. Irrigation was carried out once or twice a week on demand. To maintain the crop, various techniques were adopted, such as butting, hoeing, and leaf pruning or leaf thinning following local best practice. Pest management followed integrated pest management (IPM) principles, utilizing the biopesticide PREV-AM (an essential oil-based contact product) at a concentration of 0.3 mL L⁻¹ of water. The biopesticide was applied four times monthly to effectively control mites and leaf miners. Two manual weed control sessions were conducted for the bare soil treatments during the whole crop cycle. Later, as the plants occupied a larger area, harvesting was required along with infrequent manual weeding operations (Farooq et al., 2019).

A total of 15 plants were grown for each treatment, and five plants were randomly selected from each treatment group for measurement. Growth parameters were assessed 144 days after transplanting. Plant height (cm), measured from the crown to the apical bud furthest from the developed branches and the stem diameter (cm) was determined using Vernier callipers. In addition, we measured leaf number and flowering parameters.

Yield parameters were assessed to evaluate crop performance. The NKF indicated the total number of fully matured and healthy fruits per plant documented at harvest. Fruit Set (FS) was computed as the proportion of flowers that successfully matured into fruits, measured by dividing the Number of Knotted Fruits (NKF) by the total number of flowers per plant and multiplying by 100 as shown in Equation 4 (Nkansah et al., 2021).

$$FS(\%) = \left(\frac{NKF}{NF} \right) * 100 \quad (4)$$

Where NKF: Number of Knotted Fruits and NF: Number of Flowers

Total yield was expressed in tonnes per hectare (t/ha). It was calculated by summing the weights of all harvested fruits from each experimental plot and extrapolating to the hectare scale based on the plot size. Successive harvests were conducted at 119, 132, 153, and 182 days after planting (DAP), with a cumulative total yield also measured at the end of the experiment on 15 May 2023 (194 DAP).

2.4 Soil quality indexing

The total dataset approach was used to calculate a soil quality index (SQI) based on measured soil attributes under all treatments (Vasu et al., 2016). The soil quality indicators used to calculate the SQI included: soil organic matter, total N, available P, exchangeable K, soil pH and EC. Each indicator was given score by using standard scoring functions (SSF) based on its relationship to soil quality. There are three SSF which are generally used for soil quality indicators scoring: 'More is Better (MB)' function for a positive relationship between the soil quality and the indicator, 'Less is Better (LB)' function for a negative relationship between the soil quality and the indicator, 'Optimum Range (OR)' function for soil quality indicators with optimum threshold values (Lenka et al., 2022). These scoring functions were used to transform each measured indicator into a unitless score ranging from 0 to 1. Thus, SOM, N, P and K parameters were scored according to the MB function. Soil EC and pH were given scores by the LB and OR scoring functions, respectively. The upper, lower and optimum threshold values for the studied soil quality indicators were obtained from existing literature. SOM threshold values were sourced from (Rieke et al., 2022), EC and pH from (Amami et al., 2021) and N, P, K from (Toth et al., 2024).

In order to compute the composite SQI, the obtained scores for all soil attributes were summed and divided by the total number of indicators (Equation 5) as follows (Amami et al., 2021).

$$SQI = \sum_{i=1}^N \frac{Si}{N} \quad (5)$$

where Si is the given score to each indicator based on a specific SSF (MB, LB and OR), N represents the total number of soil quality indicators.

2.5 Statistical analysis

Data related to individual soil attributes, SQI and plant parameters were first tested for normality using the Shapiro-Wilk test and for homogeneity of variance using Levene's test. The data were then analyzed using one-way ANOVA. The Duncan's Multiple Range Test was used to separate means when ANOVA results indicated significant differences at ($p \leq 0.05$) level. Additionally, principal component analysis (PCA) was carried out

to determine the relationship among eggplant yield, growth parameters, and soil attributes. For soil microbial parameters, a non-metric multidimensional scaling (NMDS) analysis was carried out. All statistical analyses and graphs were conducted using OriginLab v2024 (OriginLabs Inc., Northampton, MS, USA). All data are presented as means $\pm$ SE.

3 Results

3.1 Effect of mulch material on soil properties

3.1.1 Soil physical and chemical properties

In the 0–20 cm soil layer during the growing season, BM had the highest soil temperature, followed by WM, CM, SM while CK

had the lowest soil temperature (Figure 3). The same trend was recorded at all measurement dates. Soil temperature gradually increased during the late stage of the eggplant growth period, with the results at day 144 following transplantation (Date 6) revealing that the mulching material significantly affected soil temperature. Soil covered with BM (23.7°C) maintained relatively high temperatures throughout the reproductive period, followed by the CM treatments (22.7°C). These values were significantly ($p \leq 0.05$) higher (9.4% and 4.5%, respectively) compared to the WM (21.7°C) and SM treatments (21.1°C). The lowest soil temperature was observed in the CK treatment (20.7°C), which was 12.6 and 8.6% lower than the black polythene and compost mulch treatments (Figure 3A).

Statistical analysis (ANOVA) showed that the differences in soil water content between the treatments were statistically significant ($p \leq 0.05$) (Figure 3). Results revealed that black and white plastic

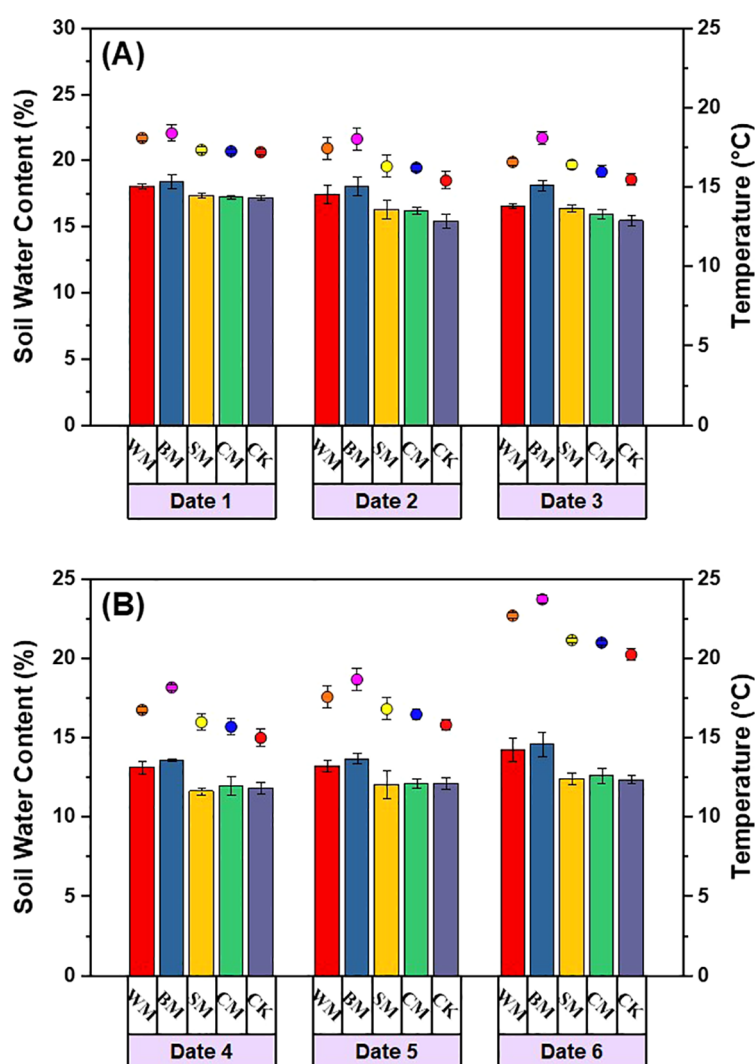


FIGURE 3

Effects of different mulching practices on soil temperature (bare) and soil water content (circle). WM, white polythene mulch; BM, black polythene mulch; SM, straw mulch; CM, compost mulch and CK, un-mulched soil on different measurement dates (A) Date1, 2 and 3 and (B) Date 4, 5 and 6. Boxes with different lowercase letters indicate significant differences between different mulch treatments ($p \leq 0.05$). Values represent means $\pm$ SE ($n = 3$).

