Scientific Reports

https://doi.org/10.1038/s41598-026-49328-y

Article in Press

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Received: 25 June 2025

Accepted: 14 April 2026

Published online: 21 April 2026

Cite this article as: Zahedifar M., Moosavi A.A. & Gavili E. Biochar-mediated enhancement of soil quality and nutrient availability to spinach under water-limited conditions. *Sci Rep* (2026). https://doi.org/10.1038/s41598-026-49328-y

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Biochar-Mediated Enhancement of Soil Quality and Nutrient Availability to Spinach under Water-Limited Conditions

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Abstract

Biochar as a soil amendment can mitigate plant water stress. But its effects on soil quality in calcareous soils, particularly under varying moisture conditions, have not been studied. Therefore, this three replicated factorial greenhouse study evaluated the effects of cattle manure-derived biochar (0 (B0), 25 (B25), 50 (B50), and 100 (B100) t ha^{-1} which are equivalent to 0, 1.25, 2.5, and 5%wt, respectively) on spinach yield and the soil quality indices (SQI) of the postharvest soils under three soil moisture levels (100% (W100), 70% (W70), and 55% (W55) of field capacity, FC). Soil quality indices and their grades were assessed using a total of 27 soil indicators (TDS) and minimum (MDS) data sets derived from principal component analysis (PCA), with the Nemoro (NQI) and integrated (IQI) soil quality indices. PCA identified six principal components (PCs) with eigenvalues >1, accounting for 94.77% of cumulative variance. The most influential indicators (MDS) comprised soil iron, copper, and nitrogen concentrations, mean weight diameter (MWDd), and geometric mean diameter (GMDd) from dry sieving, and ΔGMD (with eigenvectors of 0.745, 0.565, 0.958, 0.801, 0.863, and 0.743, respectively). Correlations between IQI-TDS, IQI-MDS, NQI-MDS, and most plant and soil properties were positive, except for electrical conductivity, sodium adsorption ratio, and soil sodium concentration. PCA revealed that B50W55 and B100W55 were the most effective treatments, showing higher PC1 and lower PC2 scores, and were associated with improved greenness index, water repellency, penetration resistance, plant nitrogen, phosphorus, and sodium, as well as soil potassium, magnesium, and iron. Quality grades of the biochar-treated soil varied from III to IV under drought conditions. The highest soil property scores were achieved with 100 t ha^{-1} biochar, whereas the best plant property scores occurred with 50 t ha^{-1} biochar at 55% FC. The lowest scores across all properties were observed in the control (no biochar). Based on the sensitivity index and efficiency ratio, IQI-MDS was identified as the optimal model for representing soil quality in relation to crop yield. Overall, biochar application enhanced soil quality indices and crop yield by supplying nutrients and improving soil attributes. These findings highlight biochar’s potential to sustain soil health and productivity under drought conditions, which are increasingly common in arid and semi-arid regions.

Keywords: Drought stress, soil quality indicator, sensitivity index, efficiency ratio.

Introductions

Soil quality is the functional capacity of soil under various management regimes across different environmental conditions. Sufficient information, preserving and improving soil quality, is necessary to improve plant production and to maintain environmental security for the future. Furthermore, evaluating soil quality and determining its indicators will play a fundamental role in achieving sustainable agriculture. Soil quality influences the five criteria on which sustainable land management is based: productivity, security, protection, viability, and acceptability[1]. The concept of soil quality can be grouped into two comprehensive categories, consisting of soil functions and soil use. According to Andrews et al.[2], water flow and retention, nutrient cycling, and maintenance are considered as one of the most important soil functions, whereas the definition of soil use is related to its various uses, such as agriculture. To sum up, the mentioned two groups are interrelated and have been integrated. Soil quality assessment is evidence of the relationship between soil function and use. According to Samaei et al.[3], the concept of soil quality is the capacity of soil to sustain plant productivity, maintain or increase water quality, and assistance of human health and habitation. Land use and management practices as the major factors that can be considered to influence soil quality as a result of the alteration in soil attributes[4]. According to Riahinia and Emami[5], there are many various methods and criteria to evaluate soil quality, including scorecards, field kits, and laboratory analysis. Estimating soil quality using laboratory analysis has received more attention than others due to its quantitative nature, flexibility, and simplicity[6]. Soil attributes, as good indicators, are recommended for soil quality evaluation. Selecting proper indicators, scoring them, and combining the indicator scores into an index are the main steps to an index of soil quality[7]. Two methods are commonly used to monitor soil quality, including total data set (TDS) and minimum data set (MDS)[8]. According to Yao et al.[9], MDS could be calculated from TDS using multiple and linear regression analysis, discriminant analysis, factor analysis, and scoring functions. Based on the diversity of soil quality evaluation indicators, the MDS method is often used in these studies to reduce the required time, cost, and data redundancy[10,11]. Zeraatpisheh et al.[8] showed that both TDS and MDS methods described soil quality properly; however, the MDS method was finally proposed to classify soil quality using fewer soil properties.

Two quantitative integrated approaches, including Integrated Quality Index (IQI) and Nemero Quality Index (NQI), are commonly used to evaluate soil quality in such a way that using the summation of the multiplication of the values of the selected properties and their weights in the form of a simple linear relation to determine IQI[12]. IQI is a linear and additive approach that calculates an overall score using a weighted average of the scores of individual soil indicators[12, 13,14] Some advantages of this approach are: i) simplicity, easy to understand, calculate, and communicate, and the final score directly represents the weighted average of all indicators; ii) compensatory nature (high scores of some indicators can compensate low scores of others); and iii) stability and robustness (IQI is less sensitive to extreme values and outliers in a single indicator). However, the following disadvantages exist with the IQI approach: i) masking critical limitations (A soil can reach a moderately good IQI while one or two severely limiting indicators exist that would make it unsuitable for use); ii) assuming independent indicators, which is often false; and iii) probably underestimating sensitivity.

In contrast, the NQI approach is determined using average values and minimum properties, following the methods proposed by Qin and Zhao[15]. Indeed, NQI is a non-linear, root-mean-square approach that incorporates a "Nemero" factor for the worst-performing indicator[13, 14, 15]. It is designed to be sensitive to pollution or severe limitations. Some advantages of this approach are: i) highly sensitive nature to the worst attribute due to highlighting limiting factors and factoring in the minimum indicator score, which is crucial for identifying critical limitations such as very severe salinity, toxic contamination, etc. In other words, only a single very small score will result in a remarkable decrease in the final SQI. ii) one-out, all-out philosophy that is excellent for risk assessment. Indeed, this is in line with the ecological principle that an ecological system can be critically damaged by only one stressor, even if other indicators are good. However, NQI has the following disadvantages: i) exaggerating the overall quality status. For instance, 20 excellent indicators alongside one or two poor indicators result in low soil quality and misrepresent its overall functional capacity. ii) less reflective of integrated function that may not accurately represent the soil's overall quality or productivity if no single severe limiting factor exists. and iii) complex interpretation: The final NQI that is driven by both the mean and the extreme scores is harder to interpret than a simple average.

Based on the findings of Brejda et al.[16], using the principal component analysis (PCA) method, when faced with a large number of variables in soil quality studies, soil properties are classified into a few components that can be estimated as related to the soil-specific functions. PCA is a powerful statistical tool in soil quality assessment. Its main advantages are that address the inherent complexity and multivariate nature of soil systems, including: reducing complexity and identifying key indicators (drivers); enabling indicator selection (MDS); eliminating correlation-related statistical issues; determining weights for calculating soil quality indices; identifying latent relationships and processes; and enabling effective visualization and grouping[13,14, 17].

Addition of amendments (e.g., biochar) to the soil is one of the appropriate land management practices that influences soil quality as a result of the change in soil physical (structural stability, porosity, aeration, surface area, and water holding capacity), chemical (cation exchange capacity, pH, ion exchange, nutrient retention, and transformation) and fertility-related attributes[18, 19]. The mentioned improvements in soil properties as well as plant growth in response to biochar application are of vital importance, particularly in arid and semiarid regions that commonly face a water shortage crisis. The use of biochar as a suitable soil amendment has been suggested in various studies[13,17, 20]. Biochar with high surface area, porosity, charge density, and cation exchange capacity (CEC) can help increase the retention of nutrients and water. The higher the concentration of available nutrients in the soil solution, the greater their absorption by the plant, resulting in increased plant yield. Water conservation, especially in arid and semi-arid regions, is one of the management priorities of these lands. Zahedifar et al.[20] showed that the soil quality was improved with high application rates of biochar under drought stress, so biochar as a soil conditioner could increase water retention capacity in soil.

Many researchers stated that biochar amendment influences soil nutrient status through the source of nutrients for plants and microorganisms, affecting the mobility and bioavailability of nutrients, and altering soil properties, nutrient reactions, and cycling in the soil[21-23]. According to Hossain et al.[24], biochar, as an environmentally friendly soil amendment with high surface area and porosity, improves the soil nutrient retention capacity. Biochar, which reduces leaching and gaseous loss, can increase nitrogen (N) retention and phosphorus (P) availability. Biochar addition increases soil pH, so it alters plant nutrient availability and uptake. The impact of biochar on N concentration and uptake by plants is variable[25,26]. The positive and negative effects of biochar application on P uptake have been reported[27,28]. According to Fazal and Bano[29], the potassium (K) content in maize was increased with biochar application. The addition of poultry manure-derived biochar decreased the calcium (Ca) and magnesium (Mg) content in Lettuce[30], whereas it increased them in Chicory. There are inconsistent results about biochar addition on Ca, Mg, zinc (Zn), copper (Cu), iron (Fe), and manganese (Mn) uptake by plants[31,32]. Biochar as a nutrient source improves nutrient use efficiency. Rafique et al.[33] reported that fresh and dry weights of maize were increased with biochar application. Similar results were obtained by others[34,35]. Higher chlorophyll was obtained in wheat[36] and soybean[37] plants when grown on biochar-amended soils. Maintaining soil quality for increased production is of particular importance in areas facing drought stress.

Therefore, research is being conducted in arid and semi-arid regions to achieve this goal. As mentioned before, the soil quality takes into consideration soil chemical, physical, and nutritional attributes either jointly or individually to evaluate if soil functioning under various land uses, environmental stress, and land management practices is aggrading or degrading[2,38].

The central hypothesis of the research was that the application of biochar can mitigate the adverse effects of drought stress on plant growth through improving soil conditions and overall soil quality, and improving soil quality indices determined using different approaches. While previous studies have investigated the individual effects of biochar on soil quality or plant responses to drought, to the best of our knowledge, few studies have examined the interactive effects of cattle manure-derived biochar, application rate, and drought severity on plant growth and soil quality indices, particularly in calcareous soils within a single integrated framework. Therefore, to address this gap, this study aimed to (1) evaluate the impact of biochar levels on spinach yield and soil–plant nutrients status under different levels of soil moisture conditions; (2) determine quality indices of postharvest soils based on TDS and MDS indicators using PCA in response to the applied levels of biochar and soil moisture conditions; (3) select the most effective soil attributes to calculate soil quality indices; and (4) determine the soil quality grades concerning the applied treatments.

