



Research article

Co-composted biochar amendments modulate soil microclimate and phenology to enhance saffron yield under saline field conditions

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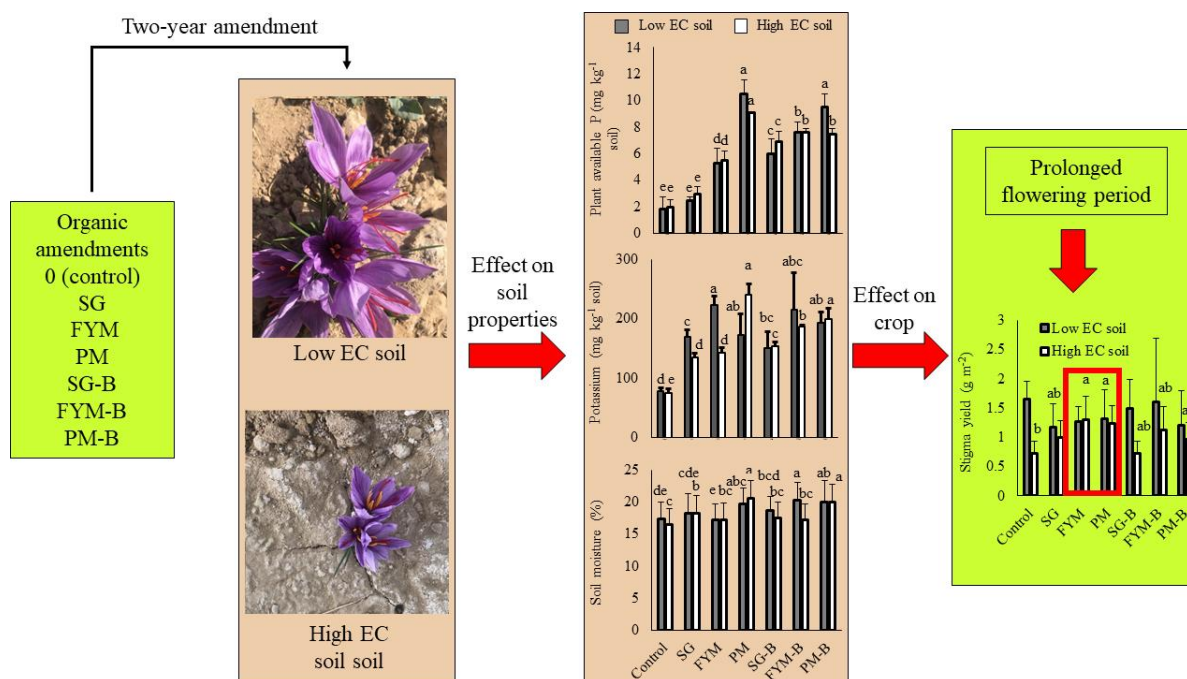
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Abstract: A two-year field study was conducted in soils with low and high electrical conductivity (EC): 0.25 dS m⁻¹, and 1.95 dS m⁻¹ respectively). The high EC soil was transported from agricultural land. Composted manures obtained from sheep/goat (SG), dairy (FYM), and poultry (PM) farms and manures co-composted with biochar made from *Acacia nilotica* L. wood (SG-B, FYM-B, and PM-B) were added to the soil for two consecutive years. The influence of these organic fertilizers on soil properties, flowering period, and fresh yield of saffron (*Crocus sativus* L.) stigma was examined. Analysis of soil collected after the harvest of the second-year crop revealed that organic fertilizers caused a significant two- to fourfold increase in the concentration of potassium and bioavailable phosphorus in both low EC soil and high EC soil. After two years of cropping, the EC of high EC soil dropped to 0.94 to 1.71 dS m⁻¹ under various treatments. In the low EC soil, FYM-B triggered 2–3 days of early flowering in both cropping years. However, this prolonged flowering period did not cause any increase in stigma yield. Furthermore, in this soil, for the first-year crop, all organic fertilizers reduced stigma yield by 41–44% compared with control treatment, whereas no difference among treatments was observed for the second-year crop. The stigma yield in the high EC control soil was significantly lower than in the low EC control soil by 26% and 56% for the first- and second-year crops, respectively. In high EC soil, no difference among treatments was observed in the stigma yield of the first-year crop. However, for the second-year crop in the high EC soil, all organic fertilizers prolonged the flowering period; moreover, the FYM and PM treatments also increased stigma yield by 78% and 70% respectively ($p < 0.05$). In conclusion, organic fertilizers influenced the flowering period of saffron and significantly increased the concentrations of potassium by 79%–218% and phosphorus by 187%–455% in the high and low

EC soils. The PM in the high EC soil was found to be more suitable for stigma yield and soil properties when applied for two years; relative to control, this organic fertilizer caused the highest significant increase in potassium (218%), phosphorus (371%), and soil moisture (24%) during the critical flowering period. This treatment also prolonged the flowering period and the increased yield of stigma (70%) in the second-year crop in the high EC soil.

Keywords: flowering period; composted manures; co-composted biochar; soil moisture; soil nutrients

Graphical abstract



1. Introduction

Saffron (*Crocus sativus* L.) is an expensive spice with medicinal properties. It is used in the textile industry as a dye, and in the pharmaceutical and confectionery industries. The price of saffron stigmas ranges from €1500–2200 kg⁻¹ [1] because it takes approximately 75–100 flowers to produce 225–300 stigmas, which equals only ~0.5 g dry weight [2]. Climatic and edaphic conditions influence the cultivation and yield of saffron stigmas. This medicinal crop grows well in a cold, dry Mediterranean climate and in soils containing high sand fractions (e.g., sandy loam and sandy silt loam) [3]. Temperature controls the initiation of flowering in saffron [4]. A two-year field trial in a sandy loam soil at the University of Rhode Island, United States, showed that 12–28 °C was the optimal temperature for its cultivation [5]. Koocheki et al. [6] found that saffron required less water in clay loam soil under semiarid climatic conditions (mean annual rainfall and temperature: 254.3 mm and 16 °C, respectively). Studies have shown that 600 mm of rainfall during the growing season in sandy loam soil under semiarid climatic conditions was adequate for the cultivation of saffron under a rainfed irrigation system [7]. Soil nutrients also play a significant role in the cultivation of this medicinal crop [8]. Empirical evidence suggests that organic wastes as soil amendments significantly improve the growth

of this crop. For instance, Esmaeilian et al. [9] reported a 15.1%–35.7% increase in saffron flower, leaf, and corm production in response to amendment with animal manure (the source of the manure was not specified) in silty loam soil under the warm arid climate of Khorasan, Iran. Similarly, many studies have demonstrated the positive influence of a mixture of compost and biochar or co-composted biochar as soil amendments on the yield of saffron stigma [10–12]. However, the influence of organic amendments on the stigma yield of this medicinal crop, through influencing soil properties such as temperature, moisture, pH, electrical conductivity (EC), and soil nutrients has not been documented.

