16 *Egypt. J. Agron.* **Vol. 46**, No.1, pp. 191 - 212 (2024)

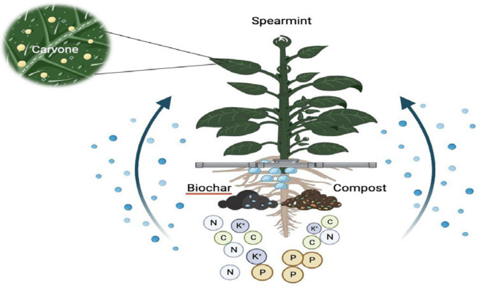
Egyptian Journal of Agronomy
http://agro.journals.ekb.eg/

The Potential Influence of Biochar and/or Compost on Spearmint Yield and Water Productivity in Newly Reclaimed Soil

Tahany Noreldin[1,*], Samia M. Abd-El Hameed[2], Mariam A. Amer[3], Mohamed A. A. Ahmed[4], and Alia Amer[2]
[1]Department of Water Requirement and Field Irrigation Research; Soils, Water and
;Environment Research Institute; Agricultural Research Center; Giza; Egypt
[2]Department of Medicinal and Aromatic plants; Horticulture Research Institute;
;Agricultural Research Center; Dokki; Egypt
[3]Agricultural Bioengineering Systems Research Department, Agricultural Engineering
;Research Institute; Agricultural Research Center, Dokki; Egypt
[4]Plant Production Department (Horticulture - Medicinal and Aromatic Plants),
;Faculty of Agriculture (Saba Basha), Alexandria University, Alexandria 21531, Egypt

MANY parts of the world are experiencing water shortages for agriculture. Since spearmint is a significant plant that uses much water, an enhanced irrigation management strategy is required. Soil additives with organic matter could potentially boost spearmint (*Mentha spicata* L.) water productivity. A field experiment was established under newly reclaimed soil throughout two growing seasons. This is to elucidate the influence of biochar, compost, and their combination under different irrigation water levels (120, 100, and 80% of crop evapotranspiration “ETo”) on spearmint yield, quality, and irrigation water productivity. The results of a split-plot design experiment indicated that the combination outperformed the individual application of compost or biochar under different irrigation levels regarding the studied variables. However, higher fresh herb yield (6.4 and 7.79 tons ha^{-1}) was recorded in the treatment receiving biochar mixed with the compost under 120% ETo in both seasons. Also, biochar mixed with compost offered the highest values of the essential oil component; carbon, under 80% ETo. Moreover, results showed that biochar and compost positively affected spearmint production by boosting leaf chlorophyll content and increasing nutrient absorption. In both seasons, data revealed that spearmint water productivity under 80% ETo was reduced by 18.28% and 7.92% relative to 100% ETo as well as 23.17% and 24.75% compared to 120% ETo using biochar combined with compost. Using a combination of compost and biochar is suggested as an extremely efficient way to boost spearmint yield and water productivity.

Keywords: biochar; compost, applied irrigation water, water productivity, spearmint (*Mentha spicata* L.)



Graphical Abstract

---

*Corresponding author email: dr.tahanynoreldin@arc.sci.eg. https://orcid.org/0000-0002-0262-3661
Received 11/06/2024; Accepted 23/7/2024
DOI:10.21608/agro.2024.297026.1444

Introduction

Medical and aromatic plants are majorly cultivated in the Mediterranean and other dry and warm regions of the world, where water deficit in agricultural systems is also problematic. The creation of diversity and sustainability can be attributed to the important role played by these systems. Furthermore, the use of organic fertilizers to manage soil nutrients is a key component of sustainable agriculture (Akanmu et al., 2023). Spearmint is *Mentha spicata* L., from the Lamiaceae family. The herb mint is a perennial with creeping rhizomes. Mint is one of the most significant herbs historically cultivated in Egypt (Edris et al., 2003). The plants in this family have large, highly serrated leaves and are an abundant source of polyphenols, which gives them powerful antioxidant qualities (Brown et al., 2019). According to Zare Dehabadi et al. (Zare Dehabadi et al., 2010), monoterpene chemicals make up a larger portion (98%) of spearmint essential oil, and then sesquiterpenes, make up a smaller portion (2%). As for the essential oil components, *Mentha spicata* may be distinguished from other mint species (Feo et al., 1998). Carvone, menthone, limonene, cis-dihydrocarveol, methyl acetate, pulegone, beta alpha-terpineol, -bourbonene, trans-caryophyllene, and alpha-pinene-and beta-pinene are some of the compounds found in this plant. Carvone is an oily, organic compound with a minty-licorice aroma that's found in many essential oils, including caraway, dill, and spearmint (Moosavy et al., 2015; Shiri et al., 2023).

Egypt is known for having an arid and semiarid climate and few water resources; hence it is essential to enhance water management for the produced crops by increasing water usage productivity and efficiency (M. A. Amer et al., 2021). In addition, sandy soils (mainly Arenosols according to WRB FAO) account for around 90% of Egyptian soils, providing considerable opportunity for agricultural expansion. These soils are distinguished by their poor physical and chemical qualities, as well as their low capacity to hold water and supply nutrients (Niel, 2021). Soil amendments improve the retentive capacity of sandy soil for water and fertilization nutrients, and they may also aid in the improvement of unfavorable structures and the increase of nutrient availability (Niel, 2021). Additionally, applying soil supplements that can aid in boosting water holding capacity and minimize water loss due to deep percolation to groundwater is required as Egypt expands its cultivation of new areas in fresh reclaimed soils. According to Sarong and Orge (2015) adding biochar to soil has been recommended as a way to boost long-term production and increase nutrient and water usage efficiency. The impact of applying biochar to several crops like tomato and wheat in Egypt has already been investigated (Ramadan and Maher Saad Saleh 2018; Ibrahim et al. 2019; Khalifa and Elareny 2020).

Biochar, a chemical and physiologically stable compound, is created by heating biological materials and pyrolyzing them (Amalina et al., 2023). Its application to soil for stability, carbon storage, and soil quality improvement has gained popularity (Hu et al., 2021; Zou et al., 2023). Biochar, due to its large surface area and porosity, can enhance soil water storage (El-Naggar et al., 2019; Sakhiya et al., 2020). It improves crop growth and production by enhancing soil aeration, nutrient retention, and availability. Biochar also affects plant root development by altering soil's nutrient and biochemical characteristics, and increasing levels of N, P, and K (Q. Wang et al., 2023; Wen et al., 2022). It provides vital elements and nutrients for plants, as noted by (Biederman & Stanley Harpole, 2013; Sun et al., 2017). Composting wastes enhance soil structure, chemical properties (pH, redox potential, conductivity, nutrients, and organic manure contents), water permeability, and soil capacity for water retention (Liu et al., 2019; Toundou et al., 2021; L. Wang et al., 2014). The amount of soil organic carbon and enzyme activity related to the breakdown of nitrogen and phosphorus were significantly increased by organic inputs, but they had no appreciable effect on the enzymes involved in the decomposition of carbon (Cui et al., 2023).

Despite the fact that extensive research has been undertaken on the use of sustainable agricultural practices that include biochar and compost as soil additive materials. Further research is necessary to determine how irrigation and soil amendments combine to increase crop output in water-scarce environments. Furthermore, little research has been performed regarding their use with aromatic and medicinal plants, especially spearmint and its oil composition. To recommend best sustainable use practices, a field study was conducted to assess the agronomical potential of biochar, compost, and their combination as co-composting additives to improve spearmint production under various irrigation levels. The study also focused on the essential oil chemical composition and the irrigation water productivity under recently reclaimed soils.

Methods

Site description

The trial site was located at the Experimental Farm of South El-Tahrir Horticulture Research Station, Ali Mubarak village, El-Bustan Area, El-Behira Governorate, Egypt (31°02′N and 30° 28′E and 6.7 m a.s.l.) during seasons of 2019 and 2020. The averages of weather parameters over the study site during the experimental period are given in (Figure1). It was obtained from the website: https://power.larc.nasa.gov/data-access-viewer/. Evapotranspiration (ETo, mm day^{-1}) was calculated using the BISm model (The Basic Irrigation Scheduling model, (Snyder et al., 2004). The Penman–Monteith equation (Monteith, 1965), as stated in the United Nations FAO Irrigation and Drainage Paper (FAO 56) by Allen et al. (1998), is used by the model to compute (ETo).

Experiment soil characteristics

Soil texture up to the 30 cm depth at the experimental site is sandy. According to (Jackson, 1973), (Wolf, 1982), and (Seilsepour et al., 2009), soil samples were taken from soil depth (0–30 cm), air-dried, crushed, and sieved through a 2-mm sieve to evaluate soil properties (Table 1).

Biochar and compost

Biochar was prepared from agricultural wastes by slow pyrolysis at 450 °C with a residence time of 2 h in the absence of oxygen. The biochar size distribution process was conducted at the Agricultural Engineering Research Institute using an Endecotts test sieve shaking machine (model number 62,02; England) into mesh size (90 µm) according to Amer et al. (2021). An electron-microscopic image of biochar is shown in (Fig. 2). The main characteristics of biochar were as follows: C 55.81%, N 2.66%, bulk density 0.57 mg m^{-3}, and pH 8.1. A commercial compost has been provided by a local manufacturer of agricultural inputs. It was prepared following normal standards produced from pure aerobic composting of biomass with chemical properties of C 32.07%, N 1.52%, bulk density 0.55 mg m^{-3}, and pH 7.72.

Trial design and treatments

The current investigation was organized in a split-plot design with three replications. The main plots were allocated to irrigation treatments, 120% ETo, 100% ETo, and 80% ETo. The subplots were assigned to soil amendment treatments and control; no added amendments, either biochar or compost (CON), Biochar (B), compost (C), and Biochar + compost (B+C) as illustrated in Fig. 3.