mulch had the highest soil water content, followed by compost mulch and straw mulch with the control soil showing the lowest soil moisture at all different measurement dates. The highest soil water content for all the treatments was recorded 144 days after transplantation, and followed the trend BM (14.6%) > WM (14.2%) > CM (12.6%) > SM (12.4%) ≥ CK (12.4%). There was no significant difference between organic mulch (CM, SM) and control treatment (CK; $p > 0.05$).

The application of various mulch materials differentially affected a range of soil chemical properties. The pH of the soil treated with white plastic mulch (WM, pH 7.22) was significantly higher than that of black mulch soils (BM, pH 7.10; $p \leq 0.05$). The straw and compost treatments ranked 3rd and 4th with a pH value of 7.04 and 6.94 respectively, while the control had the most acidic pH of 6.44 (Figure 4A).

The soil EC varied among the different types of mulch (Figure 4B). The lowest value was observed with black plastic mulch at 2.09 mS cm⁻¹, while the control treatment had the highest value of 3.24 mS cm⁻¹ ($p \leq 0.05$).

3.1.2 Effect of different mulches on soil nutrient availability

The total N contents decreased in the order: CM (6.39 mg kg⁻¹) > WM (4.57 mg kg⁻¹) > BM (3.80 mg kg⁻¹) > control treatment (1.93 mg kg⁻¹) > SM (1.05 mg kg⁻¹) (Figure 5). Available P, K and SOM also varied among treatments with CM having the greatest values (Figures 5A, B).

3.1.3 Effect of mulching regime on the Soil Quality Index

Figure 6 shows the SQI values under all treatments. Overall, significant effects of mulch type were observed. The SQI ranged

from 0.34 to 0.58 with the highest under BM and the least under the no mulch control. The BM, WM and CM treatments gave significantly higher SQI in comparison to the no mulch control and the SM treatment. Among mulch treatments, the SQI was significantly ($p \leq 0.05$) different between BM and SM treatments whereas no significant differences in SQI were seen between the WM, SM and CM treatments. Interestingly, CM treatment showed a significantly similar SQI value to BM and WM treatments.

3.1.4 Effect of mulching regime on soil bacterial and fungal communities

The ANOVA showed that mulching treatments affected bacterial and fungal community richness (Table 1). The highest values observed under organic mulch followed by white mulch (WM), black mulch (BM), with the lowest value recorded under the control treatment. However, straw mulch treatment was found to significantly increase both mesophilic fungi (1.58×10^5) and bacteria (1.99×10^6) when compared to all other treatment ($p \leq 0.05$; Table 1). Regarding the thermophilic community, straw mulch only increased the fungi community (1.47×10^5), the bacterial community was found greater under Compost mulch (1.35×10^6) which was 36, 46, 70 and 88% higher than in the SM, WM, BM and CK treatments, respectively.

Non-metric multidimensional scaling (NMDS) analysis and clustering of the soil bacterial and fungal communities in the different mulch treatments shows clear separation between mulching treatments (Figure 7). Samples under BM and WM were close to each other, suggesting similarity of these mulching types in terms of their effects on soil microbial communities. Moreover, NMDS analysis showed a potential separation between all mulching treatments and the no mulch control (Figure 7).

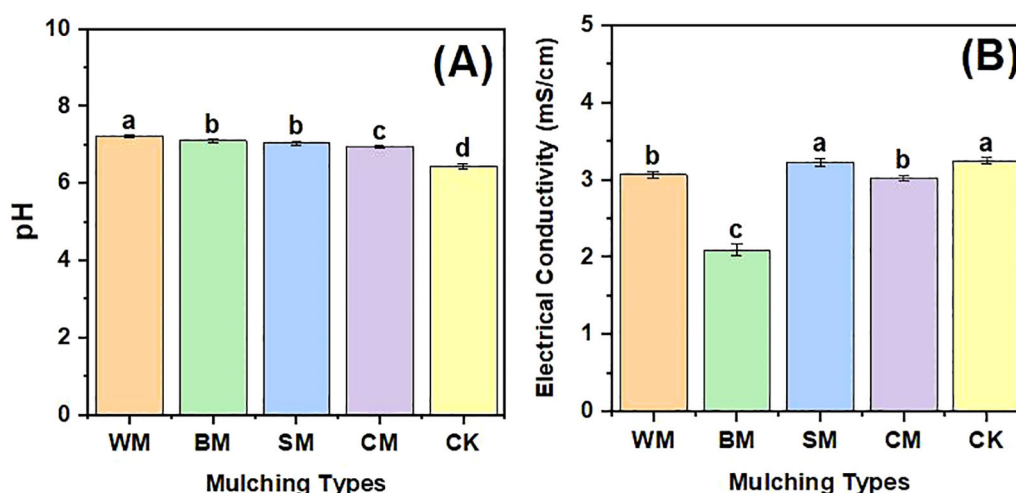


FIGURE 4

Effect of different mulching practices on (A) soil pH, and (B) soil electrical conductivity (EC). WM, White polythene mulch; BM, Black polythene mulch; SM, Straw mulch; CM, Compost mulch and CK, un-mulched soil. Boxes with different lowercase letters indicate significant differences between different mulch treatments ($p \leq 0.05$). Values represent means $\pm$ SEM ($n = 3$).