The arid agricultural lands of cold-winter Mediterranean regions generally have a high sand content and therefore are suitable for the cultivation of saffron [3,13]. However, salinity and drought are two important limiting factors for agriculture in these arid regions, leaving large areas as abandoned uncultivated lands. Nevertheless, proper management practices can overcome this problem and enable the cultivation of saffron in these soils. One of the proposed management practices to attenuate saline stress on crops is the use of organic fertilizers (e.g., manure and compost). Organic amendments reduced salinity-related stress on saffron, improved the properties of silty clay loam soil, and positively influenced yield under the semiarid climatic conditions of Badjgah, Iran [14]. Pyrogenous organic waste, known as biochar, when applied to the soil as a mixture with manure or as a co-compost with other organic wastes (e.g., manures) has been reported for its positive influence on the quality of low fertile saline soils [15–18]. Gul and Whalen [19], in their meta-analysis, reported that the availability of nutrients in biochar declines with the production temperature, and that biochar may not be a good source of nutrients if it is produced from wood and at high production temperature. However, its positive influence in low fertile soils can be achieved if it is applied with other organic wastes (e.g., manures, compost, and crop residues [19]). Furthermore, the co-composting of biochar with other organic wastes is proposed to be more favorable for low-fertility saline soils than when biochar or compost is applied separately [18]. El-Mageed et al. [20] reported that under water-stressed arid climatic field conditions, two years of amendment of co-composted biochar at a rate of 10 t ha⁻¹ (biochar produced from poultry manure and composted with soil, geranium waste, and mature compost) significantly increased the water-holding capacity, nitrogen and phosphorus contents, and microbial abundance of soil and also significantly increased the growth performance (relative chlorophyll content, stomatal conductance, and photosynthetic efficiency) and yield of eggplant (*Solanum melongena* L.). In another three-year field study, conducted in Darbaa, Nwabiagya District, Ashanti, Ghana, with a semiarid climate, Agbeshie et al. [21] found a significant increase in the concentrations of ammonium, nitrate, potassium, phosphorus, and magnesium and a reduction in the bulk density of soil amended with co-composted biochar compared with compost or biochar as the sole amendments (biochar and compost produced from aquatic *Arthropteris orientalis* (J.F.Gmel.) Posth. fern). These studies suggest that the positive influence of biochar on soil properties and crop growth performance is achieved at a greater scale when it is co-amended with other organic wastes such as co-composted biochar or biochar–compost mixtures. Furthermore, biochar-based organic fertilizers increase soil moisture and temperature besides being sources of nutrients for crops [22,23]. The increase in soil temperature and moisture in response to the amendment of organic fertilizers has also been found to have a positive influence on crop yield [24]. Early and prolonged flowering in response to an increased soil temperature and moisture, resulting from the amendment of biochar-based organic fertilizers in the soil, may result in a high stigma yield in this crop.

Balochistan is the largest province in Pakistan, covering approximately 44% of the country's total land area. Approximately 50% of the land area of this province has a cold Mediterranean climate (e.g., the districts of Pishin, Quetta, Muslim Bagh, Kila Abdullah, and Zhob). The soils in these regions mostly have a sandy to sandy loam texture. These factors (a cold Mediterranean climate and coarse-textured soil) favor

the growth of saffron. However, salinity (or high EC conditions) and drought are limiting factors for the growth of this economically important crop in many areas of these regions (see [25,26]). Currently, saffron cultivation is practiced in the Mastung and Quetta districts of Balochistan on a trial basis. It is important to know if composted manure or those co-composted with wood-derived biochar reduces high EC stress in saffron.

Organic wastes, such as the broken leftover pieces of wood-derived biochar, which is available in the timber markets of Balochistan and manures from various farms, can be utilized as organic fertilizers in the agricultural lands of Balochistan. The utilization of these wastes in agricultural lands can not only help improve the soil quality for better crop production, but it can also attenuate the pollution which is caused by the improper disposal of these bioresources. *Acacia nilotica* L. is a wild tree found in the warm arid regions of Balochistan. The wood of this tree is used for biochar production for barbecuing and it is distributed all over the country. The biochar residues are inexpensive (less than US\$0.5 kg⁻¹). Likewise, manure from sheep, goat, cow, buffalo, and poultry farms are purchased as fertilizers for agriculture. However, large amounts of these biowastes (broken leftover pieces of biochar and manure) are not utilized and can potentially cause air and water pollution. The rationale of using these biowastes, such as composts and for co-composting with biochar, can greatly help reduce pollution due to their improper utilization. The objectives of this study were to investigate the influence of composts made from sheep and goat (SG), cow and buffalo (FYM), and poultry (PM) manure feedstocks and co-composts of these manures with the biochar from *Acacia nilotica* feedstock, produced through slow pyrolysis (SG-B, FYM-B, and PM-B) on the moisture, temperature, and nutrients of the soil, as well as the flowering period and fresh stigma yield of saffron. Furthermore, this study aimed to investigate which organic fertilizer was the most suitable for the production of saffron stigma in high EC soil by improving the edaphic conditions. The hypotheses of this study were: (1) Composted manure and co-composted biochar fertilizers positively influence (increase) soil moisture and soil temperature during the flowering period of saffron and also increase soil nutrients; and (2) organic fertilizers with high nutrient concentrations also exert the most positive influence on soil properties and the stigma yield of saffron. To date, no information is available regarding the influence of composted manures and co-composted biochars as soil amendments on soil properties such as moisture, temperature, and nutrients and the stigma yield of saffron. Furthermore, no empirical evidence documents the relationship between the flowering period and the rise in soil temperature and moisture (caused by amendments with organic fertilizers), which may, in turn, influence the yield of saffron stigma.

2. Materials and methods

2.1. Study site

This experiment was conducted in the research field at Balochistan Agricultural Research and Development Centre (BARDC), Quetta (30°11'39"N 66°57'20"E) for two consecutive years (the first growing season was from September 2020 to April 2021 and the second growing season was from September 2021 to April 2022). Quetta has a cold-winter Mediterranean climate with cold rainy winters, and warm dry summers. Snowfall also occurs during winter and the temperature drops down below -15 °C in January. The cumulative annual rainfall was less than 250 mm during this experiment [25,26]. In this experiment, high EC soil (EC_{1:2}; 1.95 dS m⁻¹) was transported from an agricultural farm in Mulkiyar, Pishin District, Balochistan, Pakistan. Nonsaline soil was not transported and had not been previously cultivated. Both soils were Haplic Yermosol (Brown Chernozem) calcareous silt loams. The chemical and physical properties of these soils is reported in our published manuscripts [25,26].

2.2. Composted manures and co-composted biochar

A detailed description of the composted manures and co-composted biochar is provided in our earlier studies [25,26]. The manures used for making compost for this study were from small ruminants (SG), dairy cows (FYM), and poultry (PM). The wood of *Acacia nilotica* was used to produce biochar through slow pyrolysis at 400–450 °C in underground kilns. This biochar was purchased from the market. All manures were air-dried before composting. The production of co-composted biochar is reported in our previous articles [25,26]. Briefly, all three types of manures were separately mixed with biochar in a 1:1 ratio [24,27]. These manures and their mixtures with biochar were separately placed in plastic containers 200 L in capacity. Thereafter, the manures and biochar–manure mixtures were completely submerged in water. These containers were kept open on a balcony for 6 months (from January to June) to allow the aerobic decomposition of these organic fertilizers. Water was added to the containers every week with thorough mixing of the organic fertilizers. The properties of the compost and co-composted biochar fertilizers used in this study are provided in [25,26].

2.3. Experimental layout

The experiment layout of this study was described in [25,26]. In brief, the high EC soil was surface-applied at a thickness of 25.4 cm before the establishment of the plots. The experiment was conducted in a randomized complete block design (RCBD) with three replications for each treatment (Figure 1). The treatments were a control (no organic fertilizer added to the soil) and amendments with composted SG manure, composted FYM manure, composted PM manure, and biochar co-composted with SG (SG-B), FYM (FYM-B), and PM (PM-B). In total, 21 plots in low EC soil and 21 plots in high EC soil ($n = 42$) were established. Each plot was 1 × 1 m in size. To avoid edge effects, a buffer of approximately ~0.25 m size was made between the plots (Figure 1). Organic fertilizers were added to the plots in the month of August 2020 and August 2021 1 week before sowing of the corms. Fertilizers were surface-applied followed by mixing in the soil to up to 25.4 cm depth. In the first cropping year, 15 t ha⁻¹ of each organic fertilizer was added to the plots, and 50 t ha⁻¹ was added in the second cropping year. In each plot, the same type of organic fertilizer was added to the soil for the first-year and second-year crops.