Indeed, this research demonstrates that biochar application can be used to enhance soil resilience and sustainable agricultural production under increasing drought and water scarcity, particularly in arid regions.

Materials and methods

Study area, sample collection, and measurements

The location where the study was conducted is located in the southwest of Iran, in Fars province, near Shiraz city, at the Faculty of Agriculture, Shiraz University (52° 46' N and 28° 50' E). The mean precipitation and temperature are 376 mm and 14 ℃, respectively. The soil composite sample was collected from 0 to 30 cm depth, air dried, well mixed, and sieved (<2 mm). The sample testing and analysis processes used solutions prepared with standard methods (Table 1). The pH of saturated paste was measured using a pH meter[39], the electrical conductivity (EC) of saturated extract was measured using an EC meter[40], and soil organic matter (SOM) was measured using wet combustion[41]. Total N was determined using the Kjeldahl method[42]. Soil CEC was measured using the displacement of cations with ammonium acetate[43]. Plant available P was extracted with sodium bicarbonate ($NaHCO_3$)[44]. Plant available Zn, Cu, Mn, and Fe were extracted with Diethylenetriamine Penta acetic acid (DTPA) and read by atomic absorption spectrophotometer[45]. Textural class was determined using the hydrometer method[46].

Table 1.

Biochar preparation and analysis

The biochar was produced from cattle manure collected from the Bajdah Animal Husbandry Station, College of Agriculture, Shiraz University, Iran. The manure was air-dried at 35 to 40 °C for 48 h, powdered, sieved using a sieve with a diameter of 2 mm, and packed into aluminum bags of 2 L volume (20×10×10 cm) and slowly pyrolyzed in an electrical furnace at oxygen-limited conditions. The temperature of the pyrolysis process was continuously increased at a rate of 5 °C min^{-1} to a maximum of 600 °C for four hours. The produced biochar was then cooled down to room temperature overnight and mixed thoroughly. Some chemical characteristics of homogenized biochar were determined using the standard IBI methods[47]. The pH (10) and EC (14 dS m^{-1}) of biochar were determined in a 1:10 suspension by using the pH and EC meter, respectively[47,48]. The determination of P, N, and K concentrations (280, 20000, and 20000 mg kg^{-1}, respectively) was performed in line with the procedure outlined by Olsen[44], Bremner and Mulvaney[42], and Helmke and Sparks[49], respectively. Furthermore, Zn, Mn, Fe, and Cu concentrations (143, 271, 1311, and 31 mg kg^{-1}, respectively) of biochar were determined following the IBI method[47] and by an atomic absorption spectrophotometer.

Experimental design and spinach planting

A greenhouse pot experiment was conducted within 60 days in the Agricultural Research Station, Faculty of Agriculture, Shiraz University, Shiraz, Iran (52° 46' N and 28° 50' E). The pots were arranged in a completely randomized factorial design with three replications. Treatments consisted of three soil moisture conditions (100% (W100), 70% (W70), and 55% (W55) of field capacity) and four levels of biochar application (0, 25, 50, and 100 t ha^{-1} of soil, as B0, B25, B50, and B100, that are equivalent to 0, 1.25, 2.5, and 5%wt, respectively). In other words, we had a total of 36 (3 × 4 × 3) experimental units (pots). A mixture of 3 kg of air-dried soil and prepared biochar was transferred to plastic bags. Based on initial soil analysis and to provide sufficient nutrients for plant growth, specific and constant amounts of Fe (10 mg kg^{-1} as FeEDDHA), Zn (10 mg kg^{-1} as $ZnSO_4.7H_2O$), Cu (5 mg kg^{-1}), Mn (10 mg kg^{-1} as $MnSO_4.5H_2O$), and N (150 mg kg^{-1} as urea) were added to all bags in two stages, at the time of planting and four weeks after emergence. After drying, the soils were transferred to cylindrical plastic pots with a height of 17 cm and a diameter of 20 cm. Placing the soil and treatments first inside the plastic and then transferring them to the pot was done to ensure uniform distribution of the treatments throughout the pots. Eight spinach seeds (Viroflay, purchased from Pakan Bazr Isfahan Company) were planted in each of the pots and watered to FC conditions, and were kept under this situation with distilled water. Two weeks after germination, the number of plants was thinned to 4 per pot. Then, the previously mentioned drought stress treatments were applied to the pots during the growth periods by daily weighing the pots and compensating for the water loss by adding the required amount of water through the manual gravimetric irrigation (weigh and add or pot weighing) method using a digital scale with two decimal places (0.01 g precision), which is a common technique in controlled pot experiments, particularly in drought stress research. This method is fundamentally a form of manual, precision surface irrigation in which water is applied by hand to the soil surface of each pot based on real-time measurements. In other words, for irrigating the pots, the following steps were followed:

1- Daily weighing of each pot to determine water loss (primarily through evapotranspiration)
2- Calculating the difference between the current weight and the target weight (i.e., 100% (W100), 70% (W70), and 55% (W55) of field capacity)
3- Manually adding the required amount of water to restore the pot to the mentioned moisture level

The mentioned irrigation type was selected to achieve precise and reproducible drought stress treatments. In other words, it was chosen for its i) Accuracy in water application; ii) Reliability in drought stress induction; iii) Simplicity and low cost; and iv) Compatibility with controlled environment conditions.

It should be noted that before planting, the moisture content of the soils at the FC condition was measured using a pressure plate apparatus. The greenness index of mature spinach leaves was measured at the end of the growth period, just before harvest, using the SPAD 502 instrument.

Plant harvesting and measuring soil properties

At maturity, the aboveground parts of plants were cut, washed with distilled water, and oven-dried for 48 hours at 65℃. Consequently, weighed, powdered, and ashed at 550℃. The ashed samples were dissolved in 2 N hydrochloric acid and passed through the Whatman 42 filter paper. The concentrations of plant nutrients, such as Fe, Mn, Cu, Zn, Ca, and Mg, were determined by an atomic absorption spectrophotometer, Na and K using a flame photometer[50], and the amounts of N and P by the Kjeldahl[42] and colorimetry method[50], respectively. The available nutrient contents of the postharvest soil were measured consisted of Zn, Mn, Fe, and Cu by an atomic absorption spectrophotometer[45], the soluble Na and K by flame photometer, soluble Ca and Mg through titration with ethylenediamine tetra acetic acid (EDTA)[51], mean weight diameter (MWD) and geometric mean diameter (GMD) of soil aggregates were determined using wet and dry sieving methods[52], bulk density (BD) by core sampler[53], soil saturated hydraulic conductivity (K_h) by falling head method[54], penetration resistance (PR) by a hand handle penetrometer at FC moisture conditions, and water repellency (WR) by water droplet penetration time[55].

Determination of soil quality indices (SQIs), scoring, and weight assignment

The total data set (TDS) and the minimum data set (MDS) were used for soil quality calculation. The 27 measured/calculated soil properties were considered as the TDS in this study. According to Qi et al.[56], the principal component analysis (PCA) approach was also performed to select a representative MDS from the TDS. It should be noted that, before using PCA, two tests, including Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity, were performed in order to indicate the appropriateness of the data for structure detection and determining their suitability for further analysis. According to Andrews et al.[57], PCA was performed on all indicators, retaining components with eigenvalues ≥ 1. Within each PC, each attribute was weighted (loading factor) based on its role in the PC structure. As stated by Gao et al.[58], soil variables with loading factors within 10% of the highest value were supposed to be the factors that best represent changes in soil quality. When more than one attribute was retained under a particular PC, multivariate correlation coefficients were used to detect if any variable was superfluous and eliminated from the extracted MDS. Variables with correlation coefficients (r) less than 0.6 were included in the MDS. For r greater than 0.6, attributes demonstrating higher correlation coefficients with the maximum loading factor were prioritized as MDS indicators[57]. When the correlation coefficient between attributes was greater than 0.7, only the variables with the highest sum of absolute correlation coefficients were retained. While all the variables under each PC were retained when the correlation coefficient was less than 0.7[57]. Since soil attributes had various dimensions, standardization of the raw data was performed before calculating the integrated soil quality index to remove the influence of dimensional differences among variables. So, each attribute was scored to a dimensionless combinable value. According to Andrews et al.[57], scoring methods were used to convert and normalize indicator values into unitless scores ranging from 0 to 1. In these methods, for soil properties that were positively associated with soil function, the “more is better” or ascending function (Eq. 1) was applied. Whereas for those variables whose higher values negatively affected soil quality, “less is better” or descending function (Eq. 2) was applied. The peak limit (optimum) function (Eq. 3) was also used for soil indicators with an optimum range (e.g., pH). In this study, descending functions were used for NaS, EC, SAR, BD, PR, WR, ΔMWD, and ΔGMD. Whereas, ascending functions were applied to other indicators except those mentioned.

$$S(z)=\begin{cases}0.1 & z\le L\\ 0.9\dfrac{z-L}{U-L}+0.1 & L\le z\le U\\ 1 & z\ge U\end{cases}\qquad(1)$$

$$S(z)=\begin{cases}1 & z\le L\\ 1-0.9\dfrac{z-L}{U-L} & L\le z\le U\\ 0.1 & z\ge U\end{cases}\qquad(2)$$

$$S(z)=\begin{cases}0.1 & z<L\ or\ z\ge U_2\\ 0.9\dfrac{z-L_1}{L_2-L_1}+0.1 & L_1\le z\le L_2\\ 1 & L_2\le z\le U_1\\ 1-0.9\dfrac{z-U_1}{U_2-U_1} & U_1\le z\le U_2\end{cases}\qquad(3)$$

where SF is the scoring function; S: score; z is the value of the indicator; S(z) is the score of indicators ranging from 0.1 to 1; U and L are upper and lower critical values[56].

To determine the SQI, the integrated quality index (IQI) and Nemero quality index (NQI) were calculated (Eqs. 4 and 5):

$$IQI = \sum_{i=1}^{n} W_i N_i \tag{4}$$

$$NQI = \sqrt{\frac{P_{ave}^2 + P_{min}^2}{2}} \times \frac{n - 1}{n} \tag{5}$$

where n is the number of soil indicators, N_i is the score, and W_i is the weight of each attribute. The lowest and the mean scores of the selected indicators are shown as P_{min} and P_{ave}, respectively. To evaluate the most influential variable of PC controlling the highest variations, the selection criterion (SC) was determined as follows (Eq. 6):

$$SC = \frac{0.5}{(PC_{eigenvalue})^{0.5}} \tag{6}$$

As depicted by Table 2, SQIs are defined in four grades: suitable for plant growth as I; proper for plant growth as II; there are some limitations as III (more limitations than II), and high limitations for plant growth as IV. Finally, soil quality grades were determined.