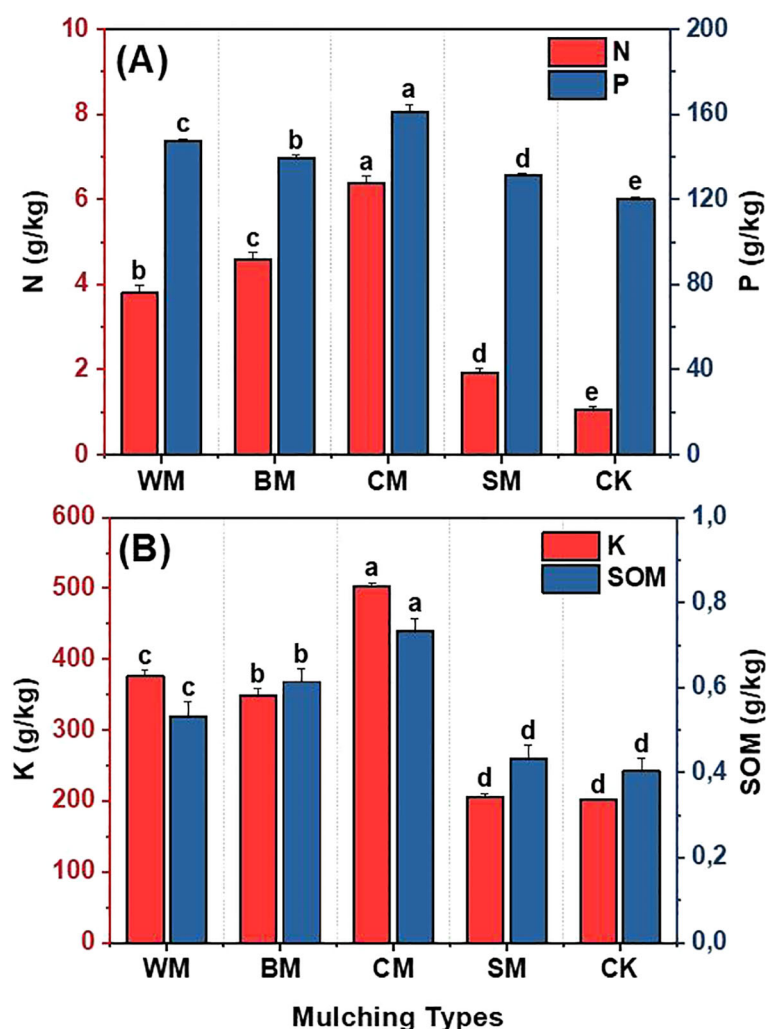


FIGURE 5

Effects of treatments on soil nutrients: (A): N; Total nitrogen (red bars) and P; Available phosphorus and (B): K; available potassium (red bars) and SOM; soil organic matter. WM, white polythene mulch; BM, black polythene mulch; SM, straw mulch; CM, compost mulch and CK, un-mulched soil. Values represent means $\pm$ SEM ($n = 3$) and columns with different lowercase letters indicate significant differences between treatments ($p \leq 0.05$).

3.2 Influence of mulch material on eggplant growth and yield

3.2.1 Vegetative growth parameters

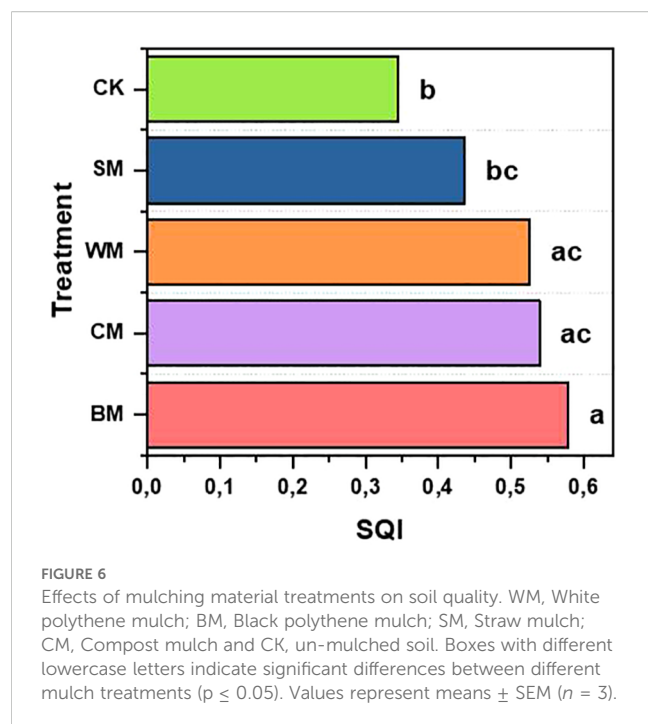
Figure 8 shows significant impact of different mulches on eggplant growth parameters. Among all the mulching treatments, the soil with synthetic mulch (BM and WM) had the most leaves ($p \leq 0.05$), while the soil covered with the two organic mulches (CM and SM) had the lowest number of leaves (Figure 8A). Figure 8B shows that the stem length for the compost mulch treatment (CM) and the straw mulch treatment (SM) were both considerably ($p \leq 0.05$) shorter than the stem length for the black (BM) and white (WM) mulch treatments. The control treatment had the shortest stem length, 26% shorter than the black mulch (BM) treatment. The number of branches per plant in the compost and plastic treatments did not differ significantly ($p > 0.05$). Polythene mulch (BM and WM) and compost mulch indicated a higher number

of branches ranging from 8.3 to 7.7 branches per plant compared to the straw mulch (SM, 5.66) and control treatments (CK, 6.4) (Figure 8C).

3.2.2 Flowering and yield parameters

The effect of different mulches on the Number of flowers (NF), Number of knotted fruit (NKF) and fruit set (FS) is shown in Table 2. Significant differences were observed in NF between the inorganic mulch treatments (WM and BM) and the control (CK). Overall, higher numbers of flowers were seen in the Black mulch, followed by the White mulch, Compost, Control being lowest in the Straw mulch. Significant difference was observed between organic mulch treatment (SM and CM) and plastic mulch (BM and WM).

The number of knotted fruits (NKF) differed significantly between the different mulches ($p \leq 0.05$). The highest NKF was recorded in the black polythene mulch, which was 39% and 65% higher than the white polythene mulch and organic compost mulch



treatment, respectively. The lowest was observed in Control and straw mulch treatment, which was 47 and 50% lower than the highest value, respectively.

In terms of fruit set (FS%), plastic mulch (BM and WM) was found to have significantly better response than the other mulching materials, continuously producing more fruit. The maximum fruit set was registered with black mulch treatment (43.57%) followed by the white mulch and compost mulch treatment. The minimum values of FS% were recorded in the control and straw mulch treatment. No discernible difference was evident between the compost and straw organic mulches and the no mulch control ($p > 0.05$; Table 2).

Mulch material treatments resulted in a significant ($p \leq 0.05$) increases in eggplant total yield. Statistically significant differences in the overall fruit yield were evident between the different mulches with the highest total yield recorded in the Black mulch treatment, being 17 and 35% higher than the white mulch film and compost mulch treatments, respectively. The straw mulch treatment had the lowest yield, 36% lower than the maximum yield in the BM treatment (Figure 9).

3.3 Multivariate analysis of soil and crop parameters using PCA and chord diagram visualization

The chord diagram demonstrated that the following factors were positively impacted by mulching material: Stem length; Number of flowers; Number of leaves; Number of knotted fruits; Number of branches; Fruit yield; Soil organic matter; Total N; Available P; Available K; Soil pH; Soil temperature; Electrical conductivity (Figure 10A). In addition, it was clear that the contribution of the application of compost mulch responded more to these indices than other treatments (13%) followed by black plastic mulch (11%) and white plastic mulch (11%). The lowest contribution was recorded in un-mulched treatment (CK, 7.7%) and straw mulch (SM, 7.5%) (Figure 10A).