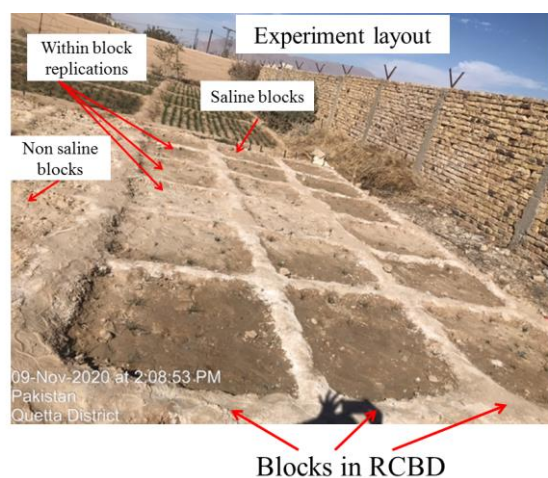


Figure 1. Experimental layout. The size of each plot was 1 × 1 m with a buffer between each plot. The plots were not open to each other to prevent the horizontal movement of irrigation water.

2.4. Cultivation, and phenological and morphological traits assessment of saffron

The details of the corms and their cultivation are reported in [25,26]. Briefly, in each plot, four rows were established as shallow ditches. Within each row, four corms were placed at a spacing of 25 cm at a depth of ~10–12 cm (4–6 inches) in the soil. Plots were irrigated immediately after sowing of the corms and were irrigated one or two times per week for the rest of the early vegetative and flowering stages. Corms germinated in September, and flowering was initiated after 15 October. Flowers were collected daily in the morning (between 8:00 and 9:30). The number of blooming flowers was recorded daily, followed by hand-picking. After harvesting, the flowers were immediately transported to the laboratory. The number and weight of the stigmas and stamens were recorded. Stigma length was measured from three randomly selected flowers from each plot. After the completion of vegetative growth (the end of March), three plants from each plot were randomly selected, and the number and length of the leaves were recorded. Subsequently, leaves taken from the entire plot were dried at room temperature for 2 weeks and oven-dried at 40 °C for 48 h. The dry biomass of the leaves was then measured.

2.5. Moisture, temperature, and chemical properties of the soil

During the flowering period of saffron, soil moisture was recorded weekly on 19 and 20 October 2020; 2, 9, 16, and 23 November 2020; 13, 20, and 27 September 2021; 4, 11, 18, and 25 October 2021; and 1 and 8 November 2021. A digital moisture analyzer (Extech MO750, Extech Instruments A Flir Company) was used for soil moisture analysis. The soil temperature was recorded on 22 October 2020, 8 October 2021, and 1 and 8 November 2021 using a manual soil thermometer (NHBS Soil Thermometer).

The sampling, processing, and analysis of soil samples is reported in our previously published article [26]. Briefly, soil samples were collected from a depth of 0–10 cm in each plot after two years of cropping and harvesting of the leaves in April 2022. Soil samples were collected using a soil corer 10 cm in diameter and 5 cm in height. After collection, the soil samples were brought to the laboratory for air-drying. The air-dried soil samples were crushed and passed through a 2-mm mesh sieve. A soil–water solution with a 1:2 w/v soil:water ratio was used for the pH and EC analyses [28]. Soil samples were extracted with ammonium bicarbonate–diethylenetriaminepentaacetic acid (DTPA) for potassium (K), nitrogen (N), and Olsen phosphorus (P) analyses [29]. Water-soluble sodium (Na) was extracted by shaking a soil–water mixture, followed by passing the sample through Whatman filter paper (Grade 42) [29]. The concentrations of K and Na were determined using a flame photometer (JENVAY PFP7), whereas N and P were quantified with a UV–visible spectrophotometer (JENVAY 6100).

2.6. Statistical analysis

The data were analyzed for normality (the D'Agostino–Pearson K^2 test). Analysis of variance (ANOVA) followed by the least significant difference (LSD) test were applied to the datasets to measure differences between treatment means for a given variable. For soil chemical analyses, two-way ANOVA was applied, where the two factors were organic fertilizers and the soil (low EC soil and high EC soil). Pearson's correlation analysis was performed on the datasets to determine the relationship between soil moisture and the yield of saffron stigma. CoSTAT and Microsoft Excel (Windows 10) were used for statistical analyses and making graphs. The graphs were further arranged in PowerPoint

slides (Windows 10) and their tiff images are presented here. As the results for soil temperature data were not significant, we did not perform a correlation analysis between soil temperature and stigma yield.

3. Results

3.1. Moisture and temperature of the soil

The amendment of fertilizers significantly influenced soil moisture (%) but not soil temperature in both soil types (Figures 2 and 3). However, the results for soil moisture were not consistent across space (soil type and fertilizer treatment) and time (year of cropping). For instance, in the low EC soil in the first year of cropping, the amendment with PM+B (co-composted biochar with poultry manure) increased soil moisture relative to the control and PM (composted poultry manure) treatments ($p < 0.05$; Figure 2). For the second-year crop in the low EC soil, FYM-B (co-composted biochar with cow and buffalo manure) and PM-B significantly increased soil moisture relative to the control, SG (composted goat and sheep manure), and FYM (composted cow and buffalo manure) ($p < 0.05$; Figure 2).

As observed for low EC soil, organic amendments did not change the soil temperature in both cropping years in high EC soil (Figure 3). Regarding soil moisture, the results were not the same as those observed for the low EC soil. The PM and PM-B treatments significantly increased soil moisture compared with FYM-B in the first cropping year (Figure 2; $p < 0.05$). In the second cropping year, relative to the control treatment, significant increases in soil moisture were observed for SG, PM, and PM-B amendments (Figure 2; $p < 0.05$). The PM and PM-B treatments increased the soil moisture by approximately 10%–20% relative to the control (Figure 2; $p < 0.05$). The raw data of soil moisture and soil temperature are provided in Supplementary Tables S1–S4.

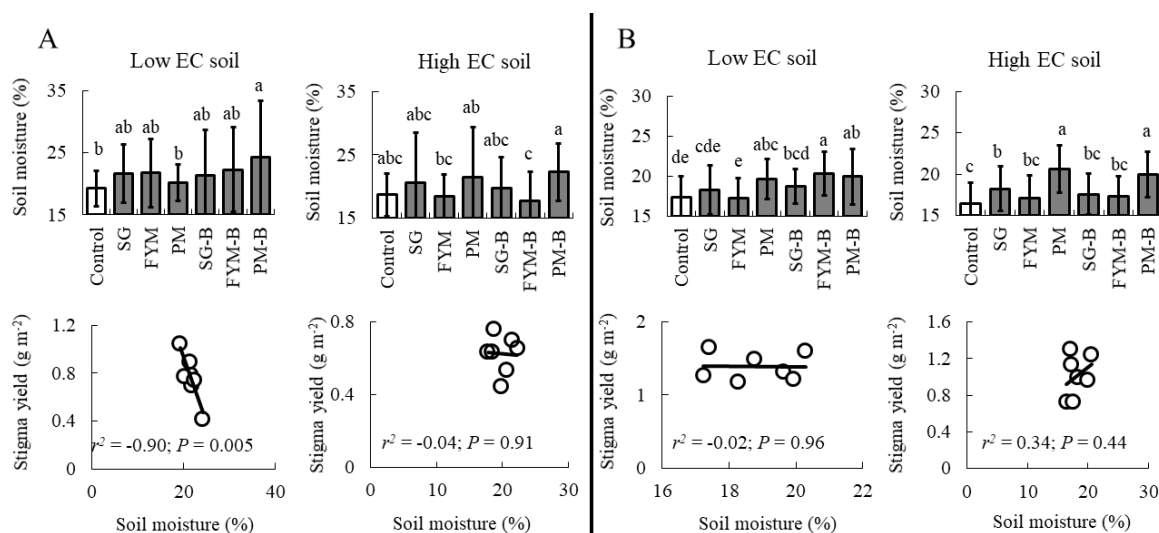


Figure 2. Moisture (%) (average \pm standard deviation (SD) of the entire sampling period) of nonsaline soil and saline soil under various treatments, and correlation between soil moisture and the fresh yield of saffron stigma (g m^{-2}) of the first-year (A) and second-year (B) crops (mean \pm SD). Bars with different letters are significantly different ($p < 0.05$). SG, composted sheep and goat manure; FYM, composted cow and buffalo manure; PM, composted poultry manure; SG-B, biochar co-composted with goat and sheep manure; FYM-B, biochar co-composted with cow and buffalo manure; PM-B, biochar co-composted with poultry manure.