Table 2.

Sensitivity index (SI) was computed using equation (7) to validate the soil quality index[59]:

$$SI = \frac{SQI_{max}}{SQI_{min}} \tag{7}$$

where SQI_{max} and SQI_{min} are the maximum and minimum of soil quality index values, respectively. To assess the efficiency of each soil quality index, the efficiency ratio (ER) was determined (Eq. 8):

$$ER = \frac{K}{N} \times 100 \tag{8}$$

where K shows the number of significant soil quality indices and all indicators. N represents the number of all possible pairwise correlations in the data set. N equals 10 and 53 for MDS and TDS in this analysis, respectively.

Statistical analysis

Statistical analysis was performed using SPSS v. 26 and EXCEL packages. The PCA analysis was performed using OriginPro 2024 to estimate the interaction between SQIs and soil-plant properties. The normality of the data was also checked using the Shapiro-Wilk test. Pearson correlation coefficients were applied to statistically analyze significant effects of soil-plant attributes on soil quality indices at the $P<0.05$ level using quantitative models based on TDS and MDS. Linking the correlation matrix along with the PCA results (the high loading factors) was also considered to strengthen the justification for selecting the MDS/TDS indicators. Furthermore, the mean values of different SQIs were statistically compared using Duncan's Multiple Range test at $P<0.05$.

Results and discussions

Soil quality determination according to the TDS and MDS indicators

The results of Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy and Bartlett's test of sphericity were summarized in Table 3. The KMO test structure of 0.639 (high value, close to 1.0) and the significance level of Bartlett's test ($p < 0.05$) alongside remarkable correlations in the data indicated that the data is appropriate for structure detection and further analysis.

Table 3.

Initial screening of indicators showed that six PCs with eigenvalues greater than/equal to one had 94.77% of total cumulative variance in the data (Table 4). The most highly weighted variables for the first principal component (PC1) were MnS, KS, PS, NS, OM, OC, BD, W, and Por (Table 4). The differences in their eigenvalues and the highest value in PC1 were less than 10%. For PC2, GMD_d was the highly weighted indicator. Under PC3 and PC4, FeS, and MWD_d, respectively, for PC5, ΔGMD, and under PC6, CuS were the highly weighted indicators. FeS, CuS, NS, MWD_d, GMD_d, and ΔGMD were selected for the MDS between variables under PC1 to PC6, respectively (Table 4). These parameters were chosen according to their larger eigenvectors. In other words, based on the results of PCA, the most influential indicators that were chosen as MDS comprise some fertility-related chemical (FeS, CuS, and NS) and structural-related physical (MWD_d, GMD_d, and ΔGMD) soil indicators. Indeed, these indicators can remarkably affect chemical and physical aspects of soil quality and its relation to plant growth.

Table 4.

According to Cox et al.[60], soil indicators with eigenvectors greater than the SC value were presumed to be the most effective to maintain in each PC. The calculated SC values of various PCs are shown in Table 4. The SC for PC1 was 0.072, and the eigenvectors for all of the indicators were greater than 0.072. In other words, all of the variables were known as the most effective variables. The determined SC for PC2 was 0.255. The most effective indicators in PC2 were all of the variables, except for MnS, NaS, MgS, PS, NS, OM, EC, OC, SAR, Kh, BD, W, Por, GMD_w, and ΔMWD. Eigenvectors for FeS, ZnS, MgS, pH, K_h, PR, WR, and ΔMWD were greater than SC (0.347) for the third PC. The most impressive factors for PC4 were K_h, MWD_d, and ΔMWD, with eigenvectors more than SC (0.0.481). Eigenvector for ΔGMD was determined as the most effective indicator in PC5. Under PC6, all variables were classified as ineffective because their eigenvectors were less than the SC value (0.806).

As depicted in Table 5, based on the TDS indicator method, the highest and lowest weights were associated with FeS and ΔGMD, respectively. Soil quality based on the MDS indicator method represented that NS and CuS had the highest and the lowest weights, respectively. The highest weight of FeS in TDS may correspond to the fact that Fe is one of the most important soil micronutrients, whose availability and activity in soil is strongly limited by alkaline pH, which is common in the studied calcareous soils. Furthermore, its chemistry and transformations are closely related to other chemical (pH, OM, EC, etc.) and physical (moisture, aeration, texture, etc.) soil attributes, and consequently, FeS concentration probably varies significantly across the samples, which explains the greatest overall variance across the indicators. In other words, this may be because soil Fe is likely a highly sensitive indicator (high variance) that varies greatly across the samples. Furthermore, it plays a key role in redox processes, phosphorus availability, and structural and aggregate stability. It is one of the master variables influencing multiple critical chemical, physical, and biological pathways within soil, as well as nutrient availability and aggregation. Furthermore, the highest weight of NS in the MDS may correspond to the fact that N is the most important macronutrient essential for plant or microbial growth. Consequently, it explains the largest proportion of total variance and shows the highest weight in soil quality.

For ΔGMD, it likely showed little variation (low variance) across the samples, or its variation pattern was almost identical to other stronger indicators (like FeS). In other words, statistically, ΔGMD provided little unique information. Furthermore, the lowest weight of ΔGMD may be because its influences are already captured by other attributes. For example, if Fe or OM strongly predicts aggregate stability, ΔGMD might add little new information, or maybe it is because most soils have similar ΔGMD. Copper (CuS) is one of the essential micronutrients whose availability is critical for certain crops and soils, but it generally affects a narrower range of soil functions compared to N, C, or physical structure-related indicators. It might have been chosen as MDS to show the micronutrient availability-related functions or because it passed a statistical screening (e.g., not perfectly correlated with other studied indicators). However, among the selected highly weighted indicators, its influence on the overall index was statistically the least. Furthermore, CuS may not have varied much in the studied samples (low variance), limiting its ability and contribution to soil quality.

Table 5.

Effect of biochar on SQIs and soil-plant properties

According to PCA, contributions from all variables were 40.2 for PC1 and 27.2 for PC2 (Fig. 1). The length and angle of principal vectors or variables show variance and covariance, respectively. All traits with smaller or closer vector angles with each other indicate a positive relation with each other (angles of < 90° and > 90°, indicating positively and negatively correlated variables, respectively, and angles of 90° showing independent variables)[20]. As mentioned, objectives close together have similar characteristics, so IQI-TDS, IQI-MDS, and NQI-MDS appeared to be highly positively correlated with MgP, BD, OM, OC, CaS, Por, NaP, KS, MgS, PS, ZnS, MnP, FeS, MnS, W, NS, and PP.

Fig. 1

The largest angles were observed between SQI and EC, SAR, and NaS, which shows a high negative correlation between them. The best treatments can be selected with increased PC1 and decreased PC2 for various soil water conditions and biochar amendment. The treatments of B50W55 (no. 9) and B100W55 (no. 12) with the higher PC1 and the lower PC2 also depicted higher scores for GI, WR, PR, NP, ΔGMD, PP, NaP, KS, MgS, and FeS. As shown in Fig. 1, having high PC1 and PC2 was obtained by B50W70, B100W100, and B100W70 treatments with the numbers of 8, 10, and 11, respectively, and scored higher values for PC, GMD_d, CuS, NQI-TDS, NQI-MDS, IQI-TDS, IQI-MDS, GMD_w, MWD_w, NaU, PU, K_h, ΔMWD, MWD_d, ZnS, MnP, Por, CaS, NS, BD, W, OC, OM, MnS, PS, and MgP. The treatments of B0W70 (no. 2), B0W55 (no. 3), B25W70 (no. 5), and B25W55 (no. 6) showed lower PC1 and PC2, with higher scores for KP, CuP, CaP, pH, EC, NaS, and SAR. The lower PC1 and the higher PC2 were observed with B0W100 (no. 1), B25W100 (no. 4), and B50W100 (no. 7) treatments, scoring higher values for NU, MgU, WW, DW, LA, MnU, FeU, CuU, ZnU, CaU, ZnP, FeP, KU, and WUE.

According to Fig. 2, application of 100 t biochar ha^{-1} under various soil moisture conditions (FC, 70%, and 55% FC) had the highest positive effects on the IQI based on the TDS indicators (0.80, 0.78, and 0.77, respectively). In other words, mean comparison indicated that the application of 100 t biochar ha^{-1} significantly ($P<0.05$) increased the IQI calculated based on both TDS and MDS under various soil moisture conditions in comparison to control or the other levels of applied biochar (Fig. 2). In soils treated by 50 t biochar ha^{-1} under 55% FC, the lowest IQI of soil was observed. The highest IQI based on the MDS (0.86) was obtained with application of 100 t biochar ha^{-1} under FC conditions; whereas, the lowest value (0.59) was observed without biochar application under 70% FC conditions.

Fig. 2.

The highest NQI based on TDS indicators (0.50) was obtained with the application of biochar at different levels (25, 50, and 100 t ha^{-1}) under FC conditions. However, the lowest NQI (0.36) was observed without biochar addition under FC conditions. As depicted in Fig. 2, the highest NQI based on MDS indicator was obtained with application of 100 t biochar ha^{-1} under FC (0.62) and 70% FC (0.60); but, the lowest value (0.48) was observed without biochar application under 70% FC and 55% FC conditions. Furthermore, mean comparison indicated that the NQI calculated based on both TDS and MDS under various soil moisture conditions significantly ($P<0.05$) increased in response to the application of 100 t biochar ha^{-1} in comparison to control or the other levels of applied biochar (Fig. 2). The PCA biplot in Fig. 3 shows both the PC scores of treatments and the loading of the soil quality indices. The results of this analysis confirm the findings stated above.