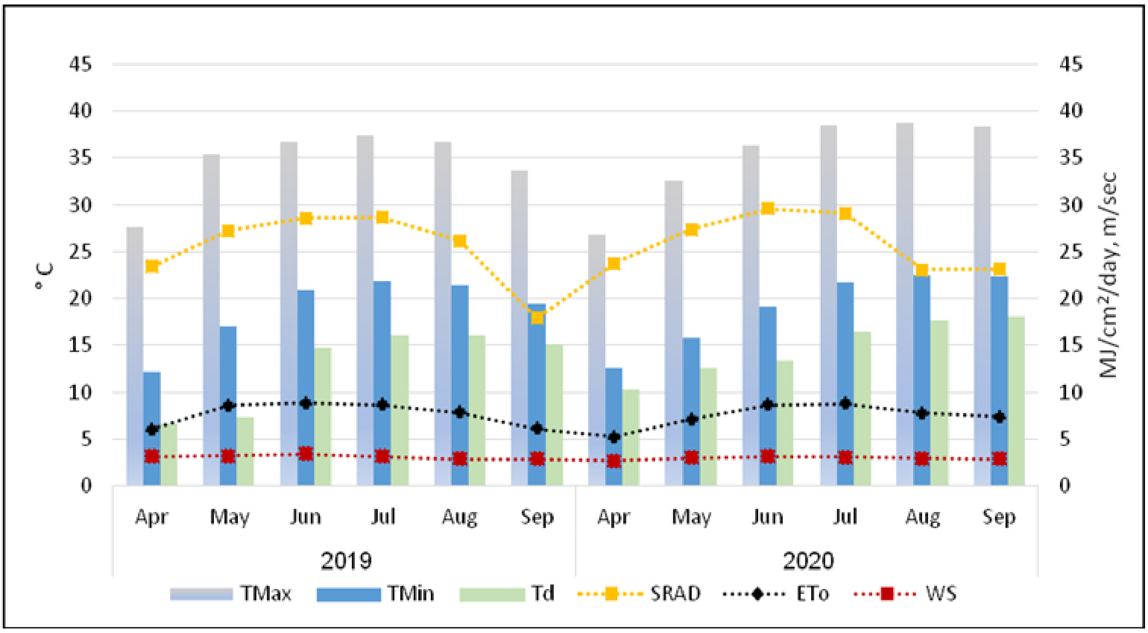


Fig. 1. Weather data for the study area in 2019 and 2020 two growing seasons. TMAX, TMIN, and Td= maximum, minimum, and dew point temperatures (°C); WS=wind speed (m/sec); SRAD= solar radiation (MJ cm^{-2} day^{-1}).

TABLE 1. Soil chemical and physical properties.

Soil texture							
Sandy							
	Silt +clay (%)	Sand (%)	Organic matter (%)	$CaCO_3$ (%)	Field capacity (%)	Wilting point (%)	Bulk density (t m^{-3})
	3.34	96.66	1.58	5.00	10.35	5.02	1.67

Available nutrients (mg kg^{-1} soil)			Soluble cations (meq l^{-1})				Soluble anions (meq l^{-1})			pH	EC (d m^{-1})
N	P	K	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	$HCO3^{-}$	$SO4^{2-}$		
23.78	2.78	110.45	1.10	0.37	1.56	0.17	1.37	0.87	0.96	8.38	0.32

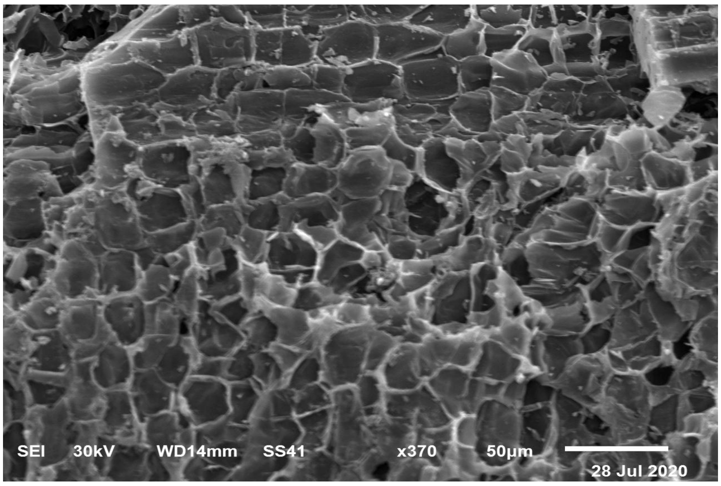
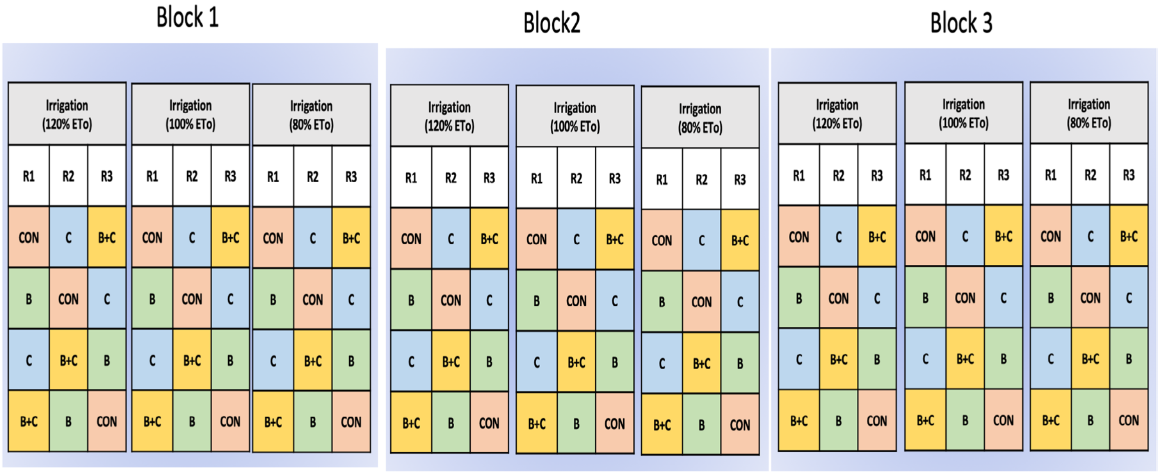


Fig. 2 An electron-microscopic image of biochar; source: own study.



Block 1

Irrigation (120% ETo)			Irrigation (100% ETo)			Irrigation (80% ETo)		
R1	R2	R3	R1	R2	R3	R1	R2	R3
CON	C	B+C	CON	C	B+C	CON	C	B+C
B	CON	C	B	CON	C	B	CON	C
C	B+C	B	C	B+C	B	C	B+C	B
B+C	B	CON	B+C	B	CON	B+C	B	CON

Block2

Irrigation (120% ETo)			Irrigation (100% ETo)			Irrigation (80% ETo)		
R1	R2	R3	R1	R2	R3	R1	R2	R3
CON	C	B+C	CON	C	B+C	CON	C	B+C
B	CON	C	B	CON	C	B	CON	C
C	B+C	B	C	B+C	B	C	B+C	B
B+C	B	CON	B+C	B	CON	B+C	B	CON

Block 3

Irrigation (120% ETo)			Irrigation (100% ETo)			Irrigation (80% ETo)		
R1	R2	R3	R1	R2	R3	R1	R2	R3
CON	C	B+C	CON	C	B+C	CON	C	B+C
B	CON	C	B	CON	C	B	CON	C
C	B+C	B	C	B+C	B	C	B+C	B
B+C	B	CON	B+C	B	CON	B+C	B	CON

Fig. 3 Experiment layout. where: CON= control, B= biochar, C= compost, B+C= biochar + compost.

Trial setup

In this study, before planting the spearmint plants, homogeneous mixing of biochar at 3.1 tons ha^{-1} (1ha ≈ 2.3805 feddan(and/or compost at the recommended dose of 24.4 tons ha^{-1}, as well as calcium superphosphate (15.5% P_2O_5) at the rate of 0.96 tons ha^{-1} with the surface layer of soil (0-30 cm). Spearmint stolons (15–20 cm in length with 10-12 leaves) were obtained from the Farm of Medicinal and Aromatic Plants Department, El-Kanater El-Khairiya, Qalyubia Governorate, Egypt. Stolons were transplanted at 25 cm apart in the mid of April for each season. Fertilizer and other recommended cultural practices were timely implemented until harvest according to the recommendation of the Ministry of Agriculture and Land Reclamation recommendations, Egypt. Using a drip irrigation system with 2 l/h discharge, water treatments were applied every three days after the plants were established. The mean of two harvests were conducted at 60% flowering, one at the beginning of July and the other at the beginning of September, during each growing season.

Plant performance was determined by measuring height (cm), and fresh weight (tons ha^{-1}). Essential oil percentage was analyzed by hydro-distillation for 3 hours using a Clevenger-type apparatus according to the methods described by Guenther (1950). The obtained volatile oil was evaluated in the Central Laboratory, Institute of Food Industry and Nutrition, National Research Center, Cairo, Egypt. by gas chromatography (Agilent 8890 GC system) equipped with a mass spectrometer (Agilent 5977B GC/MSD). Samples were diluted with hexane (1:19, v/v). The HP-5 MS column (30 m x 0.25 m internal diameter and 0.25 m film thickness) was installed in the GC. Analysis was fulfilled using carrier gas (helium) at a flow rate of 1 ml min^{-1} at a split ratio of 20:1, injection volume of 2 µl and the following temperature program: 50 °C for 0 min; rising at 4 °C min^{-1} to 240 °C and held for 0 min; rising at 10 °C/min to 280 °C and held for 5 min. The injector and detector were kept at 280°C. Electron ionization (EI) at 70 eV was used to obtain mass spectra; with a spectral range of m/z 40-550 and a solvent delay of 5 min. The spectrum fragmentation pattern was compared with those stored in Wiley and NIST Mass Spectral Library data to determine the identification of different constituents.

Photosynthetic pigment content in the fresh leaves was determined according to the protocol of Saric et al. (Saric et al., 1967). From 85% methyl alcohol extract by absorbance reading at 660, 640, and 440 nm, Calculations were made according to the equations proposed by (Benitez, 1989; Holm, 1954; Porra et al., 1989), as given below:

$$\text{Chlorophyll a (mg } g^{-1} \text{ tissue)} = 9.784 \times \text{A660} - 0.99 \times \text{A640}\ (V\ 1000'W) \text{ .... (1).}$$

$$\text{Chlorophyll b (mg } g^{-1} \text{ tissue)} = 21.426 \times \text{A640} - 4.65 \times \text{A660}\ (V\ 1000'W) \text{ .... (2).}$$

$$\text{Total Carotenoids (mg } g^{-1} \text{ tissue)} = (4.695 \times \text{A440} - 0.268 \times (\text{A660} + \text{A640}))\ \ (V\ 1000'W) \text{ ... (3).}$$

Determination of available macronutrient in spearmint leaves was determined according to Linder (1944), the dry herb of spearmint was digested using sulfuric acid, salicylic acid, and hydrogen peroxide**.** Nitrogen was ascertained using the micro-Kjeldahl apparatus according to Horneck and Miller (2019). Phosphorus and potassium were estimated according to the procedures defined by (Murphy & Riley, 1962) and (Feilden, 1983), respectively.