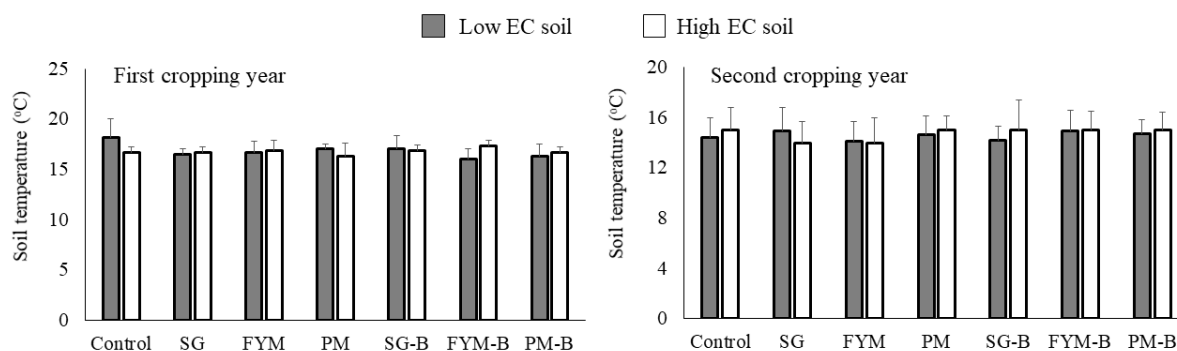


Figure 3. Temperature (°C) (Average \pm SD of the entire sampling period) of the low EC soil and high EC soil under various treatments. SG, composted goat and sheep manure; FYM, composted cow and buffalo manure; PM, composted poultry manure; SG-B, biochar co-composted with goat and sheep manure; FYM-B, biochar co-composted with cow and buffalo manure; PM-B, biochar co-composted with poultry manure.

3.2. Chemical properties of the soil

The chemical properties of the low and high EC soils after two cropping years are presented in our previously published reports [25,26]. The raw data on the soil properties are provided in Supplementary Tables S5 and S6. Two years of amendment with these organic fertilizers did not change the pH of low EC or high EC soils. In both the low EC soil and the high EC soil, organic fertilizers significantly increased the concentration of potassium compared with the control treatment ($p < 0.05$; Figure 4). Moreover, in the low EC soil, no difference among composted manures and those co-composted with biochar was observed (Figure 4). In the high EC soil, co-composted biochar fertilizers significantly enhanced potassium concentrations compared with the corresponding composted manures (SG-B versus SG, FYM-B versus FYM, and PM-B versus PM; $p < 0.05$; Figure 4). No difference among treatments was observed regarding sodium and mineral nitrogen contents in the low EC soil. In the high EC soil, the SG-B treatment increased the sodium contents significantly compared with the SG treatment. Except for the SG and FYM treatments, all other treatments significantly increased mineral nitrogen in the soil relative to the control, and the FYM-B treatment increased mineral nitrogen compared with the FYM treatment ($p < 0.05$; Figure 4). Except for SG, all other organic amendments increased the concentration of Olsen P compared with the control in both the low EC and high EC soils ($p < 0.05$; Figure 4). Moreover, compared with the composted manures, those co-composted with biochar (except for PM and PM-B in the low EC soil) also significantly increased the phosphorus contents in the low EC and in high EC soils ($p < 0.05$; Figure 4).

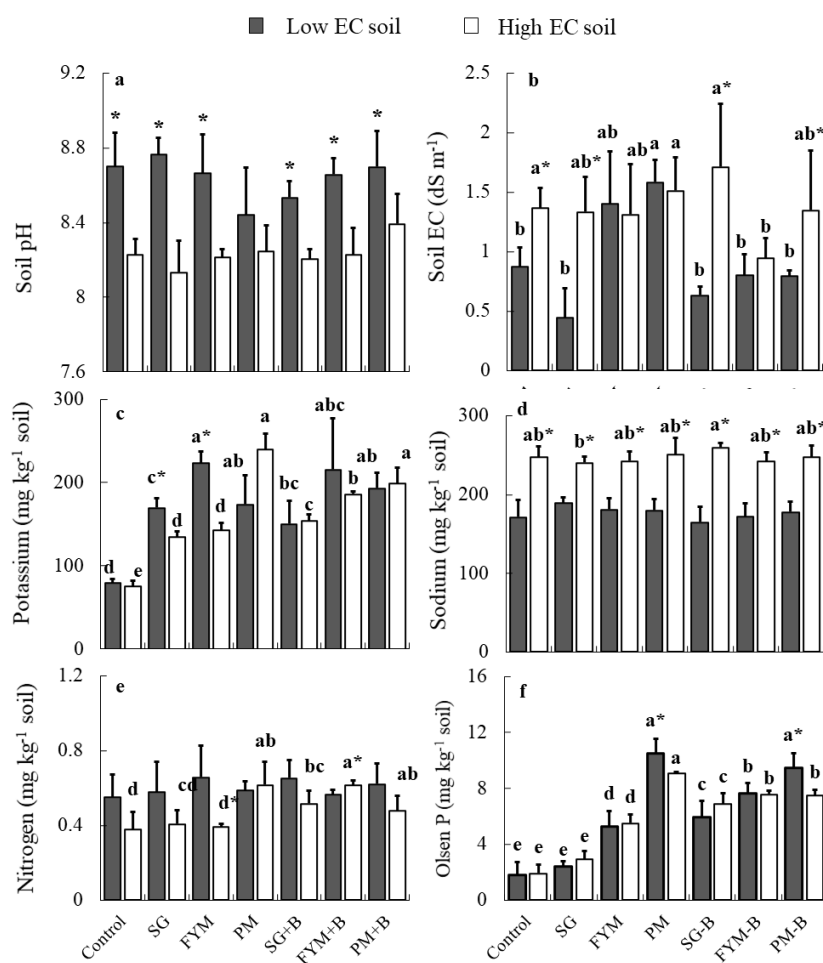


Figure 4. Soil properties, pH (a), electrical conductivity (EC) (b), potassium (c), sodium (d), mineral nitrogen (e), and Olsen P (f) for the interaction between organic fertilizer (control, SG, FYM, PM, SG+B, FYM+B, and PM+B) and soil type (low EC soil and high EC soil) (mean \pm SD). Within soil type (nonsaline or saline), bars with different letters show significant differences among various treatments ($p < 0.05$). In contrast, bars with * indicate differences among soil types for a given treatment ($p < 0.05$). Bars with no letters (results for soil nitrogen) indicate no difference among treatments. SG, composted goat and sheep manure; FYM, composted cow and buffalo manure; PM, composted poultry manure; SG-B, biochar co-composted with goat and sheep manure; FYM, biochar co-composted with cow and buffalo manure; PM-B, biochar co-composted with poultry manure.

3.3. The flowering period of saffron

For first-year crop, flower initiation was observed on 28 October 2020, with the flowering period lasting 19 days, and it ended on 23 November 2020. For the second-year crop, flower emergence started on 20 October 2021, continued for 18 days, and ended on 12 November 2021. The raw data on the flowering period of saffron are provided in Supplementary Table S7. In the low EC soil, the flowering of the first-year crop began 3–4 days earlier under the FYM-B (biochar co-composted with cow and buffalo manure) and SG-B (biochar co-composted with goat and sheep manure) soil amendments, whereas, early flowering for the second-year crop was observed only in FYM-B-amended soil ($p < 0.05$; Figure 5). In the high EC soil, prolonged flowering of saffron was observed

under the FYM (composted cow and buffalo manure), PM (composted poultry manure), SG-B, and FYM-B treatments for the first-year crop and under all fertilizer-amended treatments compared with the control for the second-year crop ($p < 0.05$; Figure 5).