Fig. 3

Based on the results obtained, the application of biochar, especially at the highest application level, had a significant positive effect on increasing soil quality. These findings are consistent with the results of others. Zahedifar et al.[20] stated that the addition of 100 t ha^{-1} biochar increased soil quality indices significantly. Biochar with a porous structure can increase soil porosity, form aggregates, which in turn improve the stability of the aggregate and total porosity, so that it stores more water[61,62]. In other words, higher doses of biochar are beneficial because they convert the soil from merely amended to a re-engineered soil. High doses of biochar create a stable and reactive porous medium that improves water and nutrient retention, as well as microorganism population and activity, resulting in higher soil quality, plant growth/productivity, and mitigating the adverse effects of climate imbalances, particularly in challenging conditions or degraded soils. In other words, higher doses of biochar more strongly and positively affect soil chemical, physical, and biological properties (soil quality) that are necessary for optimal plant growth. The comparison of mean value showed that the application of 100 t ha^{-1} biochar increased IQI based on TDS and MDS indicators (0.78 and 0.46, respectively). In other words, the results of mean comparison indicated that only the application of 100 t biochar ha^{-1} significantly ($P<0.05$) increased the mean value of IQI calculated based on TDS over various soil moisture conditions by 22.55% as compared to that of the control. Whereases, there were no significant differences among the applied biochar levels with respect to their effects on the mean value of IQI calculated based on MDS over various soil moisture conditions (Fig. 4). However, the 2.07%, 4.90%, and 6.62% increases in the IQI-MDS in response to the application of 25, 50, and 100 t biochar ha^{-1} as compared to that of control were not statistically significant. According to Fig. 4, the highest NQI based on TDS and MDS (0.42 and 0.52, respectively) were observed with the addition of the highest level of applied biochar (100 t ha^{-1}), which were significantly ($P<0.05$) higher than those of the others. That is to say, application of 25, 50, and 100 t biochar ha^{-1} resulted in 4.46%, 9.07%, and 11.08% increases in NQI-TDS and 1.37%, 3.70%, and 7.43% increases in NQI-MDS as compared to those of the controls. However, only the 9.07% and 11.08% increases in NQI-TDS and only the 7.43% increase in NQI-MDS were statistically significant. Furthermore, results of mean comparison indicated that the applied levels of soil moisture conditions had no significant effect on both IQI and NQI calculated based on the TDS (Fig. 4). Whereas, both IQI and NQI calculated based on the MDS at 100% and 70% FC conditions were significantly ($P<0.05$) higher than those of 55% FC conditions (Fig. 4). Under FC conditions (W100), the highest IQI based on TDS (0.79) and IQI based on MDS indicators (0.64) were obtained; however, other soil moisture conditions did not influence significantly (Fig. 4).

The observed conflicting results between TDS and MDS-based soil quality assessments are expected and instructive, inherently due to the trade-off between comprehensiveness and parsimony. The conflict may highlight that the chosen MDS may not be suitable for all specific treatments or contexts under study. Furthermore, choosing the most important indicators as MDS for reducing the data may ignore the minor role of the other indicators, which consequently results in relatively different SQIs. However, the final goal is to develop MDS that are robust to minimize the conflicts.

Fig. 4

Association of SQIs with shoot fresh and dry weights of spinach

As can be seen from Fig. 5, the highest shoot fresh (wet) and dry weights of spinach (128.77 and 14.36 g pot^{-1}, respectively) were obtained with application of 25 t biochar ha^{-1} under FC conditions (B25W100).

Fig. 5

In this treatment, the calculated IQI and NQI based on MDS indicators were 0.59 and 0.48, respectively. The relationships between SQI and EC are shown in Fig. 6. The notable point is that the changes in the charts (Figs. 5 and 6), including their ups and downs, are similar to each other. Shoot dry and fresh weights of spinach were lower at the higher levels of the applied biochar, due to the increased soil salinity compared to that of the low levels. These findings are similar to those of others[20].

Fig. 6

As depicted by Fei et al.[63], Yao et al.[64], and Sun et al.[65], biochar can form macro and micro pores, as well as connectivity, increase soil porosity, reduce bulk density, and water holding capacity. On the other hand, biochar addition, due to improving soil porosity, increases capillary movement of water and, as a result, salt accumulation after water evaporation[66]. According to Fig. 7, linear scoring of plant properties and soil physicochemical attributes was altered under various soil moisture conditions and biochar addition. In linear scoring approach, the maximum scores between soil physicochemical properties were observed for FeS, ZnS, MnS, CuS, KS, CaS, MgS, PS, NS, OM, K_h, BD, W, Por, MWD_w, GMD_w, PR, WR, and ΔGMD (0.85, 0.92, 0.92, 0.77, 0.93, 0.94, 0.98, 0.92, 0.89, 0.90, 0.70, 0.94, 0.95, 0.94, 0.91, 0.81, 0.93, 0.91, and 0.93, respectively) with application of 100 t biochar ha^{-1} under 55% FC, 70% FC and FC conditions (Figs. 7a, b). Nevertheless, the maximum scores for Nas, EC, and SAR (0.97, 0.96, and 0.92, respectively) were obtained without biochar application under 55 and 70% FC (Figs. 7a, b). Concerning the measured plant properties, the maximum scores were obtained with application of 25, 50, and 100 t biochar ha^{-1}, without drought stress (W100) for FeP, KP, NP, FeU, ZnU, MnU, CuU, KU, CaU, MgU, PU, and NU (0.79, 0.97, 0.84, 0.89, 0.85, 0.91, 0.94, 0.91, 0.75, 0.96, 0.95, and 0.83, respectively) (Fig. 7c).

Fig. 7

The highest and the lowest calculated total scores, as influenced by soil nutrient contents, were 7.66 (which corresponded to the soils receiving 100 t biochar ha^{-1} without drought stress) and 4.16 (without biochar addition under soil moisture conditions of 70% FC), respectively. The highest and the lowest total scores concerning soil properties were 12.43, with application of 100 t biochar ha^{-1} under

55% FC, and 9.92 under FC condition without biochar. Furthermore, these scores, as influenced by plant attributes, were the highest (14.77) with the application of 25 t biochar ha^{-1} under FC conditions. It was the lowest (9.92) without biochar application under soil moisture conditions of 55% FC (Fig. 7). The overall results showed that the highest score in relation to soil attributes was obtained with the application of 100 t biochar ha^{-1}, and in relation to plant properties, with the addition of 25 t biochar ha^{-1}. The lowest score in all studied properties was obtained without biochar application. Zahedifar et al.[20] showed that the maximum total score, in relation to soil properties, was obtained with application of 100 t biochar ha^{-1} under 55% FC conditions, whereas the minimum score was reported without biochar addition under FC conditions. According to Xu et al.[67], the existence of functional groups as electron acceptors or donors on the biochar surface can adsorb heavy metals, increase the immobilization or complexation of them, as a result, it contributes to environmental health[68]. Ndor et al.[69] and similarly, Are[70] reported that soil moisture content was increased after application of biochar. Seleiman et al.[71] and Palansooriya et al.[72] stated that biochar, due to its high CEC, maintains nutrients, decreases their leaching, and improves nutrient absorption, such as NH_4^+, K^+, Ca^{+2}, and Mg^{+2}, by roots through releasing H^+ to charge equilibrium in the soil. Adekiya et al.[73], who also found higher content of N, P, K, S, Ca, and Mg in soils amended with biochar compared to un-amended soils.

Soil quality grades as influenced by biochar under drought stress

Soil quality grades from the IQI based on the TDS indicator had high grades (I) with application of 100 t biochar ha^{-1} under FC, 70% FC, and 55% FC moisture conditions (Table 6).

Table 6.

Results showed that biochar application improved soil quality grades from III to II or I for the IQI based on TDS. Under deficit moisture conditions, the positive effect of biochar on soil properties improvement, such as porosity and aggregates, followed by water storage capacity, is very important. As shown in Table 6, the soil quality grades from the IQI based on the MDS indicator method had high grades (I) with the application of 100 t biochar ha^{-1} under different moisture conditions. Similarly, the positive and effective role of biochar in improving soil quality grades from III or II to I was also clearly evident in this case as well. These results were also obtained, with a lesser grade of improvement, for the NQI based on the TDS indicator (from grade of III to II, under various soil moisture conditions), and for the NQI based on the MDS indicator (from grade of IV to III, under various soil moisture conditions). These findings were in agreement with Zahedifar et al. (2025)[20], who reported that the highest IQI-TDS was obtained with application of 100 t biochar ha^{-1} under 70% and 55% FC conditions. Increasing the soil quality grade from IV to I for the IQI-TDS approach, the result of high application rate of biochar under soil drought stress, confirmed that the biochar's ability is especially important in arid and semi-arid areas that face water shortage problems.

It is worth mentioning that one limitation of this study is that field capacity was determined using the control soil and applied uniformly across all biochar treatments, without adjusting for the potential effects of higher biochar rates on soil water retention. As biochar can alter porosity and soil hydraulic properties, particularly at application rates of 50 and 100 t ha^{-1}, future studies should measure field capacity separately for each biochar treatment to more precisely evaluate moisture-dependent effects.

Correlation analysis between measured properties and quality indices

As shown in Fig. 8, the correlation analysis was performed using OriginPro software. Results showed that there were positive correlation (hereafter significance at the probability levels of $p < 0.01$ and $p < 0.05$ represents by ** and *, respectively) between IQI-TDS and soil Fe, Zn, K, Mg, N, OM, OC, B.D, Por, W, plant Na, P, N and P uptake (0.84^{**}, 0.79^{**}, 0.65^{*}, 0.75^{**}, N^{**}, 0.80^{**}, 0.80^{**}, 0.71^{**}, 0.58^{*}, 0.70^{*}, 0.63^{*}, 0.83^{**}, 0.76^{**}, and 0.61^{*}, respectively), but, negative correlation with plant K (-0.71^{**}). Furthermore, there were positive correlation between IQI-MDS and soil Mn, K, Ca, Mg, P, N, OM, OC, Kh, B.D, W, Por, MWD_w, GMD_w, plant Na, Mg, P, N, uptake of N and P (0.91^{**}, 0.94^{**}, 0.87^{**}, 0.88^{**}, 0.89^{**}, 0.93^{**}, 0.92^{**}, 0.92^{**}, 0.61^{*}, 0.89^{**}, 0.92^{**}, 0.93^{**}, 0.73^{**}, 0.59^{*}, 0.91^{**}, 0.61^{*}, $0.91^{**}0.64^{*}$, 0.80^{**}, and 0.71^{**}respectively). However, negative correlation with soil Na (-0.76^{**}), EC (-0.81^{**}), SAR (-0.73^{**}), and plant Zn (-0.70^{*}). The positive correlation were observed between NQI-TDS and soil Mn, Ca, P, N, OC, OM, Kh, B.D, W, Por, GMDd, MWDw, GMDw, ΔMWD, plant Mg, uptake of Na, Mg, P, N, and PR (0.75^{**}, 0.63^{*}, 0.82^{**}, 0.66^{*}, 0.71^{**}, 0.71^{**}, 0.72^{**}, 0.72^{**}, 0.70^{*}, 0.60^{*}, 0.58^{*}, 0.83^{**}, 0.69^{*}, 0.59^{*}, 0.64^{*}, 0.90^{**}, 0.63^{*}, 0.86^{**}, 0.59^{*}, and 0.78^{**}, respectively). This quality index had a negative correlation with soil Na (-0.73^{**}), EC (-0.72^{**}), and SAR (-0.69^{**}). According to the correlation analysis results, there were positive relations between NQI-MDS and soil Mn, K, Ca, Mg, P, N, OC, OM, Kh, B.D, W, Por, MWDw, plant Na, Mg, P, N, uptake of Na and P (0.93^{**}, 0.88^{**}, 0.84^{**}, 0.84^{**}, 0.91^{**}, 0.93^{**}, 0.87^{**}, 0.60^{*}, 0.83^{**}, and 0.72^{**}, respectively). Similar to other calculated SQI_s, the negative correlation was obtained between NQI-MDS and soil Na (-0.73^{**}), EC (-0.82^{**}), SAR (-0.68^{*}), and plant Zn (-0.62^{*}). Results showed that there were positive correlations between all soil quality models and soil N, OC, OM, B.D, Por, and W; among the four calculated soil quality indices, positive correlations were obtained between three indices and soil Mg, Ca, P, Mn, Kh, and MWD_w. This indicates the importance of providing nutrients and some soil attributes to increase soil quality, which can ensure its health as part of the ecosystem.