PCA visual representation of the data showed that the first two PCs (PC1, PC2) had eigenvalues >1 and explained 85.4% of the total variability effectively explaining all the differences among the 13 indicators (Figure 10B). Therefore, PC1, PC2 were retained for further analysis. The PC1 with an eigenvalue of 9.03 explained 64.3% of the variance and for 9 components (EC, soil water content, available K, shoot length, number of leaves, flowers and branches, and fruit yield) had the highest weights. However, EC was found in the second quadrant, where it shows a negative relationship with other parameters predominantly situated in the first and fourth quadrants. The PC2 had an eigenvalue of 3.07 and explained 21.2% of the variance, and for this component, SOM, temperature and total N had the highest factor loadings (Figure 10B). The highly weighted factors under each PC were subjected to correlation analysis to reduce redundancy.

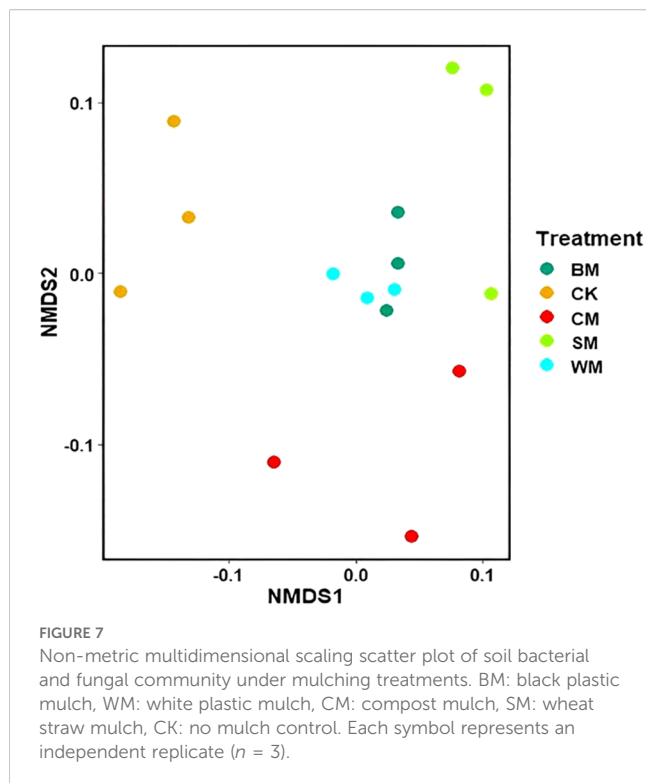
3.4 Correlation analysis

The correlation analysis revealed significant associations among soil properties, plant growth traits, and crop yield (Figure 11). The number of fruits ($r = 0.887$), stem length ($r = 0.874$), number of branches ($r = 0.858$), number of leaves ($r = 0.847$), soil water content ($r = 0.875$), and temperature ($r = 0.816$) all showed high positive correlations with yield, suggesting that these factors are strongly related to production of Eggplant. Soil pH also showed a positive correlation with yield ($r = 0.777$), while electrical conductivity (EC) displayed a strong negative relationship with

TABLE 1 Effects of various mulching treatments on bacterial and fungal abundance.

Treatments	Mesophilic (35°C)		Thermophilic (45°C)	
	Bacteria (CFU/g)	Fungi (CFU/g)	Bacteria (CFU/g)	Fungi (CFU/g)
CM	$0.90 \times 10^6 \pm (0.29)$	$1.36 \times 10^5 \pm (0.08)$	$1.35 \times 10^6 \pm (0.32)$	$1.27 \times 10^5 \pm (0.40)$
WM	$0.82 \times 10^6 \pm (0.12)$	$1.32 \times 10^5 \pm (0.15)$	$0.73 \times 10^6 \pm (0.12)$	$0.76 \times 10^5 \pm (0.11)$
BM	$0.56 \times 10^6 \pm (0.09)$	$0.78 \times 10^5 \pm (0.08)$	$0.41 \times 10^6 \pm (0.005)$	$0.43 \times 10^5 \pm (0.04)$
SM	$1.99 \times 10^6 \pm (0.22)$	$1.58 \times 10^5 \pm (0.24)$	$0.83 \times 10^6 \pm (0.33)$	$1.47 \times 10^5 \pm (0.44)$

The values are presented as means, with standard error indicated in parentheses.



yield ($r = -0.824$) and most plant traits, including number of fruits and leaves. Soil organic matter (SOM) was positively associated with yield ($r = 0.593$), as well as with nitrogen ($r = 0.935$), phosphorus ($r = 0.984$), and potassium ($r = 0.986$), which also showed moderate positive correlations with yield (Figure 11).

4 Discussion

4.1 Effect of mulching practices on soil properties, microbial communities and soil nutrient availability

Mulching practices play a crucial role in soil management due to their impact in regulating soil organic matter, fertility, aggregate stability, productivity, and biological activity (Wang et al., 2023). Our results demonstrate that different mulch materials have very different impacts on soil moisture and temperature with black and white plastic being the most effective in conserving soil water and altering heat exchange between the soil and the atmosphere. Organic compost mulch also contributes to moisture retention, although to a lesser extent than the synthetic plastic mulches. Overall, synthetic plastic mulches generally appear to retain more soil moisture than organic mulches due to their less permeable nature, which helps minimize evaporative losses. According to (Emakpor et al., 2025), plastic mulches reduce rapid water loss by minimizing direct exposure to wind and sunlight. In contrast, organic mulches such as compost can increase soil water retention by improving water penetration and decreasing surface runoff; nevertheless, because of their porous nature, they do allow

some evaporation (Li et al., 2024). We conclude that plastic mulch is better at maintaining soil moisture levels in the short term, whereas organic mulches may help preserve soil moisture over the long run by enhancing soil organic matter and structure (Song et al., 2025). In addition to its effect on moisture retention, we show that each mulch type differentially alters soil temperature dynamics. Plastic mulch, especially transparent or black polyethylene, retains heat from the sun and raises the temperature of the soil, which is advantageous for early plant development in colder climates (Emakpor et al., 2025). On the other hand, organic mulch keeps the soil warmer in the winter and cooler in the summer, acting as an insulator and reducing temperature fluctuations (Ma et al., 2024). Plant development, microbiological activity, and overall soil health are all impacted by the combined effects of temperature regulation and moisture conservation under various mulch types, making mulch selection an essential component of agricultural productivity optimization (El-Beltagi et al., 2022a).

This study also demonstrated the importance of mulch type in modulating soil pH. White plastic mulch appears to promote soil alkalization, possibly by reflecting more sunlight, thereby lowering soil temperature and delaying the breakdown of soil organic matter, that would otherwise release acidifying compounds (Kuo et al., 2025). Alternatively, plastic mulch films are also known to contain large amounts of CaCO_3 fillers (ca. 1–5%) that can also increase soil pH. In contrast black plastic mulch films absorb more heat, speeding up the mineralization of organic matter and microbial activity which over time might cause a drop in pH (Muñoz et al., 2022). Despite being beneficial for soil fertility, compost mulch can result in moderate acidification by releasing organic acids during decomposition (Itabana et al., 2024). When high-C materials like wheat straw are employed, their slow breakdown is known to produce organic acids leading to soil acidification (Qiu et al., 2020).