Crop water relation

Applied irrigation water

The amount of applied water was computed according to (Vermeiren, 1984) the equation is as follows:

$$AIW\ = \frac{ETo \times I}{Ea\ (1-LR)} \text{ .... (4).}$$

Where; AIW = depth of applied irrigation water (mm), ETo = reference evapotranspiration (mm d^{-1}), I = irrigation intervals (days), Ea = irrigation application efficiency of the irrigation system, LR = leaching requirements, the values of ETo and water consumptive use were calculated using the BISm model (Snyder, 2000).

Crop water productivity (WP)

The mint water productivity was calculated using the equation proposed by (Zhang, 2003):

$$WP\ 1\!\!\!= \frac{\text{Mint } yield, Y\ (kg\ ha^{-1})}{Applied\ irrigation\ water\ (m^3\ ha^{-1})} \text{ .... (5).}$$

Statistical analysis

To assess the average ± standard deviation

(SD) of triplicates, data were statistically calculated. Statistical analysis was accomplished at a 0.05 level of significance by two-way analysis of variance (ANOVA) using the SPSS program for Windows (Version 21) (SPSS, IBM Corporation, Armonk, New York, USA). Cluster analysis, Principal Component Analysis (PCA), and biplot, for the essential oil components, were completed by using the software XLstat-Pro 2023 (Addin soft) (Cozzolino et al., 2009).

Results and Discussions

Soil chemical properties

Soil pH decreased significantly ($p < 0.05$) in the soil amended with biochar, compost, and their mixtures as given in Table 2. Compared to the untreated soil, the biochar application decreased soil pH by 5.06%, 6.00%, and 6.68% under 120% ETo, 100% ETo, and 80 % ETo, respectively. Combined biochar and compost significantly decreased soil pH as compared to the application of biochar (B) or compost (C) alone under all the irrigation treatments. Moreover, data demonstrated that the addition of soil amendments greatly enhanced the available N, P, and K. In addition, when biochar and compost were combined (B+C), the amount of available N, P, and K rose significantly in comparison to when biochar or compost treatment was applied alone (Table 2). As seen in Table 2., the data indicated that at the irrigation of 120% ETo, biochar mixed with compost application (B+C) significantly increased the available N by 6.21% and 10.56%, available P by 2.5% and 3.75%, and available K by 2.18% and 3.98%, as compared with treated soil with biochar or compost alone, respectively. Moreover, at the irrigation of 80% ETo, B+C enhanced the available N by 5.53% and 10.06%, available P by 16.12% and 20.73%, and available K by 3.65% and 7.21%, as compared to biochar or compost alone, respectively. Likewise, adding compost and biochar raised the total organic carbon in the soil by 19.2% and 76.1% compared to biochar and compost, respectively, under 120% ETo. Whereas, the increase in carbon in the soil under 80% ETo was about 16.46% and 72.7% when adding biochar and compost compared to using biochar and compost individually, respectively.

Plant performance

The response of spearmint growth to the applied biochar and compost under the different irrigation levels is shown in Figs. (4a) and (4b), generally in both seasons, all irrigation treatments had a significant influence on the spearmint performance. Data showed that the irrigation treatments of 120% ETo had the maximum values of plant height, and fresh weight (tons ha^{-1}) followed by irrigation treatment of 100% ETo, then 80% ETo of irrigation. In addition, (Figs. 4a and 4b) indicated that the combined application of the two amendments; biochar and compost presented a pronounced effect as compared to the solo applications. Moreover, biochar mixed with compost application (B+C) gave a significantly superior value of spearmint plant height and fresh weight (tons ha^{-1}) compared to the influence of biochar (B) or compost (C) solely. In this concern, plant height at the application of B+C increased by 30.95% compared to control under 120% ETo, while increased by 34.47% and 29.67% under 100% ETo and 80% ETo respectively. Likewise, the fresh weight yielding at the application of B+C showed an increase of 30.26%, 33.17%, and 26.98% compared to the control under the irrigation treatments 120%, 100%, and 80% ETo. Data resulting in the second season had been obtained with similar trends of increasing.

TABLE 2. Soil chemical properties as affected by biochar, compost, and their mixtures after spearmint harvesting plants.

Treatments		N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Total organic C %	pH
Untreated soil (without biochar or compost)		29.00	3.11	170.15	10.7	8.3
(120%)	**B**	33.21	3.90	184.00	16.7	7.90
	C	31.67	3.85	180.60	4.94	7.89
	B+ C	35.41	4.00	188.10	20.67	7.87
(100%)	**B**	39.61	4.90	193.20	17.12	7.83
	C	37.87	4.52	189.97	5.501	7.91
	B+ C	41.80	5.42	196.74	23.33	7.84
(80%)	**B**	44.22	6.35	212.17	20.45	7.78
	C	42.11	6.00	204.33	6.68	7.80
	B+ C	46.81	7.57	220.21	24.48	7.72

B= biochar, C= compost, B+C= biochar + compost.

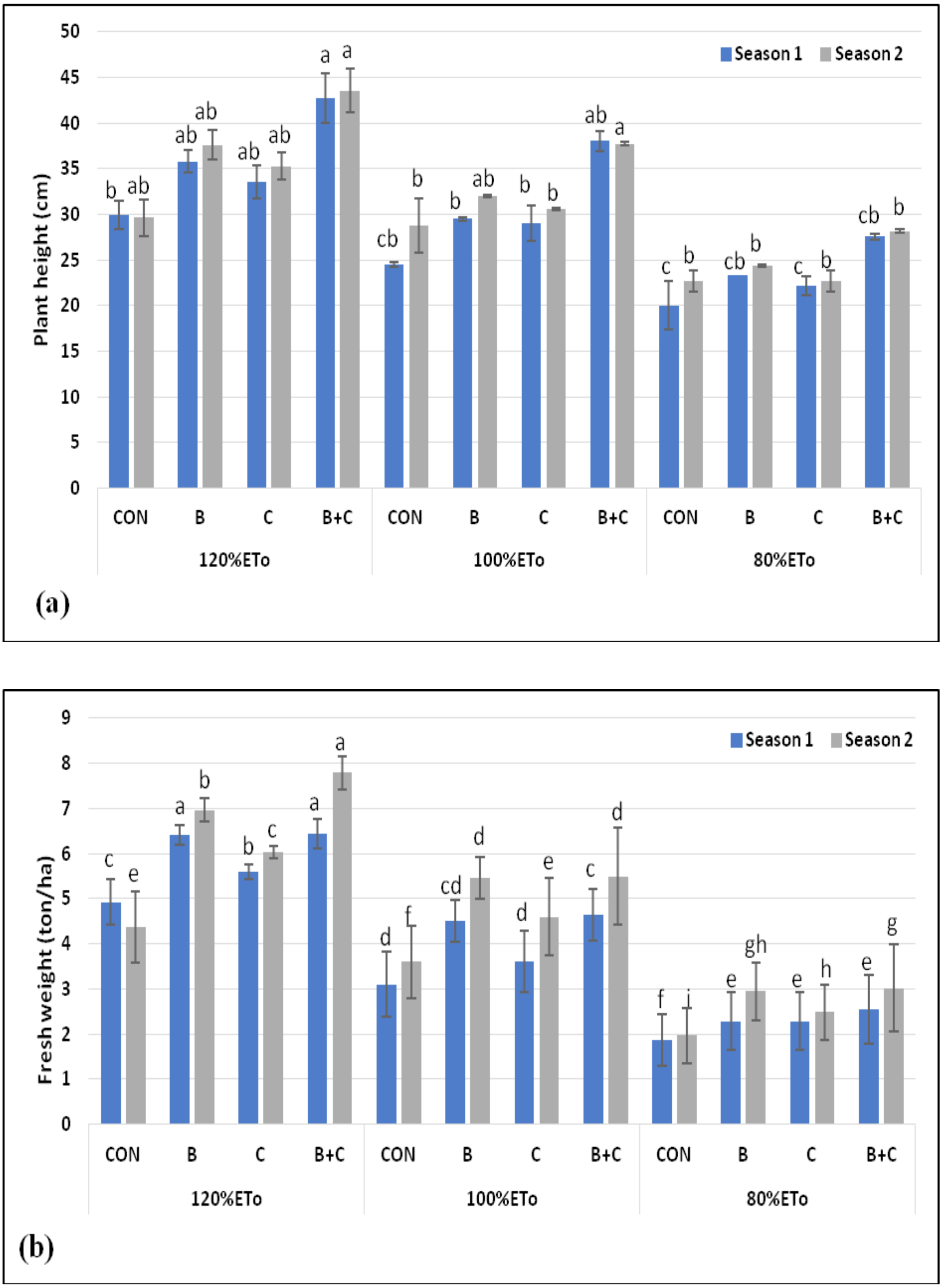


Fig. 4. Correlation of irrigation and soil amendment treatments on spearmint plant height (a), fresh weight (ton/ha) (b) during two successive seasons. Where: CON= control, B= biochar, C= compost, B+C= biochar + compost. Letters above bars indicate significantly different means according to the Duncan test (α = 5%) within the same year, Season 1 = 2019, Season 2 = 2020.