The observed negative correlations between soil quality indices (specifically IQI-MDS) and Na, EC, and SAR are expected. But the observed negative correlation between IQI-MDS and plant Zn uptake is unreasonable. However, it can be explained by several key soil chemistry and plant physiology principles. In essence, as overall soil quality improves (higher IQI-MDS), the conditions often become less favorable for Zn availability and uptake by plants, even though the total amount of Zn in the soil might be the same or even higher. These unfavorable conditions comprise the following probable items:

- High-quality soils, as indicated by the observed positive correlations (high OM, Ca, Mg, N, and P), often result in a neutral to slightly alkaline pH. Although pH was not listed in the reported correlations, it is a key soil attribute controlling nutrient (e.g., Zn) availability to plants. In other words, Zn availability to plants is highest in acidic to neutral soils (i.e., pH of 5.5 to 7.0). In alkaline conditions (pH > 7.0), Zn converts to insoluble compounds (e.g., Zn carbonate and Zn hydroxide) and becomes locked up in the soil and unavailable to plant roots.
- There was a strong positive correlation between soil quality and soil Ca, Mg, and P. Ca and Mg, similar to Zn, are divalent cations and consequently they can compete directly with Zn for uptake by plant roots. So that the increased concentrations of Ca and Mg in high-quality soils can reduce Zn uptake by plant roots. Furthermore, the complex P-Zn interaction may be one of the reasons. In other words, high P can form insoluble Zn phosphate complexes in soil, interfere with Zn translocation within the plant, and increase plant growth, leading to a decrease in Zn concentration in plant tissues due to the dilution effect.
- Organic matter (OM) generally positively affects soil quality and nutrient holding capacity. In the short term, fresh, decomposing OM can release Zn and chelates that improve its absorption by plant roots. However, long-term and in stable soils, the stable and well-decomposed OM (humus) can tightly adsorb Zn due to imposing strong binding sites that make it less available for immediate plant uptake. Therefore, high OM content in a high-quality soil may act as a sink for Zn.

Sensitivity index and efficiency ratio

The summary statistics of soil quality indices, sensitivity index (SI), and efficiency ratio (ER) between soil quality index value and soil indicators are presented in Table 7. The IQI-TDS showed the most SI with the value of 1.47, while the least SI was related to NQI-MDS with the value of 1.32.

Table 7.

The computed ER for different soil quality indices models is shown in Table highlighted6. The IQI-TDS, having an ER of 66.66%, was ranked first, followed by NQI-MDS, NQI-TDS, and IQI-TDS with ERs of 33.33%, 14.81%, and 11.11%, respectively. According to Isong et al.[60], the final prioritizing of different indices was conducted by summation ranks of two criteria, with an assumption that the two selected criteria (SI and ER) have an equal share in the final decision. The lowest rank belonged to IQI-MDS, so it was selected as the best model to represent soil quality and crop yield in this research.

Fig. 8

Conclusion

Nowadays, drought and a decrease in soil quality are occurring rapidly in different parts of the world. Therefore, assessing and estimating soil quality and monitoring the factors affecting its improvement are very important and of great concern in order to maintain sustainable agricultural systems. Soil attributes, as good indicators, are recommended for soil quality evaluation. Biochar as a soil conditioner is commonly used to improve soil fertility, increase plant production, and decrease the adverse effects of water stress on plants. We aimed to evaluate the impacts of 0, 25, 50, and 100 t ha^{-1} of cattle manure-derived biochar on spinach yield and the soil quality indices (SQI) of the postharvest soils under 100, 70, and 55% of field capacity (FC) moisture conditions. The Nemero (NQI) and integrated (IQI) soil quality indices under the applied treatments and their grades were calculated using a total data set (TDS) of 27 soil indicators and the minimum data set (MDS) selected by the principal component analysis (PCA). PCA analysis revealed that six principal components (PCs) comprising the most influential indicators of soil iron, copper, and nitrogen concentrations, dry sieving-obtained mean weight (MWD_d), geometric mean (GMD_d), and aggregates diameter and ΔGMD that explained 94.77% of the cumulative variance. Furthermore, PCA showed that the most effective treatments with respect to their impacts on the studied characteristics were B50W55 and B100W55. Quality grades of the biochar-treated soil varied from III and I (IQI-TDS of nearly 0.63 to 0.81; IQI-MDS of nearly 0.61 to 0.87), III to II (NQI-TDS of nearly 0.37 to 0.50), and IV to III (NQI-MDS of nearly 0.51 to 0.63) under the studied drought conditions. Overall, regarding their effects on soil attributes, the highest score was obtained with the application of 100 t ha^{-1} biochar, and in relation to plant growth and properties, was obtained with the addition of 25 t ha^{-1} biochar. Whereas the lowest score in all studied properties was obtained without biochar application. In other words, the application of biochar, especially at the highest application level (100 t ha^{-1}), had a significant positive effect on improving soil quality, especially under drought conditions. The sensitivity index and efficiency ratio revealed that IQI-MDS was the best approach to representing soil quality with respect to crop yield. In conclusion, results confirmed that biochar could improve soil quality indices and crop yield through supplying nutrients and improving growing media. In other words, the addition of biochar as a soil conditioner and a stable source of organic matter can improve the health of soils as a major part of the environment, as well as crop yield, owing to the changes in soil physical, chemical, and nutritional properties, particularly under drought conditions that commonly occur in arid and semi-arid regions of the world. It is recommended to evaluate the effect of various levels of biochar produced from different sources on the growth and chemical composition of different plants, as well as the quality of a wider range of soils, in future studies.

Statements and Declarations

Acknowledgments

Biochar sample preparation and subsequent analyses were conducted at the Agricultural Research Station, College of Agriculture, Shiraz University, in Shiraz, Iran. Spinach seeds were sourced from Pakan Bazr Isfahan Company. The plants were cultivated and maintained in the research greenhouse of the Faculty of Agriculture, Shiraz University, until harvest. Soil and plant analyses for the experiment were also performed at the Department of Soil Science, College of

Agriculture, Shiraz University. The authors would like to express their gratitude to Shiraz and Fasa Universities for their invaluable support.

Funding

This work was supported by Shiraz University, Ali Akbar Moosavi (Grant No. 93GCU1M148056) and Fasa University, Maryam Zahedifar.

Author Contributions

MZ contributed to data curation, software, formal analysis, writing, reviewing, and editing, validation, conceptualization, and visualization. AAM contributed to project administration, methodology, software, supervision, validation, conceptualization, writing, reviewing, and editing. EG contributed to data curation, methodology, investigation, validation, and visualization.

Data Availability

All data generated or analyzed during this study are included in this published article.

Competing Interest

The authors declare competing interests.

Note: This study was conducted in the Agricultural Research Station, College of Agriculture, Shiraz University, Shiraz, Iran. It should be noted that the corresponding authors are academic staff of the college and no permission was required to access the field site.

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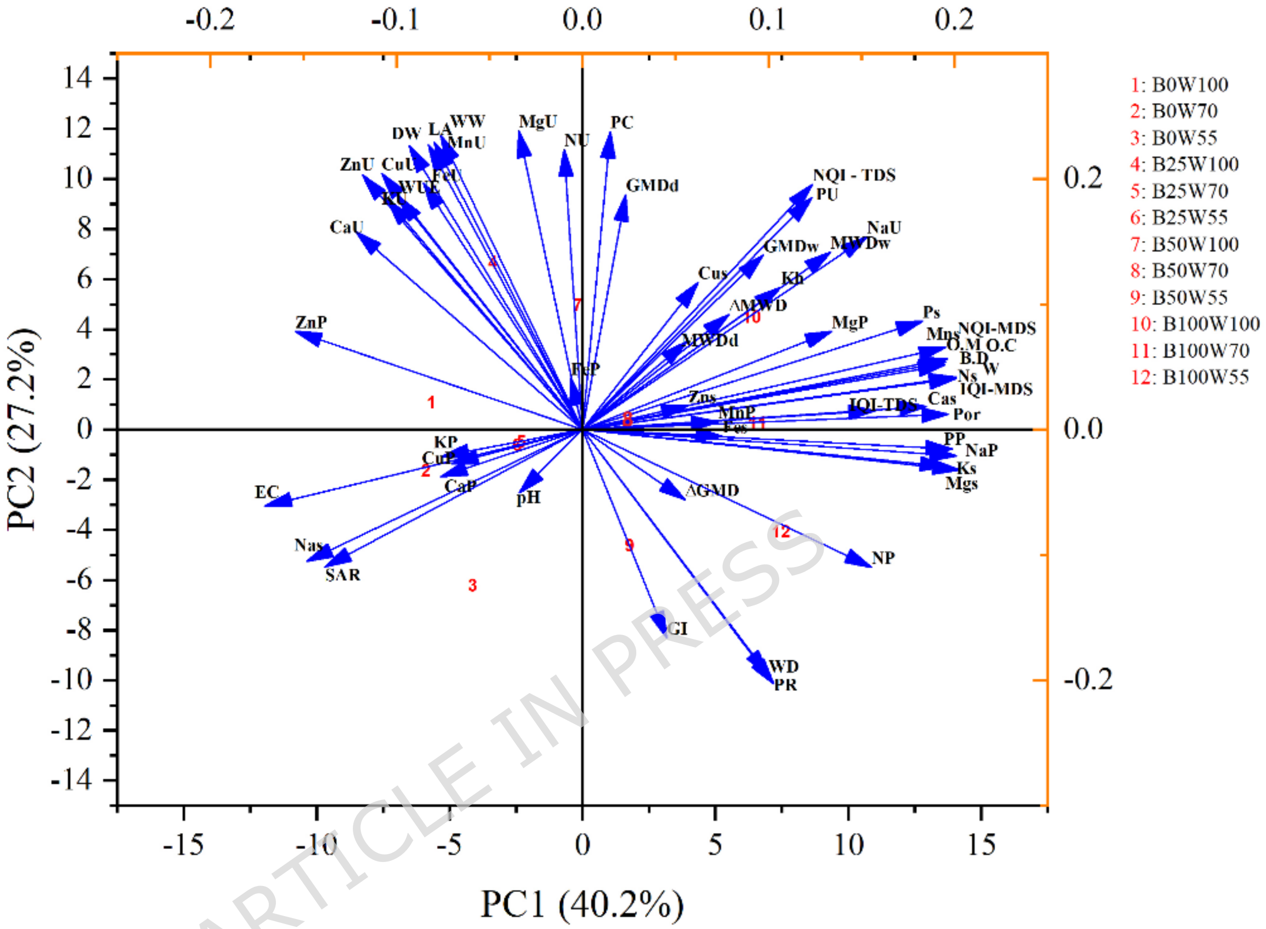