(Quamruzzaman et al., 2024), hypothesized that mulches can affect EC in opposing ways. First, the decomposition of organic mulch releases nutrients into the soil, which can increase soluble salts concentration on the soil surface, resulting in higher EC. Second, the mulch layer can absorb or intercept water-soluble salts, allowing water to reach the soil while minimizing salt buildup, which consequently results in a lower EC (Figure 3). In conclusion, mulch effects on EC are complex, involving mechanisms such as reduced leaching, modified moisture levels, and altered nutrient availability through the breakdown of organic matter. As demonstrated here, the net impact will depend on a range of factors such as mulch type, soil properties, and climatic conditions.

The increase in soil temperature observed with the black polythene mulch treatment can be attributed to the material's ability to absorb and retain heat (Sajjad et al., 2022). Similarly, organic compost mulch can raise temperatures by creating a microenvironment that traps heat. These findings align with those reported by previous studies that have also observed higher soil temperatures under plastic mulch treatment [40] (Zahed et al., 2022). The lower soil temperature in the control treatment may result from the lack of surface cover, leaving the soil directly exposed to ambient environmental conditions. Mulch acts as an insulating layer that reduces heat loss during cooler periods while

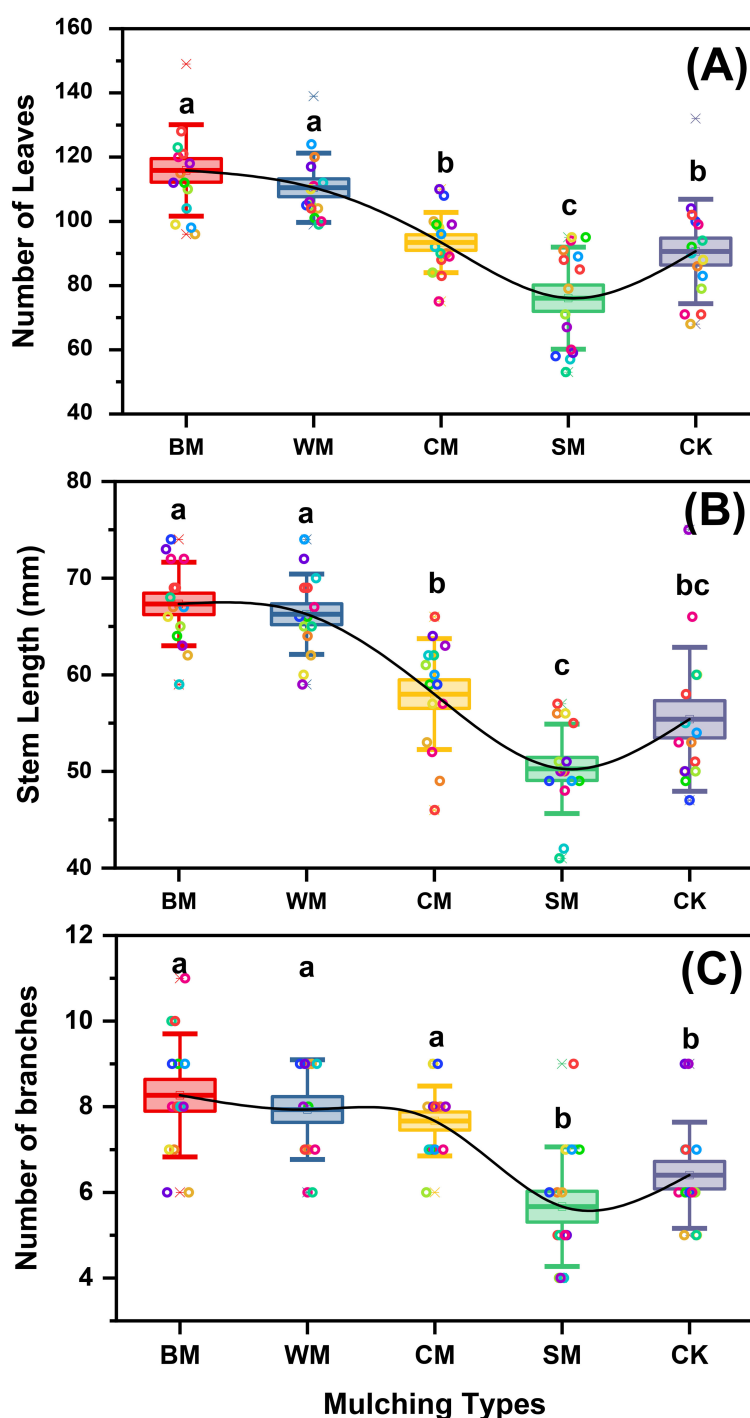


FIGURE 8

Box plots showing the effect of mulch types on eggplant vegetative growth parameters (A) Stem Length; (B) Number of leaves and (C) Number of branches. BM: black plastic mulch, WM: white plastic mulch, CM: compost mulch, SM: wheat straw mulch, CK: no mulch control. Boxes with different lowercase letters indicate significant differences between different mulch treatments ($p \leq 0.05$). Values represent means $\pm$ SEM ($n = 3$).

minimizing heat gain during hotter periods (El-Beltagi et al., 2022a). As a result, early in the cropping season, when the soil temperature is often low, mulching with plastic film increases the temperature of the topsoil. Our findings are consistent with studies in maize which have shown that soil temperature at a depth of

0.10 m is considerably greater in plastic-covered systems than in unmulched counterparts. (Wang et al., 2019; Siedt et al., 2021), (Mak-Mensah et al., 2022) also found that the average soil temperature at a depth of 0.10 m in plastic-film-mulched plots increased by 0.5 to 4.5°C in comparison to the unmulched controls,

TABLE 2 Effect of different mulch types on eggplant flowering parameters: Number of flowers (NF); Number of Knotted fruits (NKF) and Fruit Set (FS).

Treatments	Number of flowers (NF)	Number of Knotted fruits (NKF)	Fruit Set (%) (FS)
BM	33.13 ± 6.07 (a)	14.33 ± 3.37 (a)	43.57 ± 3.11 (a)
WM	30.60 ± 6.29 (a)	10.30 ± 3.67 (b)	39.51 ± 3.28 (b)
CM	23.06 ± 5.06 (b)	8.60 ± 2.19 (c)	35.67 ± 4.09 (c)
SM	18.93 ± 5.06 (b)	7.20 ± 2.59 (d)	33.35 ± 3.03 (c)
CK	22.40 ± 4.98 (b)	7.66 ± 3.01 (d)	34.37 ± 3.20 (c)

Different lowercase letters indicate significant differences between different mulch treatments ($p \leq 0.05$). Values represent means $\pm$ SEM ($n = 3$).

demonstrating the effectiveness of plastic-covered ridges in raising soil temperature during the early growing season when temperatures are low. However, applying agricultural straw mulch typically cools the soil in the spring, which hinders crop establishment since the cool seedbed postpones the emergence of seedlings.