The simultaneous application of compost and biochar has been identified as a promising and effective way to improve soil that will increase plant development and yield because of their synergistic effects (Qian et al., 2023). Applying biochar or compost significantly increased soil chemical properties and spearmint performance compared to the control although biochar was more effective than compost additives. Furthermore, spearmint yields from applying biochar and compost (B+C) combined were superior under all irrigation conditions (Table 2 and Fig. 4). More research is being done on the relationship between compost and biochar in mixed applications (Antonangelo et al., 2021; Wu et al., 2017). It is worth mentioning that biochar has a higher content of stable organic carbon composites than compost, which causes it to slowly decompose in the soil (Eissa, 2019; Mahmoud et al., 2018). However, Jien et al. (2015) hypothesized that the combination of compost and biochar was superior to either material alone for stabilizing and preserving carbon since compost can help with biochar's nutrient deficiencies, and biochar may prolong compost's lifespan within the soil (Elias et al., 2020; Jien et al., 2018; Sanchez-Monedero et al., 2018). Consequently, it improves the physiochemical properties of the soil, the activity of soil enzymes and microbes (Ali et al., 2021; Brendecke et al., 1993), stimulation of root development, and the uptake of water-soluble nutrients, all of which contribute to increased crop productivity (Almaroai & Eissa, 2020; Netherway et al., 2019; Oram et al., 2014; Sohi & Lopez-Capel, 2009). Following the co-composting process, the biochar-compost shows changes in its cation exchange capacity (CEC) (Antonangelo et al., 2021). This function is allied with the surface properties of soil organic and organic mineral components, which include cation and anion exchange capacity, physical and chemical adsorption, and desorption properties. These features define nutrient availability, cation equilibrium, and the efficacy of fertilizers and xenobiotic compounds, as well as the improvement of soil structural stability as well as faunal, microbial, and enzymatic activities stimulation that influence the C, N, P, and S cycles (Masmoudi et al., 2020; Niel, 2021; Yuan et al., 2023).. Basil growth was reported to be enhanced by a mixture of biochar and chemical fertilizer, but the use of biochar alone wasn't enough to improve crop growth (Pandey et al., 2016). Jain et al. (2017) found that biochar amendment can significantly enhance the biomass of *Bacopa monnieri* L. and reduce metal accumulation in plant tissues. In other works, (Li et al., 2021; Liang et al., 2019) indicated that biochar, when combined with mineral fertilizer, has been shown to increase maize yield by 20%, which enhances plant growth and nutrient solubilization. Also, Mumivand et al. (2023) found that the use of 6% biochar resulted in a 12% increase in plant height, as well as an increase in internodes, shoots, leaf width, and length. According to many studies, the addition of biochar enhances, stem width and biomass as well as plant height in rice, tea, and tomato plants (Chen et al., 2021; Gao et al., 2020; Zou et al., 2023).

Physiological parameters

Essential oil content (%) and GC analysis

The oil content shown a slight increase with biochar application in both biochar (B) and biochar + compost (B+C) treatments under all irrigation treatments (Fig. 5). The oil content didn't change significantly between the 2019 and 2020 seasons. According to Fig. 5, essential oil (%) witnessed increases of 38.15%, 39.88%, and 40.15% for the values of the rise brought on by the use of B+C at 120%, 100% ETo, and 80%. In the second season, B+C applications at 120%, 100% ETo, and 80%, respectively, witnessed increases of 41.01%, 29.79%, and 34.46%. Additionally, the first season's progressive values with B+C were 1.19% at 100% ETo, 1.01% at 80% ETo, and finally 0.97% at 120% ETo, with the second season exhibiting the same trends.

The volatile compounds of spearmint oil samples taken from the 2nd cut in the second season were evaluated by GC-MS. By comparing the mass spectra with the available commercial mass spectra libraries, volatile chemicals were found (Wiley and NIST). About 30 volatile constituents were detached and settled, and the results are shown in (Table 3). The most abundant compounds of essential oils were D-limonene (3.56-18.36 %), 1,8 cineole (2.27-10.23%), anethol (1.67-10.53%), while other compounds were exposed in much lower quantities (< 2%). Regards the results in (Table 1), the application of the different soil amendments at the different irrigation treatments showed a positive influence on the carvon percentage. It could be concluded that the application of B+C at 120% ETo gave the highest carvon content (67.34%), followed by B (64.55%) and B+C (64.09%) at 80% ETo, then B+C (60.04%) at 100% ETo. Otherwise, the minimum carvon percentage was observed at the CON treatment (no soil amendments added) under the 80% ETo (43.42%).

Moreover, eco-friendly products such as biochar and compost may impact plants› essential oils production in terms of nutrient availability under abiotic stresses (Ghassemi-Golezani & Rahimzadeh, 2022). Secondary metabolites of medicinal plants have been shown to alter in response to irrigation levels, despite a reduction in plant productivity (Amer et al. 2019; Amer et al., 2019; Amer et al., 2021; Hammam et al., 2019; Pandey et al., 2016). The increase of the essential oil content at low levels of irrigation water (Fig. 5, and Table 3) was reinforced by the earlier reports on *Mentha varidis* L. (El-Gamal et al., 2021) and *Pelargonium graveolens* L. (Hammam et al., 2021). The reduction in leaf area due to a shortage of water can result in a higher density of oil glands, which can increase essential oil (Behera et al., 2014; Bettaieb et al., 2009). Furthermore, the effect of added biochar with compost as a soil amendment on spearmint, and essential oil percentages was more significant under water stress (80% of ETo). Similar findings were observed by (Beiranvandi et al., 2022; Mehdizadeh et al., 2021; Mumivand et al., 2023; Ouertatani, 2021). In addition, the current study also discovered that the combined application of biochar and compost showed a pronounced effect in imparting carvon concentration in the essential oil. This may be due to that the use of biochar with compost enhances the soil's water-holding capacity, which in turn enhances water mobility to the leaves, thus the plant's metabolic activities are enhanced, leading to the secondary metabolites production (Petruccelli et al., 2015). Also, the production of secondary metabolites is impacted by the availability and uptake of nutrients by plants through biochar application (Petruccelli et al., 2015). An earlier study (Najafian & Zahedifar, 2018) confirmed that the amount of monoterpenoids and sesquiterpenes in sweet basil oil is significantly influenced by biochar and potassium, leading to the highest essential oil concentration. Conversely, the findings from Marchese and Figueira (2005), Pandey et al. (2016), and Singh (2013) demonstrated that the oil components weren't affected by the use of biochar, whether it was alone or paired with chemical fertilizers. That is because the chemical components of oil scents are heavily influenced by environmental influences, including weather.

To explain the relationship between volatile components and soil amendment treatments, data from GC–MS were tested by Agglomerative Hierarchical Clustering (AHC) analysis and Principal Component Analysis (PCA).

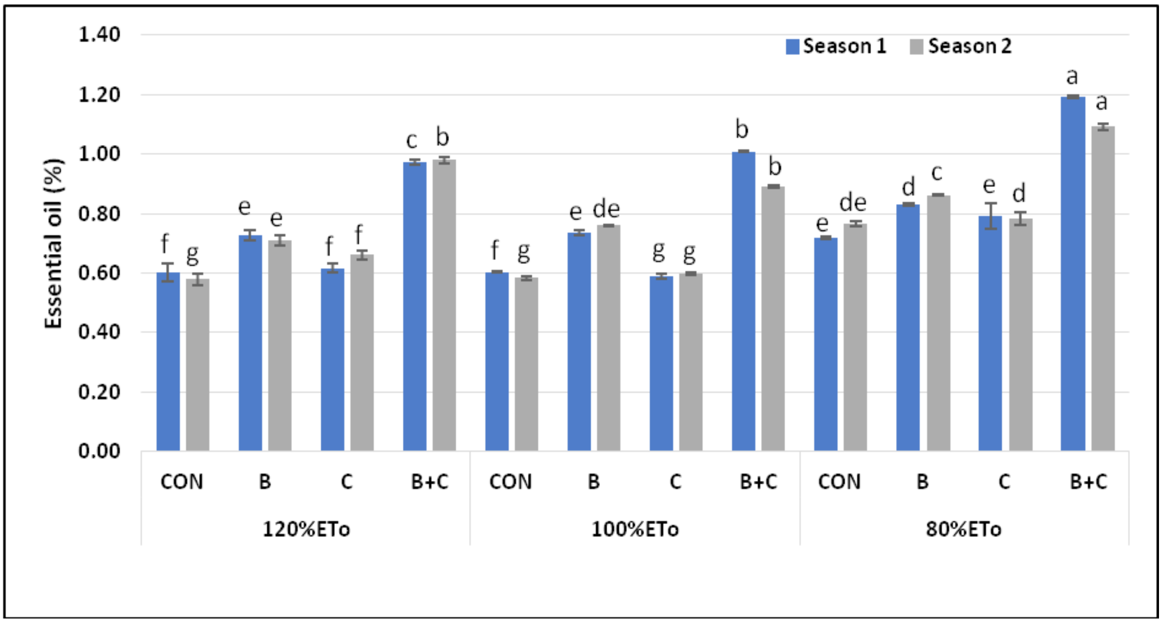


Fig. 5. Correlation of irrigation and soil amendment treatments on spearmint essential oil % during two successive seasons. Where: CON= control, B= biochar, C= compost, B+C= biochar + compost. Letters above bars indicate significantly different means according to Duncan's test (α = 5%) within the same year, Season 1 = 2019, Season 2 = 2020.

TABLE 3. GC Mass for spearmint essential oil.