Fig. 1. Pearson correlation coefficients (r) for different soil attributes as influenced by different biochar and drought stress levels. B0, B25, B50, and B100 denote 0, 25, 50, and 100 t biochar ha^{-1}, respectively; W100, W70, and W55 show soil moisture conditions of 100, 70, and 55% field capacity, respectively. FeS, ZnS, MnS, CuS, NaS, KS, CaS, PS, MgS, NS, OM, pH, EC, OC, SAR, Kh, BD, W, Por, MWDd, GMDd, MWDw, GMDw, PR, and WR are available iron, available zinc, available manganese, available copper, soluble sodium, soluble potassium, soluble sodium, soluble sodium, available phosphorus, total nitrogen, organic matter, pH of saturated paste, electrical conductivity of saturated extract, organic carbon, sodium adsorption ratio, saturated hydraulic conductivity, bulk density, saturated water content, total porosity, mean weight diameter of aggregates by dry sieving, geometric mean diameter of aggregates by dry sieving, mean weight diameter of aggregates by wet sieving, geometric mean diameter of aggregates by wet sieving, penetration resistance, and water repellency, respectively. ΔMWD is the difference of MWDd and MWDw; ΔGMD is the difference of GMDd and GMDw. FeP, ZnP, MnP, CuP, NaP, KP, CaP, MgP, PP, NP, FeU, ZnU, MnU, CuP, NaP, KU, CaU, MgU, PU, NU, GI, LA, WW, DW, WUE, and PC are plant Fe concentration, plant Zn concentration, plant Mn concentration, plant Cu concentration, plant Na concentration, plant K concentration, plant Ca concentration, plant Mg concentration, plant P concentration, plant N concentration, plant Fe uptake, plant Zn uptake, plant Mn uptake, plant Cu uptake, plant Na uptake, plant K uptake, plant Ca uptake, plant Mg uptake,

plant P uptake, plant N uptake, greenness index, leaf area, wet (fresh) weight, dry weight, water use efficiency, and pore conductivity, respectively.

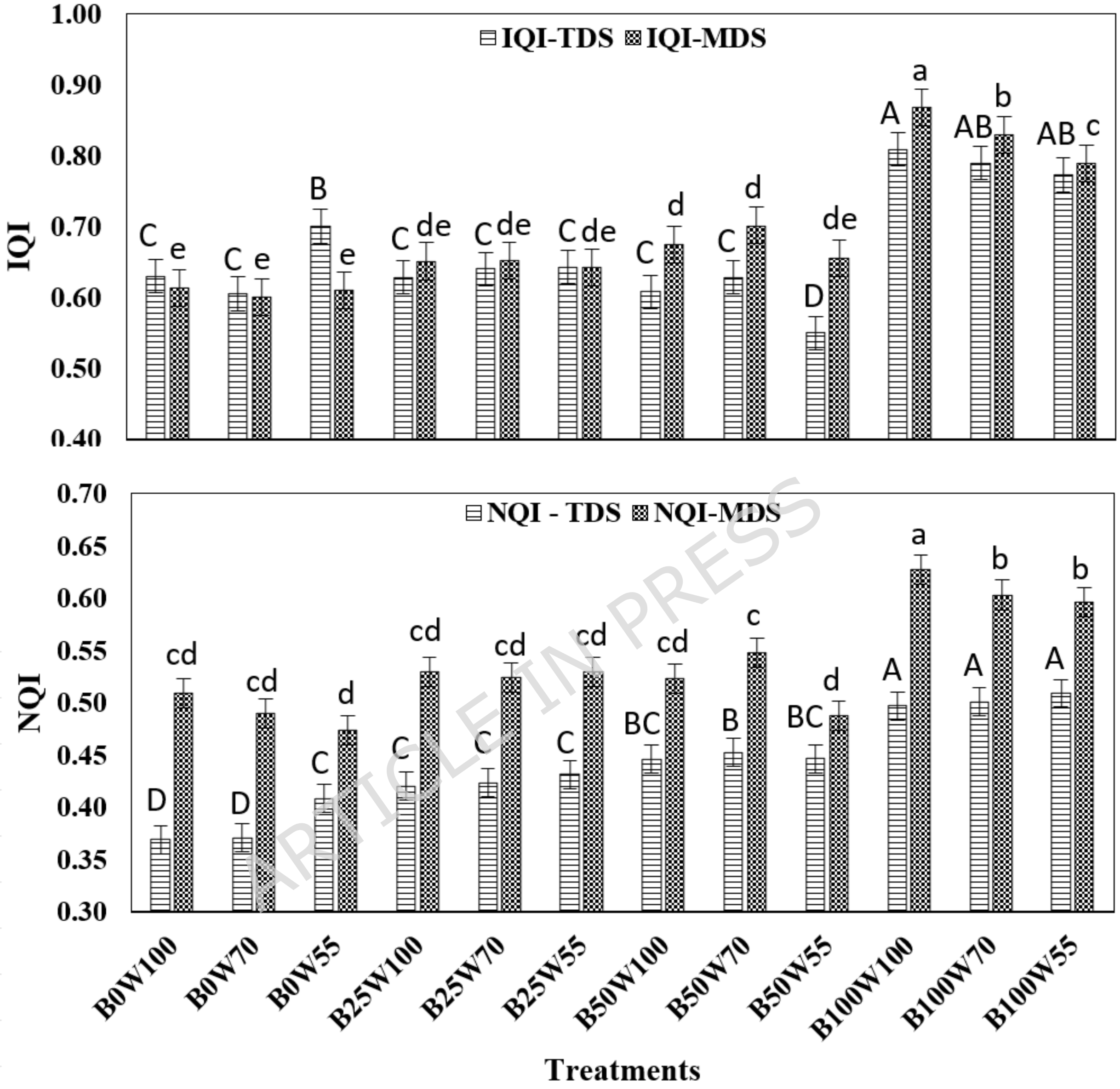


Fig. 2. Effect of different treatments on the integrated quality index (IQI) and Nemero quality index (NQI) based on the total data set (TDS) and minimum data set (MDS) indicator methods. Treatments consisted of 0, 25, 50, and 100 t biochar ha^{-1} (B0, B25, B50, and B100, respectively); soil moisture conditions of 100, 70, and 55% field capacity (W100, W70, and W55, respectively). For each soil quality index determined across different levels of applied treatments, columns followed by the same capital or lower-case letters (respectively for those calculated from the TDS and MDS) are not significantly different based on Duncan's Multiple Range test at the probability level of 0.05.

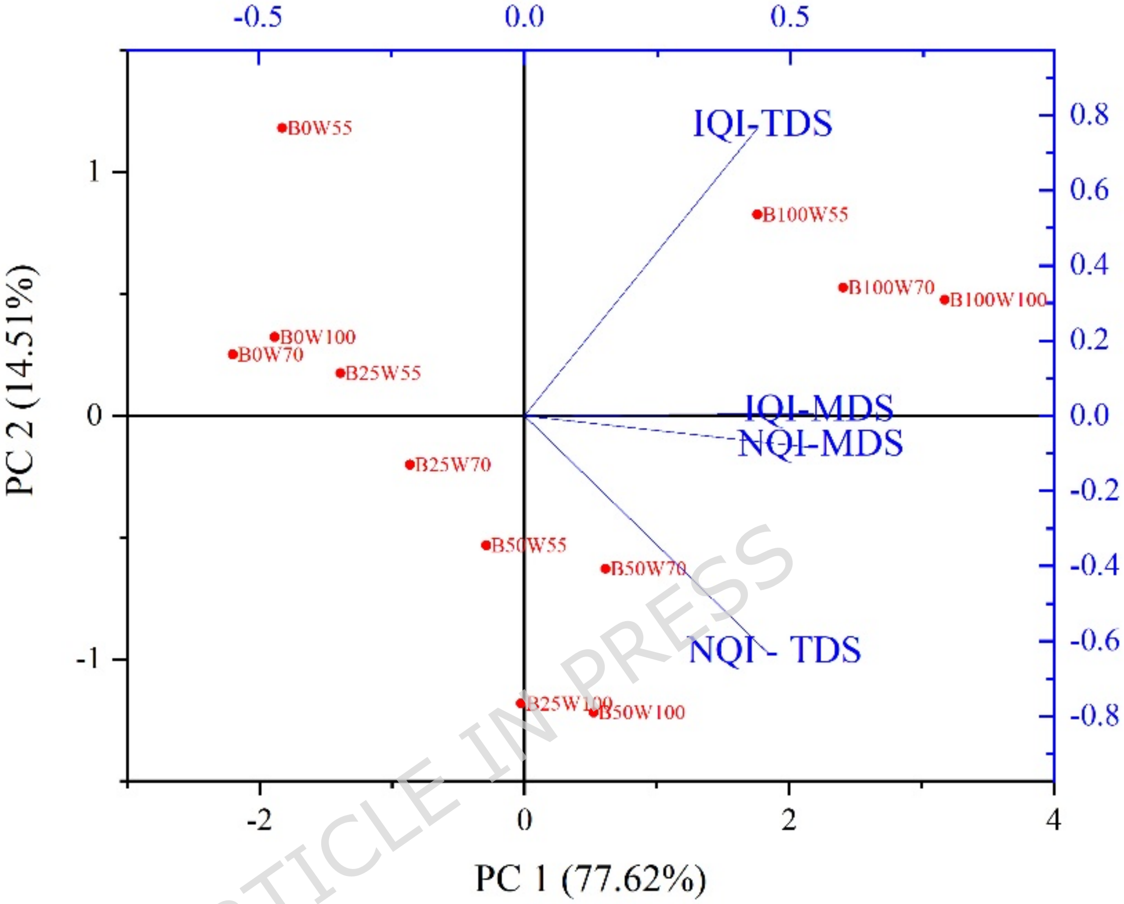


Fig. 3. Pearson correlation coefficients (r) between SQI (integrated quality index, IQI and Nemero quality index, NQI based on the total data set, TDS and minimum data set, MDS indicator methods) and different treatments (Treatments consisted of 0, 25, 50, and 100 t biochar ha^{-1} (B0, B25, B50, and B100, respectively); soil moisture conditions of 100, 70, and 55% field capacity (W100, W70, and W55, respectively).