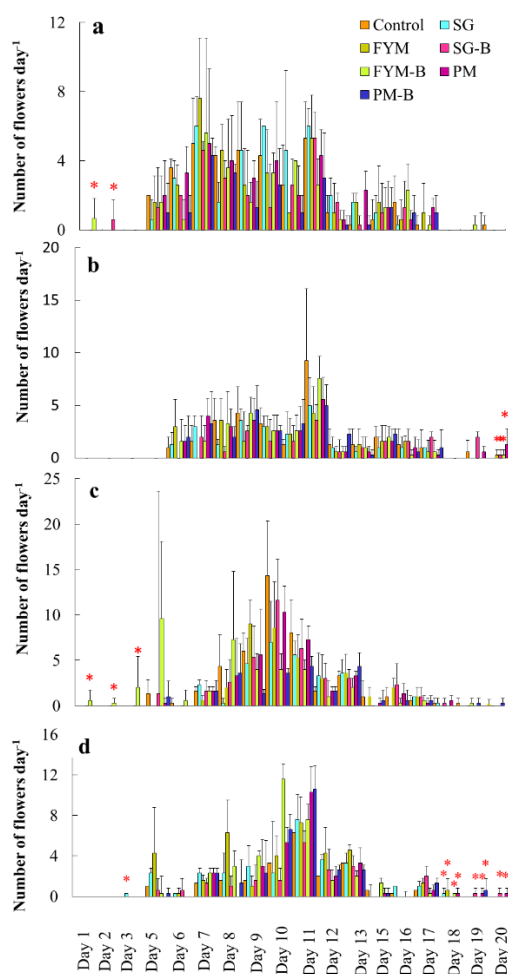


Figure 5. Phenological traits of saffron during two growing seasons. The bars are the mean (\pm SD). * indicates a significant difference of an organic fertilizer treatment relative to the control treatment ($p < 0.05$). (a) First-year crop in the low EC soil; (b) first-year crop in the high EC soil; (c) second-year crop in the low EC soil; (d) second-year crop in the high EC soil. SG, composted goat and sheep manure; FYM, composted of cow and buffalo manure; PM, composted poultry manure; SG-B, biochar co-composted with goat and sheep manure; FYM, biochar co-composted with cow and buffalo manure; PM-B, biochar co-composted with poultry manure.

3.4. Yield of stigma

The results on the fresh yield of stigma of saffron of this study are reported in our previously published manuscripts [25,26]. Raw data on the fresh yield of saffron are provided in Supplementary Table S8. For the first-year crop grown in the low EC soil, all organic amendments significantly reduced the fresh yield of stigma; furthermore, PM-B significantly reduced the stigma yield compared with the other fertilizers ($p < 0.05$; Table 1). No difference among treatments was observed regarding

fresh yield of stigma of the second-year crop in the low EC soil. In the high EC soil, no significant difference among treatments was observed for the first-year crop (Table 1). For the second-year crop in the high EC soil, FYM and PM significantly increased yield compared with the control treatment ($p < 0.05$; Table 1). Furthermore, no difference in yield among organic fertilizer treatments was observed (Table 1).

Correlation analysis revealed a significant negative influence of soil moisture on the fresh yield of saffron stigmas ($r^2 = -0.90$; $p < 0.005$; Figure 2) in the low EC soil of the first-year crop only. Furthermore, no correlation between soil moisture and stigma yield was found for the second-year crop in both soil types and in the high EC soil for the first-year crop.

3.5. Yield of stamens and dry biomass of leaves

In the low EC soil, amendment with SG significantly increased the fresh weight of stamens compared with the control for the first-year crop. However, the opposite results were observed for the second-year crop ($p < 0.05$; Table 1). No difference among treatments was observed for the first-year crop grown in the high EC soil, whereas the FYM amendment significantly increased the stamen fresh weight for the second-year crop compared with the control treatment ($p < 0.05$, Table 1). The FYM-B treatment significantly increased the dry biomass of leaves compared with the control in the low EC soil ($p < 0.05$; Table 1). No differences among treatments were observed for the dry biomass of leaves in the high EC soil (Table 1) (raw data on the length of stigma are provided in Supplementary Table S9).

Table 1. Mean (\pm SD) of stigma and fresh stamen yield, stigma length, leaf length, leaf number, and leaf dry biomass of the two sampling years.

Treatment	Yield (g m^{-2}) of stigma in nonsaline soil		Yield (g m^{-2}) of stigma in saline soil		Yield (g m^{-2}) of stamen in nonsaline soil		Yield (g m^{-2}) of stamen in saline soil		Stigma length (cm) in nonsaline soil		Stigma length (cm) in saline soil		Leaf length (cm) in nonsaline soil	Leaf length (cm) in saline soil	No. of leaves in nonsaline soil	No. of leaves in saline soil	Leaf dry biomass (g m^{-2}) in nonsaline soil	Leaf dry biomass (g m^{-2}) in saline soil
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2021	2021	2020	2020	2022	2022
Control	1.04 \pm 0.22 ^a	1.65 \pm 0.3	0.76 \pm 0.3	0.73 \pm 0.2 ^b	0.05 \pm 0.08 ^b	0.08 \pm 0.11 ^a	0.06 \pm 0.09	0.04 \pm 0.07 ^b	2.1 \pm 0.26	3.2 \pm 0.42	2.1 \pm 0.17	2.3 \pm 0.34	31 \pm 7.87	29.8 \pm 3.01	35.1 \pm 19.5	26.2 \pm 10.2	15.9 \pm 3.4 ^{ab}	13.9 \pm 2.9
SG	0.80 \pm 0.1 ^b	1.18 \pm 0.4	0.5 \pm 0.06	0.99 \pm 0.3 ^{ab}	0.06 \pm 0.1 ^a	0.05 \pm 0.08 ^b	0.04 \pm 0.06	0.06 \pm 0.09 ^{ab}	2.03 \pm 0.16	2.7 \pm 0.45	1.8 \pm 0.30	2.1 \pm 0.56	25.11 \pm 5.73	29.3 \pm 6.78	31.5 \pm 14.1	30.4 \pm 12.4	11.9 \pm 2.5 ^b	12.9 \pm 2.4
FYM	0.7 \pm 0.1 ^b	1.27 \pm 0.25	0.6 \pm 0.3	1.3 \pm 0.4 ^a	0.06 \pm 0.09 ^{ab}	0.07 \pm 0.13 ^{ab}	0.03 \pm 0.05	0.07 \pm 0.10 ^a	2.3 \pm 0.25	3 \pm 0.30	2.1 \pm 0.38	2.3 \pm 0.36	25 \pm 6.67	31.4 \pm 4.8	26.4 \pm 12.2	23.7 \pm 11.3	18.7 \pm 6.1 ^{ab}	17.4 \pm 4.2
PM	0.77 \pm 0.1 ^b	1.32 \pm 0.5	0.7 \pm 0.2	1.24 \pm 0.3 ^a	0.06 \pm 0.09 ^{ab}	0.07 \pm 0.13 ^{ab}	0.04 \pm 0.06	0.06 \pm 0.10 ^{ab}	2.2 \pm 0.32	2.4 \pm 0.27	2.2 \pm 0.21	2.5 \pm 0.40	27 \pm 5.54	30.3 \pm 5.85	27.6 \pm 8.6	37.2 \pm 19.7	18.3 \pm 5.6 ^{ab}	13.8 \pm 2.7
SG-B	0.89 \pm 0.4 ^b	1.49 \pm 0.5	0.44 \pm 0.1	0.73 \pm 0.2 ^{ab}	0.04 \pm 0.07 ^{ab}	0.08 \pm 0.15 ^{ab}	0.03 \pm 0.04	0.05 \pm 0.1 ^{ab}	2.1 \pm 0.15	3 \pm 0.25	2.04 \pm 0.43	2.2 \pm 0.40	28 \pm 4.82	25.5 \pm 2.87	23.8 \pm 9.1	23.5 \pm 9.3	17.6 \pm 5.2 ^{ab}	12.8 \pm 3.6
FYM-B	0.74 \pm 0.07 ^b	1.6 \pm 1.1	0.64 \pm 0.2	1.13 \pm 0.4 ^{ab}	0.04 \pm 0.06 ^b	0.07 \pm 0.12 ^{ab}	0.04 \pm 0.07	0.08 \pm 0.13 ^{ab}	2.1 \pm 0.35	3.04 \pm 0.26	2.06 \pm 0.37	2.2 \pm 0.3	28 \pm 4.68	29.1 \pm 5.94	26.1 \pm 10.03	31.6 \pm 16.0	17.01 \pm 3.4 ^a	13.3 \pm 1.9
PM-B	0.42 \pm 1.1 ^c	1.2 \pm 0.6	0.65 \pm 0.1	0.96 \pm 0.3 ^{ab}	0.03 \pm 0.05 ^b	0.04 \pm 0.06 ^b	0.05 \pm 0.08	0.06 \pm 0.1 ^{ab}	2.1 \pm 0.38	2.7 \pm 0.18	2.2 \pm 0.18	2.3 \pm 0.21	29.7 \pm 5.28	31 \pm 3.96	34.1 \pm 16.0	31.3 \pm 14.7	15.7 \pm 0.8 ^{ab}	12.6 \pm 3.7