Basic indicators of soil nutrients that impact crop productivity and soil fertility include soil organic matter, total N, available P and K. Applying organic mulch can directly increase the nutrient content in soil (Paul and Mandi, 2024), whereas plastic film mulching may indirectly enhance soil fertility by improving crop growth and development (El-Beltagi et al., 2019), resulting in greater root biomass, rhizodeposition and plant residue inputs (Wang et al., 2022), which in turn may elevate organic matter

and N in the soil. According to Demo et al (Demo and Asefa Bogale, 2024), compost mulch improves soil health and promotes plant growth by improving soil structure and microbial activity and recycling essential nutrients (e.g., N, P and K). By suppressing weeds and inhibiting seed germination, compost mulch also improves soil drainage, aeration, and moisture-holding capacity while reducing competition for resources (Paradelo et al., 2019). Additionally, it can protect against frost during the winter months, regulate soil temperature, and provide insulation. For plants, compost mulch therefore represents a beneficial and nutrient-rich management option (Demo and Asefa Bogale, 2024).

Our findings clearly showed that the variations in the amounts of available P, available K, and mineral N among treatments closely paralleled those in the organic matter (Qu et al., 2019). The enhanced biological activity in the soil is likely responsible for the beneficial shift in nutrient availability brought about by mulching with organic materials. Consequently, the mineralization of organic materials enhances the nutritional content of the soil (El-Beltagi et al., 2022a). The results of this study are consistent with prior research showing that mulch type can have a significant impact on the soil nutrient dynamics (Zhao et al., 2022b). For example, (Wang et al., 2019) discovered that depending on their composition and rates of decomposition, various mulch treatments may result in differing amounts of both macro- and micro-nutrients in soil.

Similar to our results, a study conducted by (Fu et al., 2021) showed that the use of plastic mulch film significantly increased SOM by 34% relative to the unmulched control. This finding also aligns with the results of (Yu et al., 2021), who reported that black plastic film mulching led to a significant increase in soil organic

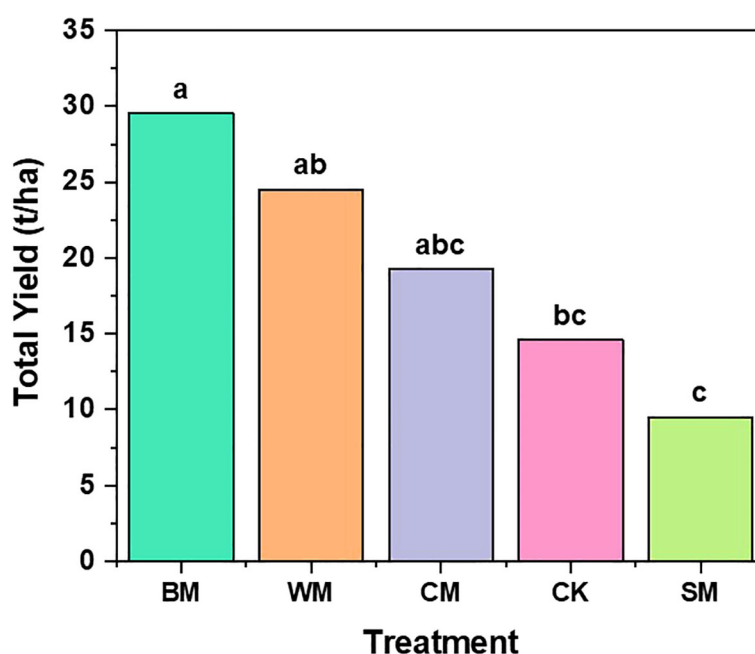


FIGURE 9

Effect of different mulching materials on the yield of eggplant. WM, White polythene mulch; BM, Black polythene mulch; SM, Straw mulch; CM, Compost mulch and CK, un-mulched soil. Boxes with different lowercase letters indicate significant differences between different mulch treatments ($p \leq 0.05$). Values represent means $\pm$ SEM ($n = 3$).

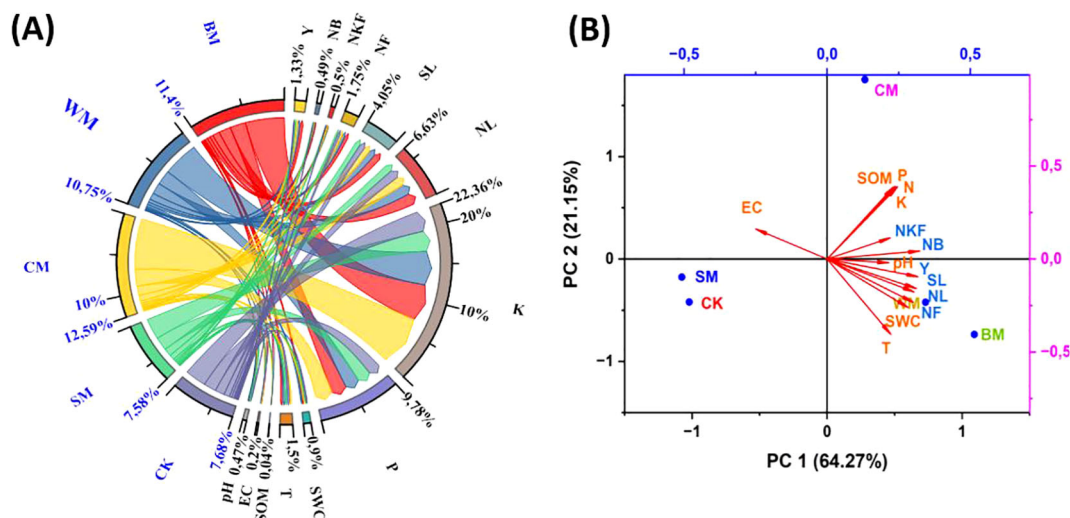


FIGURE 10 (A) Chord diagram showing the effects of the different mulch treatments on these indices. This plot links these treatments via ribbons to their associated indexes. (B) Principal component analysis shows the relationship among eggplant yield, growth parameters, and soil attributes. Stem Length (SL); Number of flowers (NF); Number of leaves (NL); Number of knotted fruits (NKF); Number of branches (NB); Fruit yield (Y); Soil organic matter (SOM); Total N (N); Available P (P); Available K (K); soil pH (pH); Soil temperature (T); Soil water content (SWC) Electrical conductivity (EC).

matter by 0.30 t C ha⁻¹ y⁻¹ in a dry agroecosystem in China. This occurrence is likely due to the biological breakdown of plant remains and the release of nutrients from organic matter within the soil system. Other studies (Daryanto et al., 2017; Zhao et al., 2022a) have also revealed that plastic film mulching promote increases in total soil N, and available P and K. Previous research has also shown that plastic mulch film can promote earthworm movement and enhance soil structure (Brodhagen et al., 2015) as well as increasing the availability of nutrients by lowering the pH of the soil (Yu et al., 2018). The straw mulch treatment resulted in a