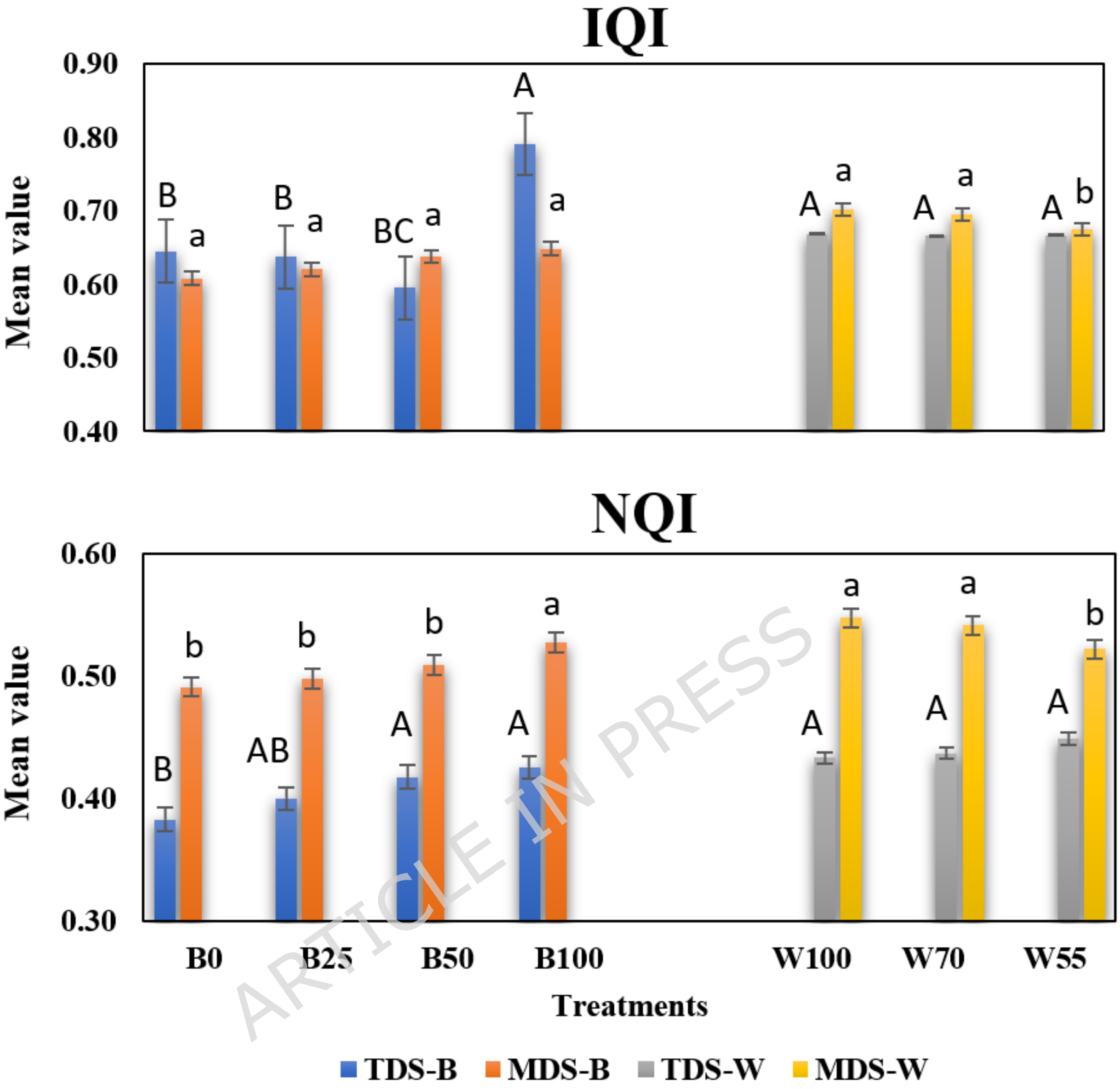


Fig. 4. The mean values of integrated quality index (IQI) and Nemero quality index (NQI) based on the total data set (TDS) and minimum data set (MDS) indicators as influenced by different levels of biochar (0, 25, 50 and 100 t biochar ha^{-1} named as B0, B25, B50, and B100, respectively) and soil moisture conditions (100, 70, and 55% field capacity named as W100, W70, and W55, respectively). For each SQIs determined across different levels of biochar (B) or moisture conditions (W), columns followed by the same capital or lower-case letters are not significantly different based on Duncan's Multiple Range test at the probability level of 0.05.

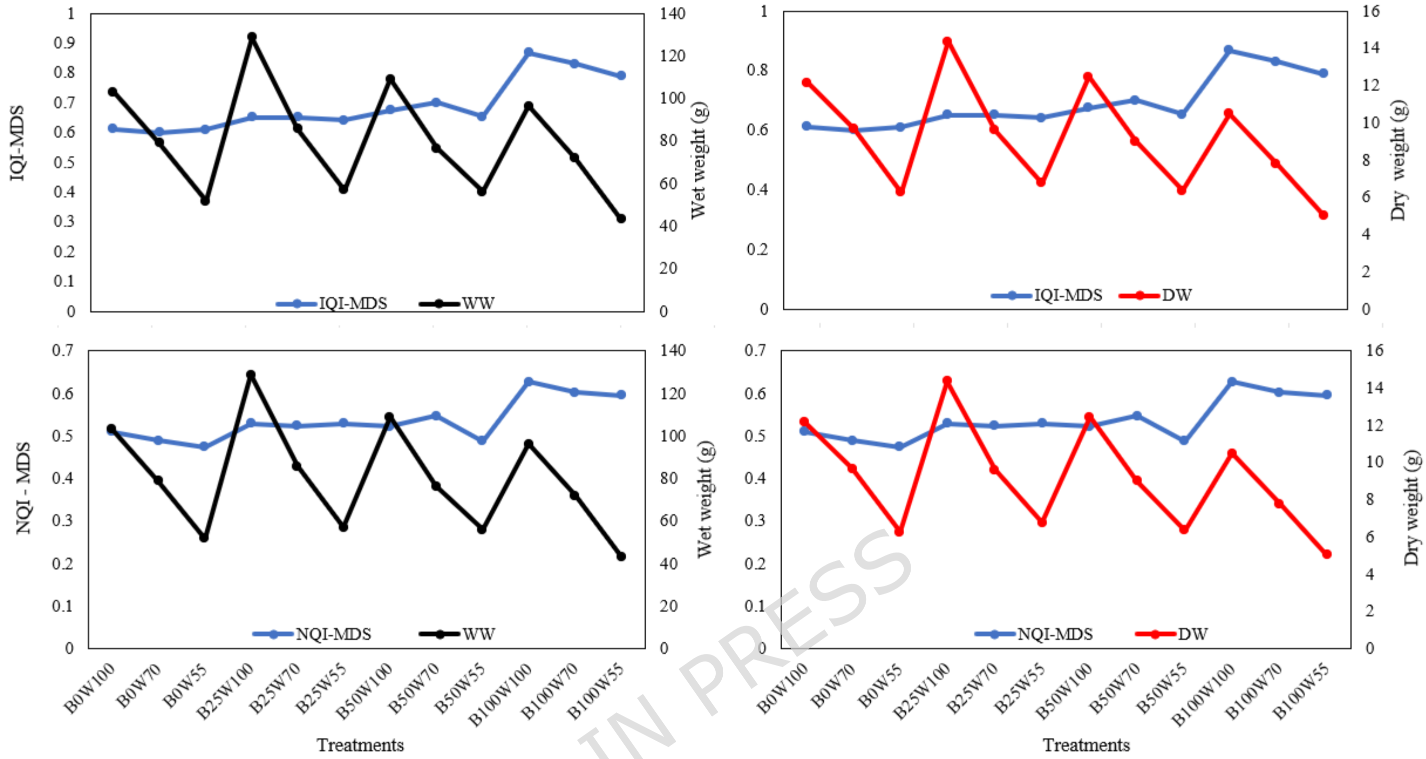


Fig. 5. Effect of applied treatments on shoot dry and fresh (wet) weights of spinach and their relations with the integrated quality index (IQI) determined based on the minimum data set (MDS) indicators (IQI-MDS) (Treatments consisted of 0, 25, 50, and 100 t biochar ha^{-1} (B0, B25, B50, and B100, respectively); soil moisture conditions of 100, 70, and 55% field capacity (W100, W70, and W55, respectively).

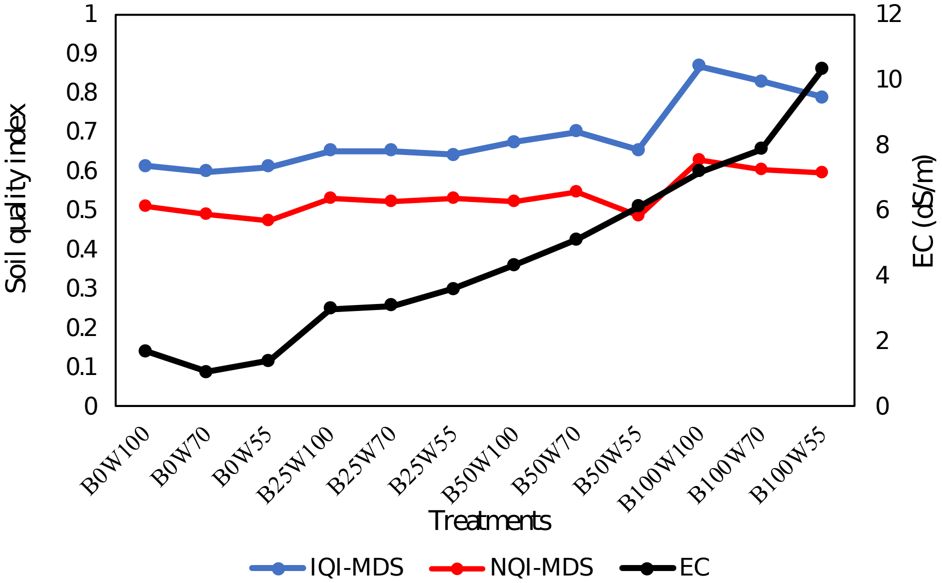
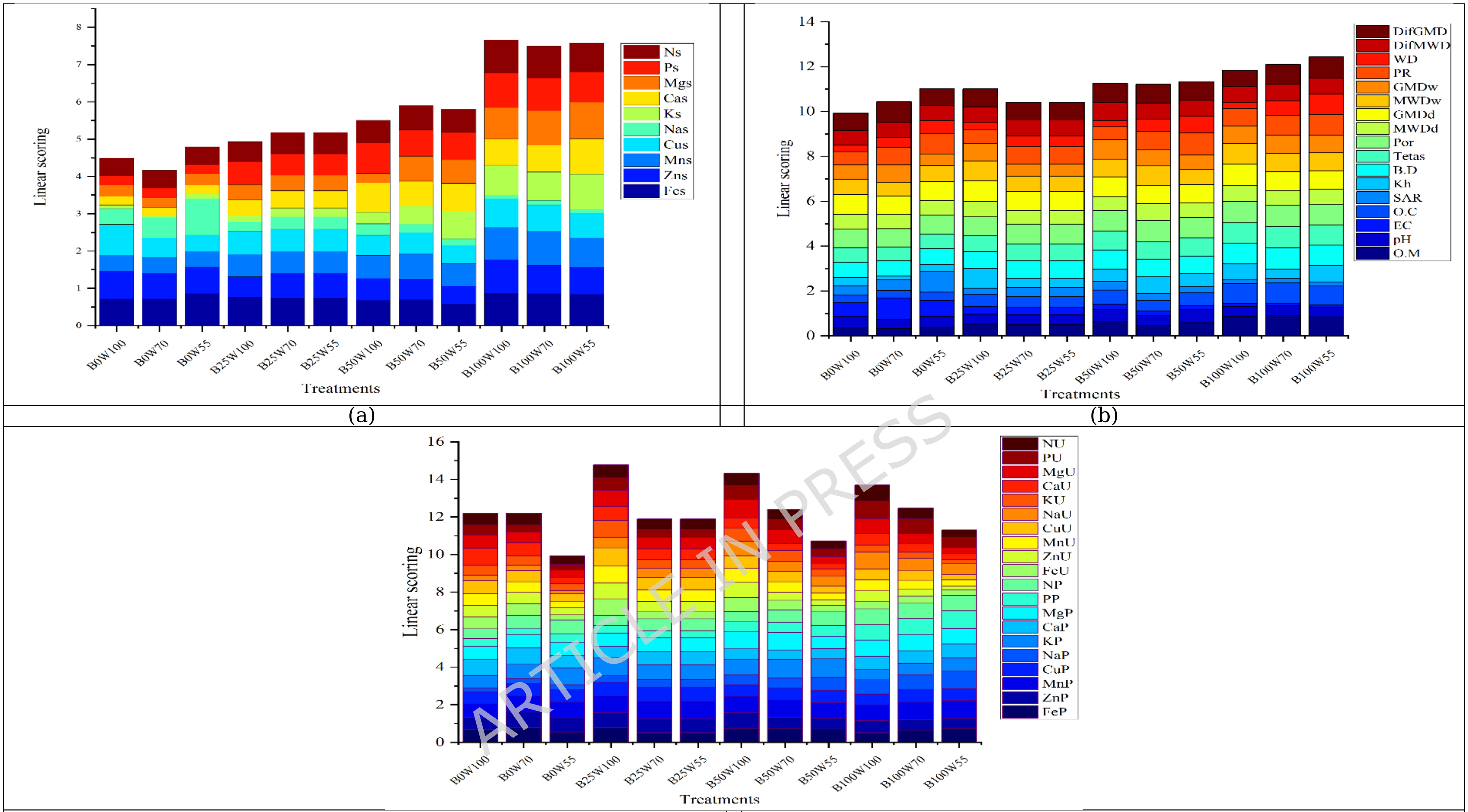