Within column, values with different uppercase letters are significantly different at $p < 0.05$. Within columns, values with no uppercase letters indicate no difference among treatments. SG, composted goat and sheep manure; FYM, composted cow and buffalo manure; PM, composted poultry manure; SG-B, biochar co-composted with goat and sheep manure; FYM-B, biochar co-composted with cow and buffalo manure; PM-B, biochar co-composted with poultry manure. Note: The data on the yield of stigma is published in our previous paper [25].

4. Discussion

4.1. Soil moisture and temperature

Variable results were observed for soil moisture in response to organic amendments for both cropping years and soil types. In the low EC soil in the first year of cropping, the PM+B fertilizer significantly increased soil moisture by ~17.5% compared with the control and PM. For the second-year crop in the low EC soil, FYM-B and PM-B significantly increased soil moisture by 7%–14% compared with the control, SG, and FYM. This result suggests that FYM-B improved soil moisture more than when this organic fertilizer was applied as composted manure. In the high EC soil, the results for soil moisture were not the same as those observed for the low EC soil. PM and PM-B significantly increased soil moisture compared with FYM-B in the first cropping year. In the second cropping year, relative to the control, the PM and PM-B treatments increased soil moisture by approximately 10%–20%.

In our study, nonsignificant results for most of the treatments for the first-year crop appeared for fresh amendments (4–5 weeks before leaf emergence), which might not allow these fertilizers to be well-mixed with the soil minerals. Wang et al. [30] reported an approximately 10–12.49% increase in soil moisture and an approximately 2%–3.4% increase in soil temperature under semiarid climatic conditions, in response to the amendment of slow-pyrolyzed maize straw-derived biochar in loamy soil (38% sand, 9.6% clay). Obia et al. [31] reported an increase in soil moisture and temperature in response to amendment with slow-pyrolyzed biochar produced from *Cajanus cajan* (L.) Huth. (pigeonpea) in sandy loam soil. Although Obia et al. [31] reported a significant increase in soil moisture and temperature, they amended the soil with biochar for one year in the field under tropical climatic conditions (moist and warm). Under these climatic conditions, a one-year period may have facilitated the occlusion of biochar-based organic fertilizers with soil mineral particles, thereby promoting soil aggregation. Well-occluded soils retain moisture [32]. The soils in our study (both the low EC soil and the high EC soil) were sandy loams. The low clay content of these soils, combined with the fresh amendment of organic fertilizers (applied concurrently with corn sowing), likely contributed to the lack of observed increases in soil moisture and temperature during the first year of cropping. Improvements in soil moisture were recorded during the second year of cropping. These effects were associated with the higher application rates of organic fertilizers in the second year (50 t ha⁻¹ compared with 15 t ha⁻¹ in the first year). Specifically, for soil moisture, notable effects were observed in the low EC soil amended with PM, FYM-B, and PM-B and in saline soil amended with SG, PM, and PM-B. The one-year interval since the initial amendment, combined with the increased application rates in the second year, likely enhanced the soil organic matter content. This increase in organic matter is a plausible explanation for the observed improvements in soil moisture. Although many authors have reported an increase in the soil temperature in response to biochar-based organic amendments [30,31]; however, compared with soil moisture, these increases were moderate. Xiong et al. [33] even found a decrease in soil temperature when wheat straw biochar was applied to the soil. In our study, we observed no effect of organic amendments on soil temperature. Using a manual thermometer to assess soil temperature is a painstaking task and special care was taken (cleaning of the bulb and placing the thermometer in soil until the movement of mercury stopped changing) in collecting soil temperature data from the field plots. However, the lack of a change in soil temperature may be because only one sample was taken in 2020 and three samples were taken in 2021; moreover, we used a manual thermometer. This could also be the reason why we did not observe any change in soil temperature.

4.2. Chemical properties of the soil

In both the low EC soil and high EC soil, organic fertilizers increased the concentration of potassium by two- to threefold compared with the control treatment. Although no difference between composted manures and their equivalents co-composted with biochar was observed in the low EC soil, co-composted biochar amendments significantly enhanced the potassium contents of soil relative to the composted manures (SG-B versus SG, FYM-B versus FYM, and PM-B versus PM) in the high EC soil. Our findings for the high EC soil align with those of Qayyum et al. [34], who observed a significant increase in the soil potassium concentration following the application of peat-derived biochar co-composted with farmyard manure at a rate of approximately 10 t ha^{-1} .

There was no difference among treatments regarding the concentration of mineral nitrogen in the low EC soil. However, in the high EC soil, except for the SG and FYM treatments, all other treatments significantly improved the concentration of mineral nitrogen in the soil compared with the control treatment. However, when comparing composted manures versus those co-composted with biochar, significant differences in the concentration of N were only observed between the FYM and FYM-B treatments. The FYM-B treatment increased the concentration of nitrogen by approximately 33% compared with the FYM treatment. Our results for the high EC soil are consistent with the empirical evidence reporting that the amendment of composted manures and co-composted biochar and organic fertilizers increase the concentration of mineral nitrogen in the soil [35,36]. For instance, the amendment of red clay soil with biochar derived from willow wood and co-compost composed of green waste, bagasse, and chicken manure at a rate of 25 t ha^{-1} resulted in a significant increase in nitrate, ammonium, and potassium concentrations compared with the control [35].

Organic amendments caused two- to fourfold significant increases in Olsen phosphorus contents in both the low EC soil and high EC soil. Another interesting finding of our study is that compared with the composted manures, those co-composted with biochar also significantly increased the concentration of phosphorus in both the low EC soil and high EC soil (except that there was no difference in the concentration of P between the PM and PM-B treatments in the low EC soil). The highest concentration of P was observed in the soil amended with PM. Our results agree with our previous findings, which showed that amendment with biochar-based fertilizers for 3 years [37,38] significantly increased the concentration of Olsen phosphorus in field soil. The positive influence of biochar-based organic fertilizers and other manures on the concentration of inorganic phosphorus has been frequently reported [19,39,40]. For instance, Sulemana et al. [41] found a 6–12-fold increase in the concentration of soil phosphorus in response to the amendment of slow-pyrolyzed sawdust-derived biochar co-composted with kitchen waste and waste made from cow manure, lettuce, cabbage, carrots, oranges, yam peels, and watermelon. Likewise, a pot-based study conducted in calcareous soil by Qayyum et al. [40] showed an approximately twofold increase in the Olsen P of soil amended with biochars produced from rice husk, cotton stalks, and vegetable waste feedstocks. In our study, biochars co-composted with FYM and SG increased the concentrations of potassium and phosphorus significantly more than the FYM or SG treatments. Interestingly, we also observed a significant increase in the mineral nitrogen concentration in soil when co-composted FYM and SG-based biochars (FYM-B and SG-B) were added to the high EC soil compared with composted SG and FYM manures. Our results are in agreement with the findings of Qayyum et al. [34] and Antonangelo et al. [18], which showed that co-composted biochars are more suitable for low-fertility high EC soils compared with when biochar or other organic wastes are applied as the sole amendments. However, this increase in the concentration of K, N, and P in the soil did not exert a positive effect on the yield of saffron stigma. The meta-analysis of Antonangelo [18] showed that the positive influence of co-composted biochar appears over

time. Therefore, long-term (more than two years) amendment of these fertilizers and their influence on saffron yield must be investigated to evaluate if these fertilizers also improve the stigma yield of saffron over time.