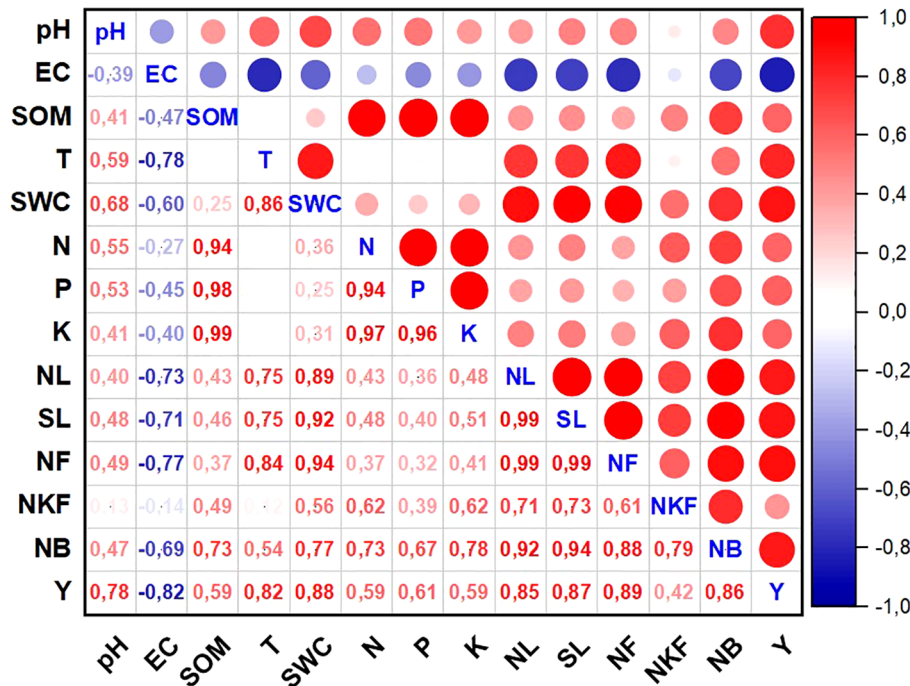


FIGURE 11 Pearson correlation analysis between soil properties and plant parameters. Stem Length (SL); Number of flowers (NF); Number of leaves (NL); Number of knotted fruits (NKF); Number of branches (NB); Fruit yield (Y); Soil organic matter (SOM); Total N (N); Available P (P); Exchangeable K (K); soil pH (pH); Soil temperature (T); Soil water content (SWC) Electrical conductivity (EC).

reduction of soil nutrient and organic matter content, aligning with previous studies. In contrast (Goodman, 2020) demonstrated that straw mulch increases soil structure, nutritional availability, and the populations of beneficial soil organisms by adding organic matter to the soil as the mulch decomposes.

Variations in microbial biomass offer important information on the rate of organic matter breakdown and are extremely sensitive markers of changes in soil nutrient dynamics [64, 65,66]. A rise in microbial biomass generally indicates that the soil is better able to mineralize organic materials, which makes it easier to supply vital nutrients needed for plant development and yield creation (Qian et al., 2021). Soil microorganisms also play an important role in regulating soil quality and nutrient recycling and thus plant development (El-Beltagi et al., 2022a, 2022b). Increased microbial activity in the soil often also results in improved soil structure, aeration and moisture retention, which accelerates microbial decomposition and boosts soil fertility because of the abundance of nutrients that influence plant growth and productivity (El-Beltagi et al., 2019; Wang et al., 2019). Here we showed that each mulch type gave rise to varying effects on the microbial population and activity (El-Beltagi et al., 2020; Ramadan and El-Beltagi, 2021). The straw mulch treatment supported the greatest number of bacteria, mesophilic fungi, and thermophilic fungi, whereas compost and white plastic mulch had the lowest numbers of thermophilic and mesophilic fungi, respectively. This richness was especially noticeable under the straw mulch treatment. In line with our finding, field research conducted in India (Hu et al., 2023), also revealed that soil bacteria, fungi, and actinomycetes grew by 2%, 12%, and 12%, respectively, under mulch treatment as opposed to no mulch conditions. In addition, previous research has also shown that straw mulching can increase soil microbial biomass by 42% (Siedt et al., 2021) and significantly increase microbial biomass in the topsoil (Patton, 2025).

4.2 Effects of mulching practices on soil quality index

Overall, considering all mulch types together, mulching significantly enhanced the Soil Quality index. (Kumar et al., 2024) calculated SQI under various organic and synthetic mulching materials and found that organic compost mulch, cowpea-living mulch and sawdust mulch yielded greater SQI than a no mulch control while black polythene mulch induced lowered the SQI value. In contrast, (Wang et al., 2024a) reported higher SQI under SM treatment compared with no-mulch, which they attributed to increases in soil organic C, total N, available K, and microbial biomass-C in soils mulched with straw. Mulch materials influence soil properties through two primary pathways: directly via their inherent composition and decomposition characteristics, and indirectly by modifying the microclimate at the soil surface, which consequently alters the chemical, biological, and physical processes within the soil profile (Pavlů et al., 2021; Dai et al., 2024). For instance, (Kumar et al., 2024) studied the effects of various mulching materials on soil properties and found significant effects

on macro- and micro-nutrients as well as on pH, temperature and water content. (Muñoz et al., 2022) carried out a comparative study and reported positive effects of plastic mulching on soil physicochemical properties as compared to straw mulching. In our study the plastic mulching systems (black and white) enhanced soil quality in comparison to the no mulch control, which we ascribe to improvements in soil nutrients (N, P and K) as well as soil pH.

4.3 Effects of mulching practices on eggplant growth and performance

The growth and development of crops are influenced by various environmental and edaphic factors (Amare and Desta, 2021). The current findings demonstrate that mulch use, especially the BM treatment, significantly enhanced eggplant growth and yield (Wang et al., 2024b). Our research also indicates that plastic mulch film use increases several growth parameters, including vegetative growth (NL, SL, NB) and flowering parameters (NF, NKF, FS), when compared to the control treatment. Our findings are supported by the work of Davis et al. (Davis and Strik, 2021) and (Yang et al., 2023), who also reported a significant increase in crop yield attributed to the application of synthetic mulches.

Plastic mulches directly influence the microclimate around plants by modifying the radiation budget, reducing soil water loss and suppressing weeds. They enhance crop production by improving fruit quality, increasing gross yield, and promoting earlier production. Stem length indicates the photosynthetic capacity of the plant and its influence on crop growth (Suo et al., 2024). In this study, the black polythene mulch produced the longest stems, followed by the white polythene mulch, suggesting that these materials enhance aerial linear growth. The stem elongation observed with plastic film mulches (BM, WM) can be attributed to their ability to retain heat in the root zone. This retention increases root activity and nutrient uptake, leading to vigorous above-ground growth. In contrast, straw mulch and control treatments resulted in shorter stems, likely due to more frequent fluctuations in soil moisture and temperature.

Applying organic mulch can enhance flower quality by improving the soil's chemical, physical, and biological properties. This improvement can lead to greater availability and absorption of nutrients. As a result, photosynthesis increases, which in turn enhances flowering and the overall quality of the flowers. These findings are consistent with research on tomato by (Mendonça et al., 2021) and pepper by (Valšíková-Frey et al., 2022).