Peak	RT	Component name	Treatments											
			120 % ETo				100 % ETo				80 % ETo			
			CON	B	C	B+C	CON	B	C	B+C	CON	B	C	B+C
1	6.34	α-Pinene	1.31	-	1.21	-	1.50	-	1.61	0.58	2.45	0.61	1.45	-
2	7.298	Sabinene	1.83	-	1.33	-	2.39	-	1.38	-	1.18	0.79	1.18	-
3	7.39	β-Pinene	2.02	-	1.92	0.51	2.31	-	2.29	1.02	2.20	1.07	2.2	0.48
4	7.708	β-Myrcene	-	-	1.01	-	1.04	-	1.05	-	1.92	0.67	0.96	-
5	7.835	3-Octanol	-	-	-	-	-	-	-	-	-	0.45	-	-
6	8.621	p-Cymene	-	0.66	-	0.5	-	-	-	-	-	-	-	1.26
7	8.73	D-Limonene	15.32	3.73	15.17	7.32	18.36	3.56	18.31	12.21	14.7	10.82	16.73	5.06
8	8.817	Eucalyptol	10.23	2.27	10.23	3.04	9.77	3.72	9.64	2.88	9.68	8.31	9.68	4.18
9	9.545	γ-Terpinene	-	-	-	0.45	-	-	-	-	-	-	-	-
10	9.805	cis-Sabinenhydrate	2.83	1.43	2.8	1.02	1.63	0.85	1.62	-	2.94	3.00	0.94	3.86
11	10.677	Linalool	-	-	-	0.59	-	-	-	-	-	-	-	0.44
12	12.23	l-Menthone	1.15	1.98	1.16	2.89	-	1.13	-	1.90	1.98	-	1.95	3.26
13	12.536	6-Methyl-cyclodec-5-enol	-	0.81	-	1.11	-	-	-	0.89	0.89	-	0.69	0.87
14	12.6	endo-Borneol	1.00	1.55	0.99	0.64	0.84	1.46	0.84	-	0.94	1.51	0.94	1.59
15	12.756	Isomenthol	0.99	3.32	0.95	1.88	-	1.62	-	2.96	3.17	-	2.17	2.15
16	12.9	Terpinen-4-ol	0.69	1.54	0.59	-	1.67	1.08	1.00	-	1.34	1.18	1.34	0.89
17	13.27	α-Terpineol	3.21	3.4	2.22	-	2.91	3.83	1.83	-	2.06	2.98	2.06	3.11
18	13.38	Dihydrocarveol	0.71	1.66	0.71	0.83	0.67	3.1	0.64	2.29	2.07	-	2.07	0.56
19	13.457	Anethole	3.28	10.53	2.29	3.22	1.98	9.64	1.92	3.53	3.51	1.67	3.51	4.61
20	14.084	trans-Carveol	-	4.07	-	0.8	1.00	8.59	1.08	1.00	2.63	-	2.63	-
21	14.442	Carveol	-	-	-	1.97	-	1.62	-	1.66	-	-	-	-
22	14.633	(±)-Pulegone	-	-	-	0.62	-	-	-	0.83	-	-	-	-
23	14.852	Carvone	52.08	57.95	54.12	67.34	52.5	57.21	55.8	60.04	43.42	64.55	47.26	64.09
24	16.071	Isomenthol acetate	-	-	-	-	-	-	-	1.95	0.89	-	0.82	-
25	16.983	Dihydrocarvyl acetate	-	-	-	0.62	-	-	-	2.23	-	-	-	-
26	17.89	Carveol acetate	-	-	-	1.37	-	-	-	1.68	-	-	-	-
27	18.531	(-)-β-Bourbonene	0.65	1.28	0.68	1.38	-	1.02	-	1.4	-	0.97	-	1.38
28	19.427	β-Caryophyllene	1.87	2.95	1.76	-	1.43	1.59	1.00	0.94	2.02	1.42	1.42	2.22
29	20.963	β-Cubebene	0.83	0.86	0.87	1.09	-	-	-	-	-	-	-	-
30	28.719	trans-Pseudoisoeugenyl 2-methylbutyrate	-	-	-	0.81	-	-	-	-	-	-	-	-

Where: CON= control, B= biochar, C= compost, B+C= biochar + compost.

Analysis of hierarchical clusters is based on the similarity between samples about the physicochemical components, HCA seeks to categorize things into groups. Figure 6 illustrates the HCA accomplished to differentiate the mint samples according to the variation of essential oil components abundance under different irrigation treatments and soil amendments. Cluster analysis in Figure (6) is used to assign the set of treatments into groups (clusters), the treatments in the same cluster are more similar in one way or another to each other than those in other clusters. In this regard, the data showed that the dendrogram highlighted three main clusters, the first cluster featuring 80 % ETo + (C), 100 % ETo + (CON), 100 % ETo + (C), 120 % ETo + (CON), and 120 % ETo + (C). In addition, the second was formed by 120 % ETO + (B), 100 % ETo + (B), while the third consisted of 100 % ETo + (B+C), 80 % ETo + (CON), 80 % ETo + (B), and 120 % ETo + (B+C), 80 % ETo + (B+C). The gotten results reinforced those already realized within PCA (Fig. 7).

As illustrated in (Fig. 7), the two first principal components F1 and F2 accounted for 60.75% of the total variance of which F1 explained 39.58% and F2 explained 22.69% variation. Samples 80 % ETo + (B), 120 % ETo + (CON), 120 % ETo + (C), 80 % ETo + (CON), 80 % ETo + (C) and 100 % ETo + (CON) and 100 % ETo + (C) were positioned in the positive F1 axis. These samples were categorized by low intensities of endo-Borneol, α-Terpineol, β-Caryophyllene, Terpinen-4-ol, 3-octanol, Sabinene, β-Myrcene, α-Pinene and β-Pinene as well high concentration of cis-Sabinen hydrate, Eucalyptol and D-Limonene compounds.

Samples of 120 % ETo + (B), 100 % ETo + (B), 80 % ETo + (B+C), 120 % ETo + (B+C), and 100 % ETO + (B+C) were located in the negative side of F1 because these samples have a comparable makeup of volatile chemicals, which includes a high concentration of the main discovered carvone molecule, there is a substantial association between them. F2 separated samples 120 % ETo + (B), 80 % ETo + (B+C), and 100 % ETo + (B) and from that 120 % ETo + (B+C) and 100 % ETo + (B+C), and sample 80 % ETo + (B) and 80 % ETo + (CON), from that 120 % ETo + (CON), 120 % ETo + (C), 80 % ETo + (C) and 100 % ETo + (CON) and 100 % ETo + (C) samples, which are fallen in the same location.

Photosynthetic pigments analysis

The impression of different irrigation treatments and soil amendments on the total chlorophyll and carotenoid content (**μ**g g^{-1}) in spearmint leaves are analyzed statistically and presented in (Table 4). These parameters were affected negatively ($p \leq 0.05$), gradually with the decrease of irrigation levels during both growing seasons in 2019 and 2020. Meanwhile, the supply of biochar and compost mitigated the harmful stress on total chlorophyll and carotenoid content created by the low irrigation treatment. The highest values of the total chlorophyll and carotenoid were recorded when spearmint plants were irrigated at 80% ETo and supplied with biochar and compost in both seasons. Likewise, lower values of total chlorophyll and carotenoid were noted in the irrigation at 80 % ETo without soil amendment (CON).

The value of chlorophyll fluorescence is a reliable tool for assessing the fluctuations that occur in PSII function in different stresses, as stated by many studies (Abd El-Mageed et al., 2019; Laird, 2008; Paradelo et al., 2016). Our observation in the current study recorded a reduction in values of the efficiency of the photosynthesis pigments relative to severe water conditions without soil amendment (CON), which might have been due to the decrease in spearmint water status which is necessary for photosynthesis (Table 4). This is consistent with the results of other authors (Laird, 2008; Lehmann et al., 2011). The water supply disturbance caused a decrease in water content in absorption tissue, leading to photosynthetic discouragement, as summarized by various investigations (Abd El-Mageed et al., 2018; Habibi, 2012).

Available macronutrient content

Regarding the interactive impact of the different irrigation levels and soil amendments on the available macronutrient concentrations in spearmint leaves, data in (Figure 8) reflected that the highest concentrations of the studied parameters were obtained by 80% ETo treatment combined with biochar and compost amendment (B+C) during the two successive seasons of 2019 and 2020. Results indicated that using compost and biochar at 80% ETo boosted the N % by 44.15% and 38.61%, K% by 35.62% and 29.78% as well as P % by 41.23 and 47.69% compared to the 80% ETo without additives in both seasons, respectively. Conversely, the treatment that produced the lowest amounts was 120% ETo without the addition of the amendment (CON).

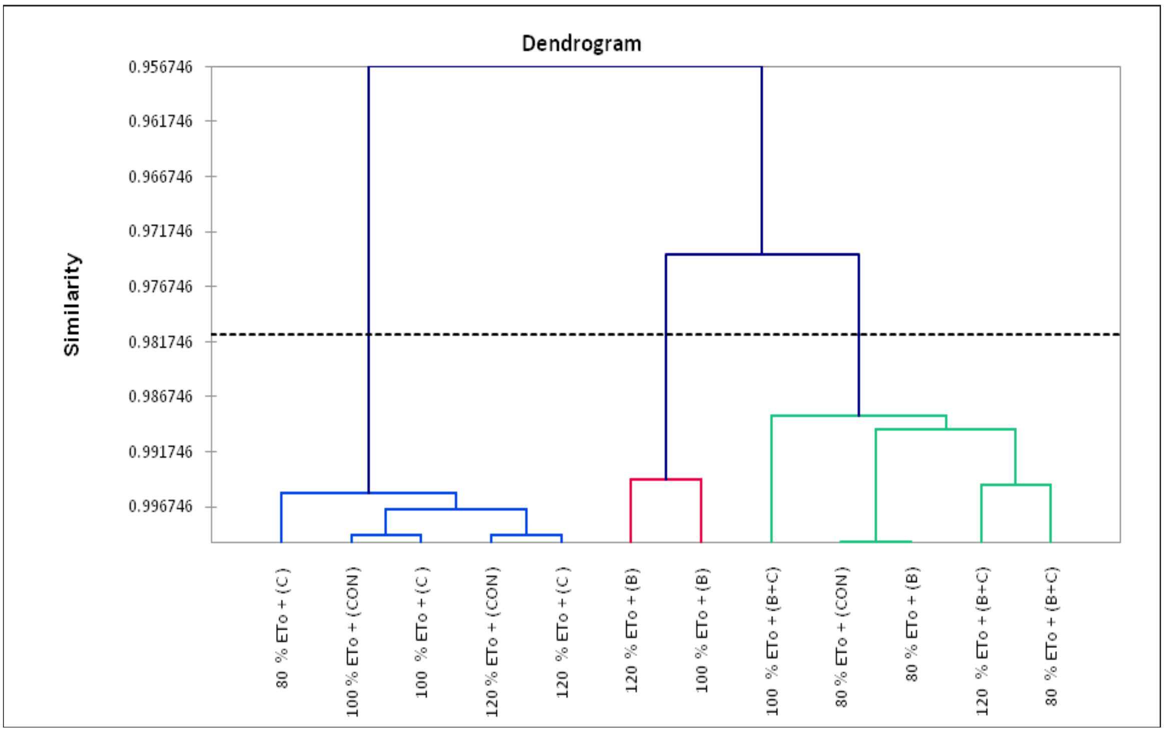


Fig. 6. Hierarchical cluster analysis of the volatile compounds of spearmint under different irrigation treatments and soil amendments. Where: CON= control, B= biochar, C= compost, B+C= biochar + compost.