4.3. The flowering period of saffron

The application of organic amendments influenced the initiation and duration of the flowering period of saffron. However, the results were not consistent over space (soil types and fertilizer treatments) and time (years of cropping). In the low EC soil, the flowering of the first-year crop began 3–4 days earlier in FYM-B- and SG-B-amended soil, whereas early flowering for the second-year crop was observed only in FYM-B-amended soil. Interestingly, no relationship was observed between flowering initiation and soil moisture. The FYM-B and SG-B treatments did not increase soil moisture or soil temperature but triggered early flowering.

Contrary to the results for the low EC soil, the high EC soil showed a greater response to organic amendments. Prolonged flowering of saffron was observed in FYM-, PM-, SG-B-, and FYM-B-amended soils for the first-year crop, and all fertilizers prolonged flowering for the second-year crop relative to the control. Furthermore, contrary to the findings for the low EC soil, a trend was observed between the flowering period and soil properties influenced by organic amendments. The SG and PM organic fertilizers increased the soil moisture. PM-B increased the soil moisture in the second cropping year. The SG treatment triggered early flowering, whereas all organic amendments prolonged the flowering period of the second-year crop compared with the control treatment.

Organic wastes such as straw mulch, stover returned to the field after harvest, composted manures, composted kitchen wastes, manures, and co-composted biochar are widely utilized as soil amendments and fertilizers. These inputs have been shown to significantly influence the flowering periods of various crops [42,43]. For instance, Ramakrishna et al. [44] demonstrated that the application of rice straw mulch in clay loam soils advanced the flowering of groundnuts (*Arachis hypogaea* L.) under field conditions. Field mulching with rice straw also increased the moisture and temperature of the soil [44]. In our study, the first-year crop showed early flowering only in the low EC soil under the FYM-B and SG-B treatments, whereas these treatments did not significantly increase soil moisture or soil temperature relative to the control. In the high EC soil, prolonged flowering was observed under the SG-B and PM treatments compared with the control for the first-year crop and under the FYM, FYM-B, SG-B, and PM treatments for the second-year crop. Our results for the high EC soil for second-year crop agree with the findings of Ramakrishna et al. [44]. Our data showed a positive relationship between fertilizer-induced changes in soil moisture and the duration of flowering period in the high EC soil. This factor resulted in a significant increase in the yield of saffron stigma in the plots amended with PM and FYM fertilizers compared with the control treatment. Our findings showed that the influence of organic amendments on soil properties and the flowering period of saffron were different in different soils. The high EC soil had a higher concentration of organic matter than the low EC soil and it was more responsive to fertilizer amendments over time.

4.4. Yield of stigma

For the first-year crop grown in the low EC soil, all fertilizers significantly reduced the fresh yield of stigma by 41%–44%. Furthermore, PM-B significantly reduced stigma yield compared with the other fertilizers. However, in the high EC soil, no significant difference among the treatments was observed for the first-year crop. Our results contradict the general observation that composted

fertilizers and co-composted biochars increase crop yield, including saffron [45]. Similar to our study, Van Zweiten et al. [46] also observed the differential influence of biochar on crop growth in different soil types. Their study showed a significant reduction in the biomass of wheat (*Triticum aestivum* L.) and radish (*Raphanus sativus* L.) when slow-pyrolyzed paper mill biochar was applied to calcarosol, which had 20.3 g kg⁻¹ soil organic carbon. However, the same biochar significantly improved the biomass of soybean (*Glycine max* L.) and radish in ferrosol, which had a higher concentration of organic carbon (36.0 g kg⁻¹ soil) [46]. Similarly, Rajkovich et al. [47] reported that the temperature of biochar produced from paper mill waste and food waste influences crop growth. They found that biochars produced at 300–400 °C reduced corn (*Zea mays* L.) yield; however, when the same feedstocks were pyrolyzed at higher temperatures (> 450 °C), corn yield was not reduced compared with the control. These studies indicate that biochar or co-composted biochar has a negative effect on crop yield, at least in the short term (the first year crop). The biochar used in this study was pyrolyzed at low temperatures (400–450 °C). The concentration of organic matter in the low EC soil was also three times lower than in the high EC soil. Our results agree with the findings of van Zweiten et al. [46] that in soil with a low concentration of organic matter, organic fertilizers reduced the fresh yield of saffron stigma in the first-year crop; however, for soil types, they caused no significant results, although both soil types in our study were calcarosols. Organic fertilizers, particularly biochar, act as a nutrient capture mechanism. In our study, fertilizers were applied just a few weeks before sowing the corms (approximately 4 weeks earlier). Freshly incorporated fertilizers might have captured nutrients and caused a temporary nutrient limitation in soil for the first-year crop, especially in the low EC soil, which had low concentrations of organic matter. This factor, along with the low production temperature of the biochar used in this study, might be the reason for the significant reduction in the yield of the first-year crop compared with the control in the low EC soil.

Interestingly, the results for the second-year crop in the low EC soil were not similar to those of the first-year crop, as no difference among treatments was observed in the fresh yield of stigma. After 2 years of cropping, fertilizers amendments significantly increased the concentrations of plant-available P and K in the soil. This suggests that for the second-year crop, nutrients were not the limiting factor; therefore, no reduction in yield relative to the control was observed for the second-year crop in the low EC soil (although, for the first-year crop, fertilizer treatments reduced the stigma yield significantly relative to the control). When comparing the poultry manure treatment with the control, another possible reason for the lower yield in the low EC soil for the first-year crop was that there is ~2.5 times more ash in poultry manure, which might have increased the EC of the soil for the first-year crop (as indicated in Figure 4 (samples collected after 2 years of cropping)). However, this treatment did not negatively influence the yield of saffron stigma in the second-year crop; instead, it caused slightly increased salinity in the soil. This indicates that poultry manure compost did not increase nor decrease stigma yield relative to the control treatment when continuously applied to the soil for 2 years.

For the high EC soil, no difference among treatments was observed for the first-year crop. However, for the second-year crop, FYM and PM significantly increased yield compared with the control treatment. Furthermore, no difference in yield among organic fertilizer treatments was observed. Ghanbari et al. [48] also reported a nonsignificant influence of cattle manure compost and a compost + biochar mixture on the stigma yield of saffron of the first- and second-year crops grown in sandy loam soil. They, however, observed a significant increase in the stigma yield of the third-year crop. Furthermore, our 3-year study with two crops (cumin (*Cuminum cyminum* L.) and sweet fennel (*Foeniculum vulgare* Mill.)) grown in calcareous soil and continuously amended with the same biochar as was used in this study, in combination with same manures (SG, FYM, and PM), showed a

significant positive influence on yield of third-year crops [37,38]. In this study, we found negative results for the first-year crop to no influence for the second-year crop from the organic amendments on stigma yield in the low EC soil. Likewise, we found no influence for the first-year crop to a positive influence for the second-year crop for a few organic amendments (FYM and PM composts) on stigma yield in the high EC soil. Our study and the findings of Ghanbari et al. [48] and Achakzai et al. [37,38] suggest that the positive influence of organic fertilizers may be observed over time after continuous amendment.

The inconsistent results for both soil types may be attributed to differences in the concentration of organic matter. Interestingly, in the high EC soil, PM fertilizer also increased soil moisture relative to the control and other organic fertilizer treatments. Organic fertilizers tend to increase soil temperature and moisture. These factors have been found to positively influence the yield of crops [23,42] as was also observed in our study for the high EC soil. The concentrations of mineral nitrogen, Olsen phosphorus, and potassium were also the highest under the PM fertilizer treatment in the high EC soil. These factors might also have collectively contributed to the significant yield improvement of saffron stigma under the PM fertilizer treatment compared with the control.