Based on our findings, mulching with the Black plastic film (BM) increased soil temperature which is positively correlated with yield of eggplant (Figure 7B). Additionally, with greater soil temperature, the BM treatment accelerated plant growth and development, which enhanced the accumulation of dry matter by maximizing the plant canopy radiation capture and increasing the photosynthetic rate for assimilate synthesis (Hossain et al., 2024), reported that the use of plastic film produced ideal circumstances for the emergence and early growth of maize (i.e., enhanced soil

temperatures), leading to a 4.9% increase in yield compared to the unmulched control. Similar to the findings of (Ogundare et al., 2016), plastic film covers also resulted in higher eggplant yields. (Abbas et al., 2024) also highlighted the ability of plastic film mulches to create a better microclimate both above- and below-ground which can enhance plant productivity.

Although plastic film mulches can improve plant yields, their effectiveness depends on their color, the average air temperature during the growing season, and the location. For potato plants, when the average air temperature exceeds 20°C, black plastic mulch results in a higher yield compared to white plastic mulch. Conversely, when the temperature is below this threshold, white plastic mulch produces greater yields. The findings revealed that plastic mulches resulted in a 29.2% increase in potato yields compared to bare soil (Li et al., 2018). In the cases of wheat and maize, plastic mulching significantly boosted plant yields, with wheat showing a 20% increase and maize demonstrating a 60% yield enhancement due to plastic mulch application (Campanale et al., 2024). Additionally, the active role of enzymes in facilitating growth and development has also contributed to the increased yields of these plants (Huang et al., 2024; Wang et al., 2024b).

4.4 Integrated analysis of soil properties and plant parameters using PCA, chord diagram and correlation analysis

The PCA biplot maps the relationships between soil and plant data, providing further insight into the relative performance of the different treatments. Improved plant performance and soil health are consistently observed in treatments employing both plastic mulch (BM and WM) and compost mulch, indicating that these treatments have similar underlying beneficial processes. On the biplot, the control treatment (CK) and straw mulch (SM) clearly separated from other treatments, highlighting their comparatively lower performance on soil and plant metrics. The PCA also emphasizes the critical role of soil temperature, soil water content, available nutrients, and organic matter in promoting plant development and production, as these factors are significantly enhanced by the effective mulching treatments (Saber et al., 2024).

The strong positive correlations observed between crop yield and vegetative traits such as number of leaves, stem length, and number of fruits suggest that a well-developed canopy and robust reproductive structures significantly enhance biomass accumulation and yield. This relationship has been documented in several crops, including eggplant (*Solanum melongena*), where shoot vigor and leaf area were positively associated with fruit yield (Miao et al., 2024); pepper (*Capsicum annuum*), where traits such as plant height and number of branches were strong predictors of yield (López-Marín et al., 2013); and tomato (*Solanum lycopersicum*), in which vegetative growth parameters such as stem diameter and number of leaves strongly correlated with fruit production (Mendonça et al., 2021).

The positive correlation between yield and soil water content further supports the idea that proper soil moisture is necessary for plant physiological functions, particularly photosynthesis and nutrient absorption. In line with research showing that moderate heat regimes increase enzymatic activity and growth rates, temperature also shown a substantial positive association with yield (Li et al., 2019a). On the other hand, the inverse relationship between yield and electrical conductivity highlights how salt negatively impacts crop performance. Due to osmotic stress, high EC levels might hinder water intake and disrupt nutrient absorption, which will hinder growth and production (Atta et al., 2023).

Moreover, the strong correlations between soil organic matter (SOM) and essential macronutrients (N, P, K), as well as yield, underline the pivotal role of SOM in sustaining soil fertility. SOM increases microbial activity, cation exchange capacity, soil structure, and water retention, all of which increase nutrient availability (Bashir et al., 2021). According to (Li et al., 2019b), the interrelationships between N, P, and K imply synergistic nutrient interactions, and their correlation with yield suggests that balanced fertilization is essential for maximum production. The results together highlight the necessity of coordinated irrigation and soil fertility management techniques that promote soil health and reduce the dangers associated with salt. Thus, techniques like conservation tillage, regulated irrigation, and organic amendments may be useful instruments to enhance yield sustainability and resilience in a range of agroecological circumstances (Al-Shammary et al., 2024).

5 Conclusions

This study evaluated a contrasting range of mulching materials under semi-arid conditions, revealing their distinct impacts on soil properties and crop performance. Each mulch type demonstrated unique benefits. For example, white plastic mulch increased soil pH while black plastic mulch maintained a higher soil temperature, enhanced soil water content, and produced the highest Soil Quality Index (SQI). In contrast, compost mulch substantially improved soil fertility by increasing organic matter, total N, and available P and K compared to the unamended control, while straw mulch proved to be the best at promoting microbial activity. Among all the treatments evaluated here, black plastic mulch proved to be most effective for enhancing eggplant growth and productivity.

Several limitations should be acknowledged when interpreting these results. This six-month polytunnel experiment, while providing controlled conditions for mechanistic understanding, may not fully represent the complex interactions occurring in open field environments over multiple growing seasons. The study was conducted on a single soil type (Fluvisol) from one geographic location in Tunisia, potentially limiting the generalizability of findings to other soil textures, climatic conditions, and agricultural systems globally. Additionally, the mulching materials were applied using only one method and

timing (20 days after transplantation), and responses may vary significantly with different application strategies, rates, or timing. The exclusive focus on eggplant as the test crop means responses of other vegetables to these mulching treatments remain unknown. The controlled polytunnel environment may also not accurately reflect the temperature fluctuations, precipitation patterns, and pest pressures encountered in open field organic farming systems. Lastly, fruit firmness, colorimetric parameters and a comprehensive metabolomic analysis could be undertaken to gain greater insights into the marketability and nutritional value of the fruit.

Overall, black plastic mulch emerged as the most effective solution for improving soil quality and maximizing eggplant yield, offering a sustainable and economically viable option for organic farming systems. However, organic mulches provided complementary benefits; compost significantly enhanced soil nutrient status while straw mulch promoted microbial diversity, suggesting that strategic combinations of mulching materials might be used to optimize both immediate productivity and long-term soil health. These findings, provide strong evidence for the adoption of plastic mulch films by organic growers in semi-arid regions who wish to simultaneously improve soil quality and crop productivity while enhancing resilience to climate variability, whether in protected environments or open field conditions.

Data availability statement

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

Author contributions

RA: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. KI: Conceptualization, Formal analysis, Supervision, Validation, Writing – original draft, Writing – review & editing. NT: Conceptualization, Methodology, Project administration, Resources, Validation, Visualization, Writing – review & editing. WS: Investigation, Methodology, Writing – review & editing. NB: Methodology, Software, Visualization, Writing – review & editing. HG: Visualization,

Writing – review & editing. FS: Supervision, Validation, Writing – review & editing. DJ: Funding acquisition, Validation, Writing – review & editing. PM: Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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Supplementary Material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fagro.2025.1603762/full#supplementary-material>

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