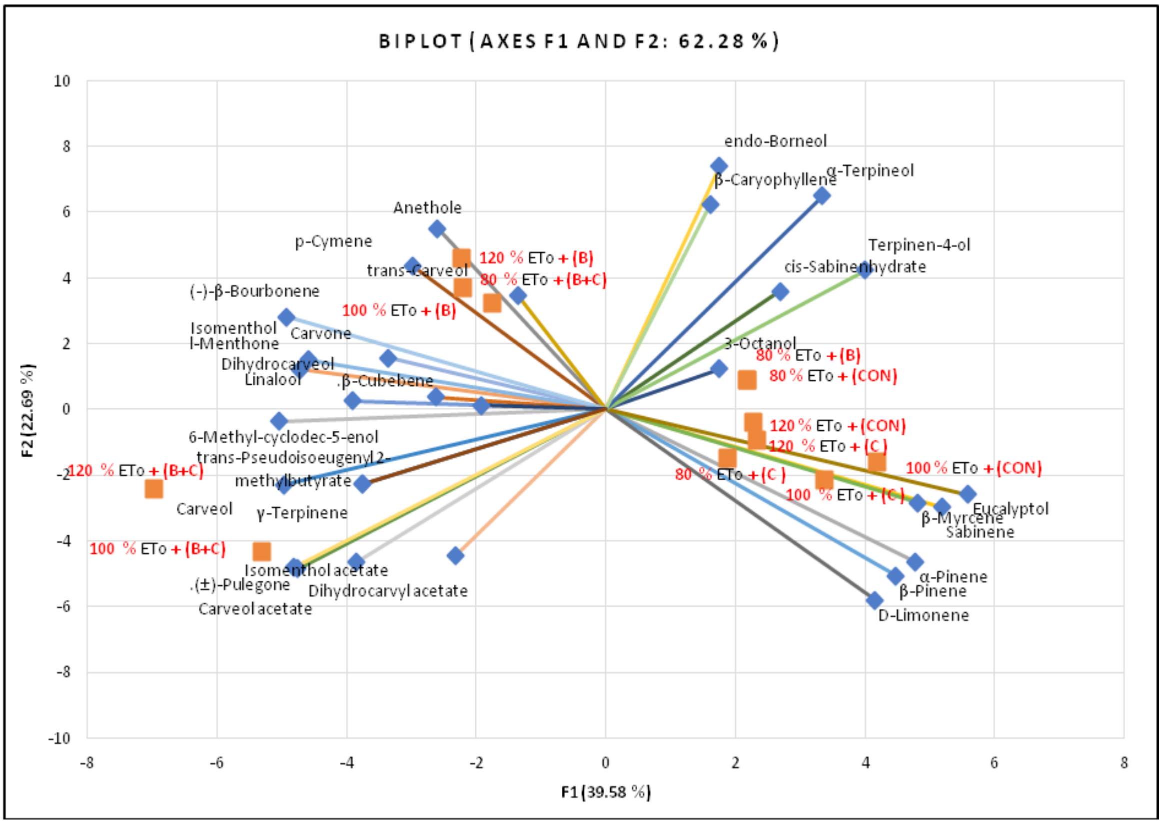


Fig. 7. Biplot analysis of the volatile compounds of spearmint under different irrigation treatments and soil amendments. Where: CON= control, B= biochar, C= compost, B+C= biochar + compost.

TABLE 4. Photosynthetic pigments content.

Treatments		Season 1		Season 2	
		Chlorophyll (a+b) µg g^{-1}	Carotenoids µg g^{-1}	Chlorophyll (a+b) µg g^{-1}	Carotenoids µg g^{-1}
120% ETo	CON	230.00 ± 2.0^{e}	139.00 ± 1.0^{e}	232.33 ± 4.06^{c}	146.33 ± 3.53^{e}
	B	261.00 ± 1.0^{d}	165.00 ± 0.0^{cd}	336.00 ± 32.01^{bc}	190.00 ± 19.14^{cd}
	C	232.00 ± 32.0^{e}	144.00 ± 17.0^{e}	238.00 ± 6.35^{e}	148.67 ± 3.18^{e}
	B+C	292.00 ± 2.0^{c}	203.00 ± 1.0^{b}	366.33 ± 4.06^{b}	268.67 ± 3.71^{a}
100% ETo	CON	192.33 ± 0.0^{f}	123.00 ± 1.0^{f}	266.33 ± 6.84^{e}	176.00 ± 3.06^{d}
	B	306.00 ± 1.0^{c}	157.00 ± 1.0^{d}	281.33 ± 7.80^{d}	195.33 ± 0.88^{cd}
	C	198.00 ± 2.0^{f}	125.00 ± 1.0^{f}	258.67 ± 3.93^{e}	180.33 ± 3.71^{d}
	B+C	343.00 ± 3.0^{b}	235.00 ± 1.0^{a}	322.00 ± 8.08^{c}	230.00 ± 3.79^{b}
80% ETo	CON	169.00 ± 1.0^{g}	97.00 ± 1.0^{g}	199.00 ± 0.58^{f}	104.33 ± 1.45^{f}
	B	305.00 ± 1.0^{c}	177.00 ± 1.0^{c}	335.67 ± 2.67^{b}	207.33 ± 0.33^{c}
	C	172.00 ± 4.0^{g}	100.00 ± 0.0^{g}	202.33 ± 0.67^{f}	120.00 ± 6.08^{f}
	B+C	390.00 ± 10.0^{a}	246.00 ± 1.0^{a}	414.00 ± 11.50^{a}	282.67 ± 3.38^{a}

Where: CON= control, B= biochar, C= compost, B+C= biochar + compost. Means with different letters within the same

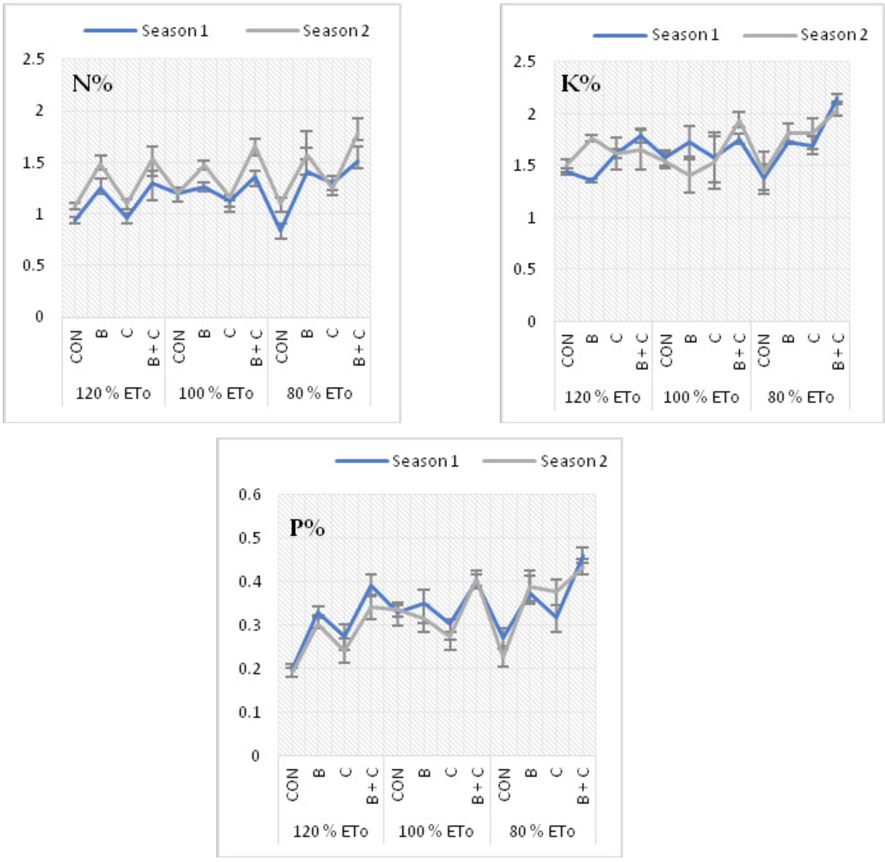


Fig. 8. Correlation of irrigation and soil amendment treatments on available macronutrient content (%) in spearmint for two successive seasons. Where: CON= control, B= biochar, C= compost, B+C= biochar + compost.

In general, adding biochar compost can improve water use efficiency by low transpiration rate and stomatal closure under water deficit. Eventually, this will assist in leaf turgidity and interior water balance in plants. Concurrently, biochar amendment can help in raising nutrient retention and supply capacity of the soil, which supports photosynthetic functioning (Abideen et al., 2020; Paneque et al., 2016). These results are in harmony with the findings of Hasnain et al. (2023) and Munda et al. (2016). On the other hand, current research revealed that the application of biochar + compost at 80% ETo increased N, K, and P uptake significantly by an average of 41.38%, 63.39%, and 44.46% as compared with that of control, respectively (Figure 8). This could refer to the indirect benefits of applied biochar and compost on the physicochemical soil parameters. These outcomes are in concurrence with those of Conversa et al. (2015) and Zhang et al. (2014) who concluded that adding compost and biochar increased the amount of micro- and macronutrient in ornamental plants because these materials increase the porosity, bulk density, and soil's ability to hold water.

Water relation

Applied irrigation water (m^3/ha)

According to the findings in (Fig. 9) the applied irrigation water for mint varied between 12384 and 8256 m^3 ha^{-1} in 2019 and 12254 to 8170 m^3 ha^{-1} in 2020, with the lowest applied water value being for 80% ETo and the greatest applied water value being applied under 120% ETo. The findings also showed that the applied water had greater values in the first season versus the second season, which is likewise explained by variations in the meteorological components.

Water productivity (WP kg m^{-3})

The link between crop yield and the amount of water required in agricultural production is quantified as "irrigation water productivity." In terms of water management, it is a valuable indicator for estimating the effects of irrigation scheduling decisions. Greater water productivity became the primary challenge for scientists in agriculture. Data represented in (Fig. 10) that the use of biochar (B) and compost (C) together had the maximum water productivity under all irrigation treatments. Consequently, the highest WP in both growing seasons was acquired under irrigation with 120% ETo and biochar +compost (B+C) application in both growing seasons, namely 1.01 and 1.26 kg m^{-3}, respectively. When, the bottommost value of WP was achieved under irrigation 80% ETo without the application of biochar and compost in both growing seasons, namely 0.70 and 0.83 kg m^{-3}, respectively (Figure 10).