For the high EC soil, the yield of saffron stigma was significantly lower under the control treatment than the stigma yield of the control treatment in the low EC soil. However, no difference between the control treatments of the low versus high EC soils was observed for the dry biomass of leaves (dry biomass of leaves was measured for the second-year crop only). The low stigma yield under the control treatment in high EC soil could be caused by osmotic stress. However, no significant differences between the low versus high EC soil for stigma yield were observed under the organic fertilizer treatments. Organic fertilizers might have ameliorated the possible osmotic stress by increasing the soil moisture content (as was observed for SG, PM, and PM-B), ultimately improving stigma yield in the high EC soil. The important findings of our study are that, despite the high EC, this soil was more responsive to the organic amendments regarding soil properties and stigma yield.

Our results provide an insight into the importance of soil organic matter for bringing about the desired outcome in terms of soil quality and crop yield when organic fertilizers are applied. Our results provide valuable information for the farmers of this province to use co-composted biochar in their fields as an inexpensive alternative to the inorganic fertilizers for the cultivation of saffron in saline soils. Composted poultry manure and its equivalent co-composted with biochar was found to be the best amendment for increasing the nutrient contents in high and low EC soils, whereas composted poultry manure also significantly increased soil moisture and the fresh yield of saffron stigma. Poultry manure is an inexpensive waste (25 kg of dry manure costs US\$9) and is produced in abundance in Balochistan. Likewise, broken leftover pieces of *Acacia nilotica* biochar is also inexpensive also (US\$ 55 for a 40-kg sack of biochar). Making compost from poultry manure or co-composting it with the leftover broken pieces of this wood-derived biochar, as an economically feasible option for farmers, can also help improve soil quality and crop yield by increasing the organic matter of soil if continuously applied for at least 3–5 years in the field at a rate of at least 50 t ha⁻¹. As is evident from our study, this proposed management practice can change the saline soil to a cultivated growth medium for saffron in this province.

Correlation analysis revealed a significant negative influence of soil moisture on the fresh yield of saffron stigma in the low EC soil for the first-year crop. We attributed the negative relationship between soil moisture and stigma yield in the first-year crop grown in the low EC soil to the temporary negative effect of fertilizers on saffron stigma yield via possible nutrient limitations. Furthermore, no correlation between soil moisture and stigma yield was found for the second-year crop in both soil types and for the high EC soil in the first-year crop.

4.5. Yield of stamen and dry biomass of leaves

As for the other traits, inconsistent results were observed for stamen yield in both years and for the low and high EC soils. The low EC soil amended with SG had significantly a higher fresh weight of stamens in the first-year crop relative to the control; however, the opposite results were observed for the second-year crop. No difference among treatments was observed for the first-year crop grown in the high EC soil, whereas the FYM amendment significantly increased the stamen fresh weight of the second-year crop relative to the control. The amendment of FYM-B significantly increased the dry biomass of leaves of the second-year crop compared with the control in the low EC soil. No differences between treatments were observed in the dry biomass of leaves of the second-year crop in the high EC soil (the dry biomass of leaves was measured for the second-year crop only). As our results did not show a strong positive and consistent influence of various fertilizers on the yield and other traits of saffron, no influence of these fertilizers was observed on the length of stigma and leaves. Our results are not in agreement with the findings of Aboueshaghi et al. [8] and other authors [49]. They reported the significant positive influence of organic fertilizers (PM as the sole organic fertilizer or as a mixture with synthetic NPK fertilizer, vermicompost, biofertilizer containing *Bacillus* and *Pseudomonas*, or the combination of biofertilizer and vermicompost) and synthetic fertilizers on stigma length compared with the control treatment, in crops grown in sandy clay soil.

4.6. Limitations of the study and future directions

We investigated the influence of composted manures and co-composted biochar fertilizers for 2 years. However, our previous study with cumin and fennel [37,38], published reports about other crops [48], and meta-analyses [18,19] suggest that the positive influence of biochar-based fertilizers appears over time when these fertilizers are continuously amended (once in a year) for a few years. Therefore, a study conducted over more than 2 years is recommended to validate our hypothesis and general findings that these important organic amendments improve soil quality and the yield of stigma of this economically important crop in the cold arid regions of Balochistan, Pakistan. Moreover, more rigorous measurements of soil moisture and soil temperature, using digital equipment, during the flowering period of saffron need to be taken to get a better insight into the factors contributing to controlling the crop's growth performance. The influence of these promising organic amendments on the stigma yield of saffron need to be examined on a temporal basis in the context of rhizosphere microbe-mediated processes related to nutrient cycling and disease control. Saffron corms produce a substantial amount of leaf biomass, which can be used as fodder for livestock. The leaf biomass production in response to these organic amendments and their nutritional quality must not be ignored.

Our study did not examine the possible effect of the high EC of the soil on the physiology of saffron, such as ion-specific toxicity, osmotic stress, or nutrient competition. Further investigation is required to assess the influence of composted manures and those co-composted with biochar on these physiological traits of saffron in high EC soil. Such a study will provide valuable information about the role of these amendments in ameliorating salinity stress through modulating the physiological traits of saffron. For instance, does high EC affect saffron's physiology through ion-specific toxicity, osmotic stress, or nutrient competition? Is the ameliorating effect of biochar primarily caused by its physical structure improving soil water–air conditions, its chemical properties adsorbing saline ions, or its regulation of the microbial community functions in the rhizosphere?

5. Conclusions

This study demonstrates the influence of composted manures and those co-composted with biochar on soil properties and stigma yield in low and high EC soils. In the low EC soil, which had three times lower concentrations of organic matter than the high EC soil, organic fertilizers reduced stigma yield relative to the control in the first-year crop. However, no significant effect was observed on the stigma yield of the second-year crop. PM proved to be the most effective treatment in the high EC soil. This treatment significantly increased mineral nitrogen, potassium, and phosphorus in the soil; increased soil moisture; prolonged the flowering period; and increased the stigma yield of saffron in the second-year crop. In the high EC soil, FYM also increased the potassium and phosphorus contents of the soil, prolonged flowering, and enhanced stigma yield but did not increase the moisture or temperature of soil. Co-composting with biochar did not provide additional benefits for stigma yield. Our study also highlights the importance of soil organic matter, as this factor showed a positive relationship with the effect of these organic amendments on soil quality and improved stigma yield over time. Long-term studies are recommended to better understand the potential of these treatments in improving the productivity and economic viability of saffron cultivation, particularly in the high EC saline soils of Balochistan.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest associated with this study.

Author contributions

Shagufta Qasim: performed research and wrote the first draft of this manuscript; Shamim Gul: Supervised research and supported in writing the manuscript; Abdul Hanan Buriro: provided field and laboratory facilities to perform this research; Tariq Ziad: provided laboratory facilities and supported the first author to analyze soil samples for chemical properties and statistical analysis. All authors have read and approved the final version of the manuscript for publication.

Supplementary description

The raw data associated with this manuscript are provided in the supplementary files. The following tables are included in the supplementary files.

Table S1: Raw data for soil moisture (%) for the 2020.

Table S2: Raw data for soil moisture (%) for the 2022.

Table S3: Soil temperature (°C) data for 2020.

Table S4: Raw data on soil temperature (°C) data for 2021.

Table S5: Raw data on pH, electrical conductivity (dS m⁻¹), potassium (mg kg⁻¹ soil), phosphorus (mg kg⁻¹ soil), sodium (mg kg⁻¹ soil), and total nitrogen (mg kg⁻¹ soil) of saline soil after 2 years of cropping.

Table S6: Raw data on pH, electrical conductivity (dS m⁻¹), potassium (mg kg⁻¹ soil), phosphorus (mg kg⁻¹ soil), sodium (mg kg⁻¹ soil), and total nitrogen (mg kg⁻¹ soil) on nonsaline soil after 2 years of cropping.

Table S7: Raw data on the number of emerged saffron flowers grown in various fertilizer-amended plots in nonsaline and saline soils.

Table S8: Raw data on fresh saffron stigma yield (g m⁻²).

Table S9: Raw data on stigma size of saffron.

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