Fig. 6. Relationships between the integrated (IQI-MDS) and Nemero (NQI-MDS) quality indices determined based on the minimum data set and electrical conductivity (EC) of the spinach postharvest soil at different applied treatments consisted of 0, 25, 50 and 100 t biochar ha^{-1} (B0, B25, B50, and B100, respectively); soil moisture conditions of 100, 70, and 55% field capacity (W100, W70, and W55, respectively).



(a)

(b)

(c)

Fig. 7. Linear scoring of soil physicochemical and plant properties as influenced by different levels of biochar (0, 25, 50 and 100 t biochar ha^{-1} named as B0, B25, B50, and B100, respectively) and soil moisture conditions (100, 70, and 55% field capacity named as W100, W70, a04 W55, respectively). B0, B25, B50, and B100 denote 0, 25, 50, and 100 t biochar ha^{-1}, respectively; W100, W70, and W55 show soil moisture conditions of 100, 70, and 55% field capacity, respectively. FeS, ZnS, MnS, CuS, NaS, KS, CaS, PS;MgS, NS, OM, pH, EC, OC, SAR, Kh, BD, W, Por, MWDd, GMDd, MWDw, GMDw, PR, and WR are available iron, available zinc, available manganese, available copper, soluble sodium, soluble potassium, soluble sodium, soluble sodium, available phosphorus, total nitrogen, organic matter, pH of saturated paste, electrical conductivity of saturated extract, organic carbon, sodium adsorption ratio, saturated hydraulic conductivity, bulk density, saturated water content, total porosity, mean weight diameter of aggregates by dry sieving, geometric mean diameter of aggregates by dry sieving, mean weight diameter of aggregates by wet sieving, geometric mean diameter of aggregates by wet sieving, penetration resistance, and water repellency, respectively. ΔMWD is the difference of MWDd and MWDw; ΔGMD is the difference of GMDd and GMDw. FeP, ZnP, MnP, CuP, NaP, KP, CaP, MgP, PP, NP, FeU, ZnU, MnU, CuP, NaP, KU, CaU, MgU, PU, NU, GI, LA, WW, DW, WUE, and PC are plant Fe concentration, plant Zn concentration, plant Mn concentration, plant Cu concentration, plant Na concentration, plant K concentration, plant Ca concentration, plant Mg concentration, plant P concentration, plant N concentration, plant Fe uptake, plant Zn uptake, plant Mn

uptake, plant Cu uptake, plant Na uptake, plant K uptake, plant Ca uptake, plant Mg uptake, plant P uptake, plant N uptake, greenness index, leaf area, wet (fresh) weight, dry weight, water use efficiency, and pore conductivity, respectively.

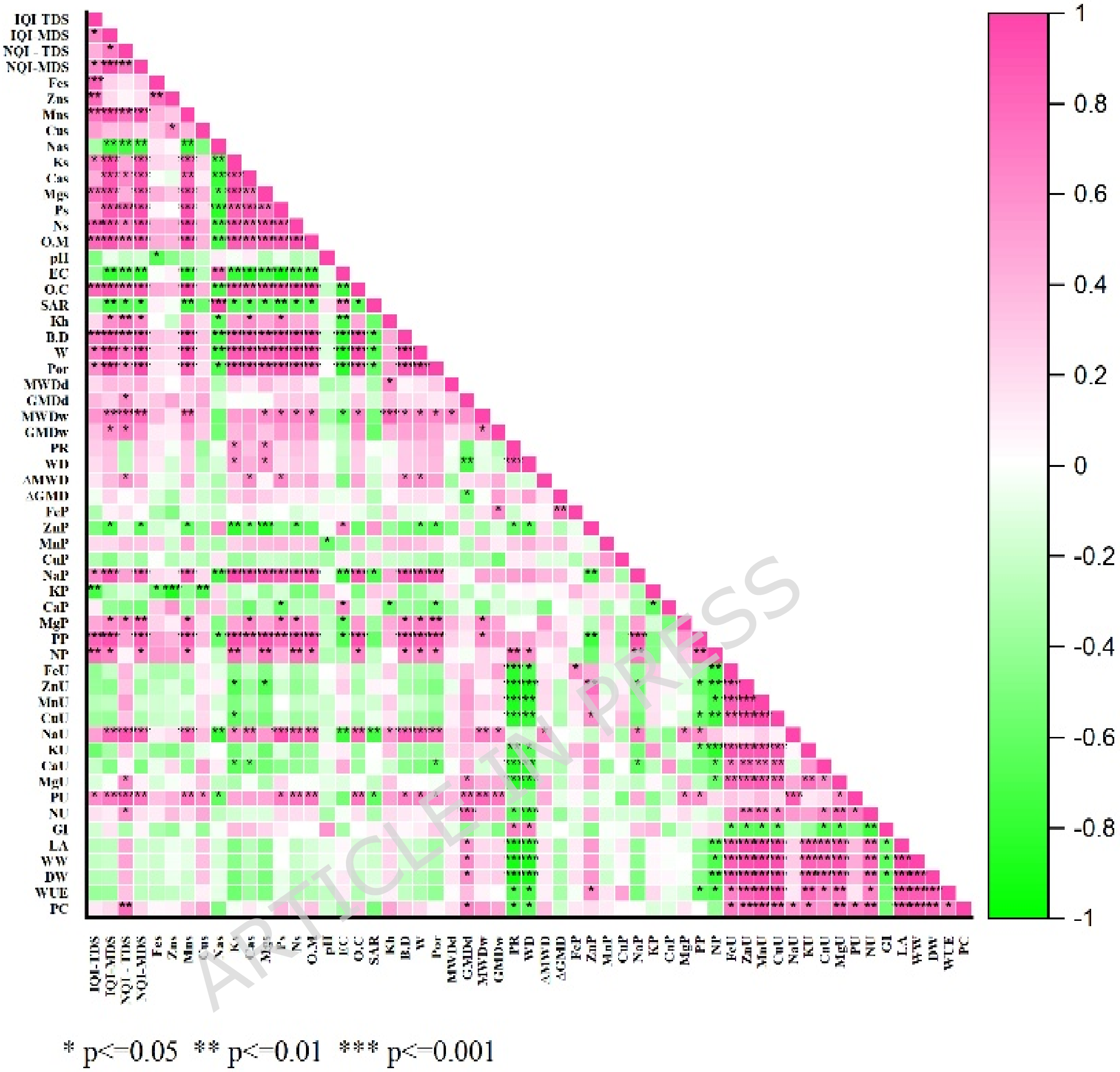


Fig. 8. Correlation analysis between soil quality indices (SQIs) and some soil–plant attributes. FeS, ZnS, MnS, CuS, NaS, KS, CaS, PS, MgS, NS, OM, pH, EC, OC, SAR, Kh, BD, W, Por, MWDd, GMDd, MWDw, GMDw, PR, and WR are available iron, available zinc, available manganese, available copper, soluble sodium, soluble potassium, soluble sodium, soluble sodium, available phosphorus, total nitrogen, organic matter, pH of saturated paste, electrical conductivity of saturated extract, organic carbon, sodium adsorption ratio, saturated hydraulic conductivity, bulk density, saturated water content, total porosity, mean weight diameter of aggregates by dry sieving, geometric mean diameter of aggregates by dry sieving, mean weight diameter of aggregates by wet sieving, geometric mean diameter of aggregates by wet sieving, penetration resistance, and water repellency, respectively. ΔMWD is the difference of MWDd and MWDw; ΔGMD is the difference of GMDd and GMDw. FeP, ZnP, MnP, CuP, NaP, KP, CaP, MgP, PP, NP, FeU, ZnU, MnU, CuP, NaP, KU, CaU, MgU, PU, NU, GI, LA, WW, DW, WUE, and PC are plant Fe concentration, plant Zn concentration, plant Mn concentration, plant Cu concentration, plant Na concentration, plant K concentration, plant Ca concentration, plant Mg concentration, plant P concentration, plant N concentration, plant Fe uptake, plant Zn uptake, plant Mn uptake, plant Cu uptake, plant Na uptake, plant K uptake, plant Ca uptake,

plant Mg uptake, plant P uptake, plant N uptake, greenness index, leaf area, wet (fresh) weight, dry weight, water use efficiency, and pore conductivity, respectively.