In addition, the mint water productivity under irrigation with 80% ETo and B+C application is decreased by 18.28% and 7.92% relative to 100% ETo at the B+C application in both seasons, respectively. On the other hand, during the two growing seasons, mint water productivity was reduced by 23.17% and 24.75% respectively, when comparing the application of B+C under 80% ETo with B+C under 120% ETo. On the other hand, the application of biochar (B) is higher in spearmint water productivity than compost (C), where B+C combined had the highest water productivity under all irrigation regimes (Fig. 10). This is because biochar retains water through capillary force, its enormous internal surface area, and highly porous structure directly affect soil moisture (Alghamdi et al., 2020; Amer et al., 2021). This increases soil porosity and overall surface area (Besalatpour et al., 2013), lowers soil bulk density (Zhou et al., 2018), improves soil water storage, and thus lessens plant water stress (Brtnicky et al., 2021). Moreover, biochar has a four times greater specific surface area than compost, because micropores in compost may have naturally decreased in specific surface area as a result of filling with other organic matter like humic compounds and microorganisms (Duan et al., 2020; Wallace et al., 2020). According to Alghamdi et al. (2020), the biochar zeta potential is crucial for the negative charges on the surface that allow hydrated cationic ions to be effectively absorbed. However, another indirect consequence of biochar is a change in soil structure, which in turn reduces the soil's ability to retain water (Besalatpour et al., 2013; Ghorbani et al., 2021). According to Wallace et al. (2020), biochar can function as an appropriate binding agent in the soil, joining soil micro-aggregates to form macro aggregates. Additionally, in soils treated with biochar, this may cause the diameter of the soil aggregates to grow (Zhou et al., 2020), changing the pore size distribution (Besalatpour et al., 2013). This is because, over time, biochar decomposes slowly (Brtnicky et al., 2021). Biochar has a higher carbon-to-nitrogen ratio than compost. This promotes soil moisture storage by indicating greater stability against decomposition and the development of more stable organo-mineral compounds on the surface of soil aggregates (Besalatpour et al., 2013; Islam et al., 2021).

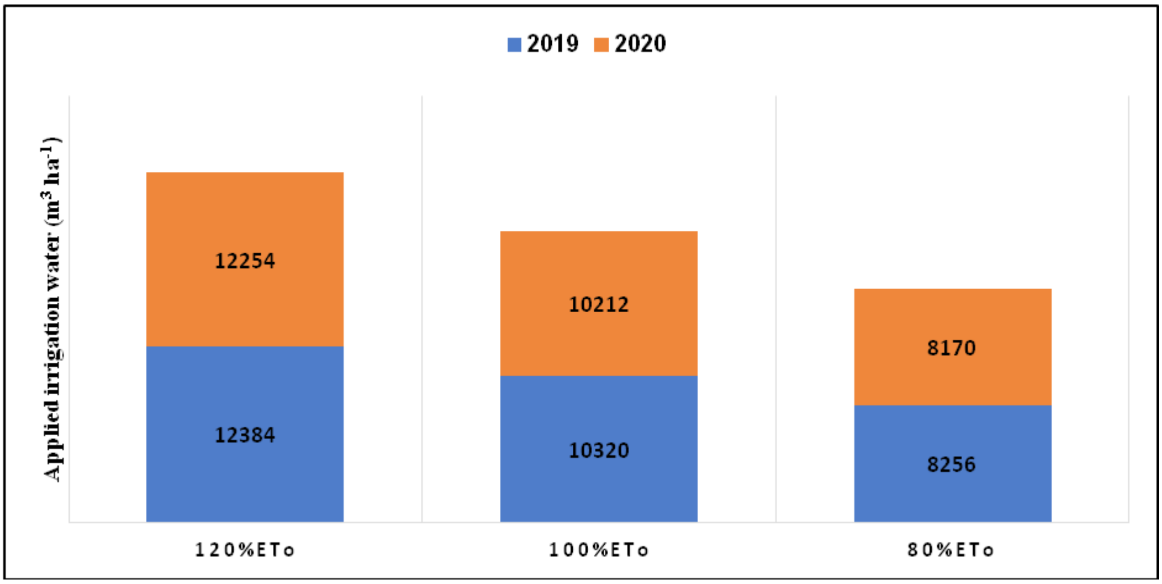


Fig. 9 Applied irrigation water (m3 ha-1) to both growing seasons of spearmint as affected by different irrigation treatments.

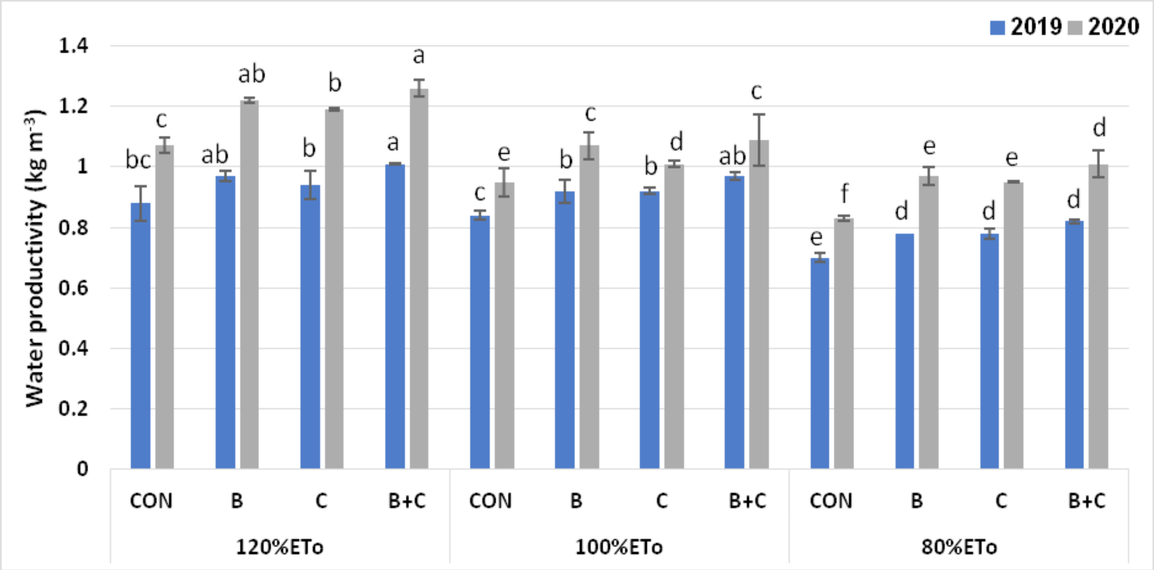


Fig. 10. Water productivity (kg m^{-3}) of both growing seasons of spearmint is affected by different irrigation treatments and soil amendments. Where: CON= control, B= biochar, C= compost, B+C= biochar + compost. Letters above bars indicate significantly different means according to Duncan's test (α = 5%) within the same year, Season 1 = 2019, Season 2 = 2020.

Conclusions

Spearmint water status, growth, and physiological attributes were significantly impacted by water limitation. The results indicated that the spearmint attributes were enhanced by the addition of biochar or compost, but the mixed application of the two amendments was superior in that regard. However, with 120% ETo, the treatment receiving about 3.1 tons ha^{-1} of biochar combined with compost at the required dose (24.4 tons ha^{-1}) produced much higher fresh herb output (6.4 and 7.79 tons ha^{-1}). Moreover, the values of the rise caused by the use of B+C at 120%, 100% ETo, and 80% saw an increase of 38.15%, 39.88%, and 40.15%, respectively. The application of biochar and compost in this research showed the ability of spearmint plants to tolerate water irrigation shortages.

Declarations

Ethics approval and consent to participate: Not applicable.

Consent for publication: Not applicable.

Availability of data and material: All data generated or analyzed during this study are included in this published article.

Competing Interest: All the authors declared that they have no competing interests.

Funding: This research received no external funding.

Author Contributions: Conceptualization, T.N., M. A. A., M.A.A.A., and A.A.; methodology, T.N., A.A., M.A.A. and S.M.A; investigation, M.A.A.; A.A. and S.M.A; resources, M.A.A., S.M.; A.A. and M.A.A.A.; writing—original draft preparation, T.N., M.A.A.; A.A. and M.A.A.A..; writing—review and editing, A.A. and M.A.A.A. All authors provided critical feedback and helped shape the research, analysis, and manuscript. Also, all authors discussed the results and contributed to the final manuscript. All authors read and approved the final manuscript.

Acknowledgments: The authors are grateful to the Horticulture Research Institute, Agricultural Research Center (ARC), Egypt, for supporting this research and its team.

References

Abd El-Mageed, T. A., El-Sherif, A. M. A., Abd El-Mageed, S. A., & Abdou, N. M. (2019). A novel compost alleviate drought stress for sugar beet production grown in Cd-contaminated saline soil. *Agricultural Water Management*, *226*. https://doi.org/10.1016/j.agwat.2019.105831

Abd El-Mageed, T. A., Semida, W. M., Taha, R. S., & Rady, M. M. (2018). Effect of summer-fall deficit irrigation on morpho-physiological, anatomical responses, fruit yield and water use efficiency of cucumber under salt affected soil. *Scientia Horticulturae*, *237*, 148–155. https://doi.org/10.1016/j.scienta.2018.04.014

Abideen, Z., Koyro, H.-W., Huchzermeyer, B., Gul, B., & Khan, M. A. (2020). Impact of a biochar or a biochar-compost mixture on water relation, nutrient uptake and photosynthesis of Phragmites karka. *Pedosphere*, *30*(4), 466–477. https://doi.org/10.1016/S1002-0160(17)60362-X

Akanmu, A. O., Olowe, O. M., Phiri, A. T., Nirere, D., Odebode, A. J., Karemera Umuhoza, N. J., Asemoloye, M. D., & Babalola, O. O. (2023). Bioresources in Organic Farming: Implications for Sustainable Agricultural Systems. *Horticulturae*, *9*(6). https://doi.org/10.3390/horticulturae9060659

Alghamdi, A. G., Alkhasha, A., & Ibrahim, H. M. (2020). Effect of biochar particle size on water retention and availability in a sandy loam soil. *Journal of Saudi Chemical Society*, *24*(12), 1042–1050. https://doi.org/10.1016/j.jscs.2020.11.003

Ali, A. M., Awad, M. Y. M., Hegab, S. A., Gawad, A. M. A. El, & Eissa, M. A. (2021). Effect of potassium solubilizing bacteria (Bacillus cereus) on growth and yield of potato. *Journal of Plant Nutrition*, *44*(3), 411–420.

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *Fao, Rome*, *300*(9), D05109.

Almaroai, Y. A., & Eissa, M. A. (2020). Effect of biochar on yield and quality of tomato grown on a metal-contaminated soil. *Scientia Horticulturae*, *265*. https://doi.org/10.1016/j.scienta.2020.109210

Amalina, F., Krishnan, S., Zularisam, A. W., & Nasrullah, M. (2023). Recent advancement and applications of biochar technology as a multifunctional component towards sustainable environment. In *Environmental Development* (Vol. 46). Elsevier B.V. https://doi.org/10.1016/j.envdev.2023.100819

Amer, A., Abdallah, M., & Noreldein, T. (2019). Enhancing spearmint productivity and water use efficiency under alternative planting practices. *Journal of Central European Agriculture*, *20*(3), 852–865. https://doi.org/10.5513/JCEA01/20.3.2282

Amer, A., Abdallah, M., Noreldin, T., & Mohamed, M. F. (2019). Nitrogen fertilizer effect on basil and water productivity under new reclaimed soils conditions. *Journal of Soils and Crops*, *29*(1), 23–31.

Amer, M. A., Noreldin, T., & Amer, A. (2021). Biochar particles size influenced the yield and water productivity of two mint (Mentha sp.) varieties under drip irrigation. In *J. Agri. Sci* (Vol. 2, Issue 2). www.techagro.org

Antonangelo, J. A., Sun, X., & Zhang, H. (2021). The roles of co-composted biochar (COMBI) in improving soil quality, crop productivity, and toxic metal amelioration. *Journal of Environmental Management*, *277*, 111443. https://doi.org/10.1016/j.jenvman.2020.111443

Behera, M. S., Mahapatra, P. K., Singandhupe, R. B., Kundu, D. K., Kannan, K., Mandal, K. G., & Amarpreet, S. (2014). Effect of drip fertigation on yield, water use efficiency and water productivity of mint (Mentha arvensis L.). *Journal of Agricultural Physics*, *14*(1), 37–43.

Beiranvandi, M., Akbari, N., Ahmadi, A., Mumivand, H., & Nazarian, F. (2022). Biochar and super absorbent polymer improved growth, yield, and phytochemical characteristics of Satureja rechingeri Jamzad in water-deficiency conditions. In *Industrial Crops and Products* (Vol. 183). Elsevier B.V. https://doi.org/10.1016/j.indcrop.2022.114959

Benitez, C. (1989). Determination of accurate extinction coefficients and simultaneous equations for assaying chlorophylls a and b extracted with four different solvents: verification of the concentration of chlorophyll standards by atomic absorption spectroscopy. In *Biochimica et Biophysica Acta* (Vol. 975). Springer-Verlag.

Besalatpour, A. A., Ayoubi, S., Hajabbasi, M. A., Mosaddeghi, M. R., & Schulin, R. (2013). Estimating wet soil aggregate stability from easily available properties in a highly mountainous watershed. *CATENA*, *111*, 72–79. https://doi.org/10.1016/j.catena.2013.07.001

Bettaieb, I., Zakhama, N., Wannes, W. A., Kchouk, M. E., & Marzouk, B. (2009). Water deficit effects on Salvia officinalis fatty acids and essential oils composition. *Scientia Horticulturae*, *120*(2), 271–275. https://doi.org/10.1016/j.scienta.2008.10.016

Biederman, L. A., & Stanley Harpole, W. (2013). Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *GCB Bioenergy*, *5*(2), 202–214. https://doi.org/10.1111/gcbb.12037

Brendecke, J. W., Axelson, R. D., & Pepper, I. L. (1993). Soil microbial activity as an indicator of soil fertility: long-term effects of municipal sewage sludge on an arid soil. *Soil Biology and Biochemistry*, *25*(6), 751–758.

Brown, N., John, J. A., & Shahidi, F. (2019). Polyphenol composition and antioxidant potential of mint leaves. *Food Production, Processing and Nutrition*, *1*(1), 1. https://doi.org/10.1186/s43014-019-0001-8

Brtnicky, M., Datta, R., Holatko, J., Bielska, L., Gusiatin, Z. M., Kucerik, J., Hammerschmiedt, T., Danish, S., Radziemska, M., Mravcova, L., Fahad, S., Kintl, A., Sudoma, M., Ahmed, N., & Pecina, V. (2021). A critical review of the possible adverse effects of biochar in the soil environment. *Science of The Total Environment*, *796*, 148756. https://doi.org/10.1016/j.scitotenv.2021.148756

Chen, X., Yang, S., Ding, J., Jiang, Z., & Sun, X. (2021). Effects of biochar addition on rice growth and yield under water-saving irrigation. *Water (Switzerland)*, *13*(2). https://doi.org/10.3390/w13020209

Conversa, G., Bonasia, A., Lazzizera, C., & Elia, A. (2015). Influence of biochar, mycorrhizal inoculation, and fertilizer rate on growth and flowering of pelargonium (Pelargonium zonale L.) plants. *Frontiers in Plant Science*, *6*(June). https://doi.org/10.3389/fpls.2015.00429

Cozzolino, D., Cynkar, W. U., Shah, N., Dambergs, R. G., & Smith, P. A. (2009). A brief introduction to multivariate methods in grape and wine analysis. In *International Journal of Wine Research*. https://www.dovepress.com/

Cui, J., Yang, B., Zhang, M., Song, D., Xu, X., Ai, C., Liang, G., & Zhou, W. (2023). Investigating the effects of organic amendments on soil microbial composition and its linkage to soil organic carbon: A global meta-analysis. *The Science of the Total Environment*, *894*, 164899. https://doi.org/10.1016/j.scitotenv.2023.164899

Duan, X.-Y., Cao, Y., Liu, T.-Z., Li, L., Wang, B., & Wang, X.-D. (2020). Nutrient stability and sorption of sewage sludge biochar prepared from co-pyrolysis of sewage sludge and stalks / mineral materials. *Environmental Pollutants and Bioavailability*, *32*(1), 12–18. https://doi.org/10.1080/26395940.2019.1710259

Edris, A. E., Shalaby, A. S., Fadel, H. M., & Abdel-Wahab, M. A. (2003). Evaluation of a chemotype of spearmint (*Mentha spicata* L.) grown in Siwa Oasis, Egypt. *European Food Research and Technology*, *218*(1), 74–78. https://doi.org/10.1007/s00217-003-0802-4

Eissa, M. A. (2019). Effect of Compost and Biochar on Heavy Metals Phytostabilization by the Halophytic Plant Old Man Saltbush [Atriplex Nummularia Lindl]. *Soil and Sediment Contamination*, *28*(2), 135–147. https://doi.org/10.1080/15320383.2018.1551325

El-Gamal, M., Serag El-Din, W. M., Farouk, S., &

Allah Mokhtar, N. Y. (2021). Integrated Effects of Biochar and Potassium Silicate on Borage Plant Under Different Irrigation Regimes in Sandy Soil. *Journal of Horticultural Science & Ornamental Plants*, *13*(1), 60–76. https://doi.org/10.5829/idosi.jhsop.2021.60.76

Elias, D. M. O., Ooi, G. T., Ahmad Razi, M. F., Robinson, S., Whitaker, J., & McNamara, N. P. (2020). Effects of Leucaena biochar addition on crop productivity in degraded tropical soils. *Biomass and Bioenergy*, *142*, 105710. https://doi.org/10.1016/j.biombioe.2020.105710

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., Zimmerman, A. R., Ahmad, M., Shaheen, S. M., & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. In *Geoderma* (Vol. 337, pp. 536–554). Elsevier B.V. https://doi.org/10.1016/j.geoderma.2018.09.034

Feilden, N. E. H. (1983). Theory and practice of anaerobic digestion reactor design. *Process Biochem.;(United Kingdom)*, *18*(5).

Feo, V. De, Ricciardi, A. I., Biscardi, D., & Senatore, F. (1998). Chemical composition and antimicrobial screening of the essential oil of minthostachys verticillata (griseb.) epl. (lamiaceae). *Journal of Essential Oil Research*, *10*(1), 61–65. https://doi.org/10.1080/10412905.1998.9700839

Gao, Y., Shao, G., Lu, J., Zhang, K., Wu, S., & Wang, Z. (2020). Effects of biochar application on crop water use efficiency depend on experimental conditions: A meta-analysis. *Field Crops Research*, *249*. https://doi.org/10.1016/j.fcr.2020.107763

Ghassemi-Golezani, K., & Rahimzadeh, S. (2022). The biochar-based nanocomposites influence the quantity, quality and antioxidant activity of essential oil in dill seeds under salt stress. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-26578-0

Ghorbani, M., Amirahmadi, E., & Zamanian, K. (2021). In-situ biochar production associated with paddies: Direct involvement of farmers in greenhouse gases reduction policies besides increasing nutrients availability and rice production. *Land Degradation & Development*, *32*(14), 3893–3904. https://doi.org/10.1002/ldr.4006

Guenther, E. (1950). The Essential Oils, Vol. IV. *The Essential Oils, Vol. IV.*

Habibi, G. (2012). *Exogenous salicylic acid alleviates oxidative damage of barley plants under drought stress* (Vol. 56, Issue 1). http://www.sci.u-szeged.hu/ABSARTICLE

Hammam, Kh., AwadAlla, S., & Noreldin, T. (2021). Response of Growth, Yield and Essential Oil of Geranium Plants to Surface Irrigation and Humic Acid Treatments. *Asian Plant Research Journal*, 39–56. https://doi.org/10.9734/aprj/2021/v7i230153

Hammam, Kh., Amer, A., & Noreldein, T. (2019). Vetiver (Vetiveria zizanioides L.) Yield and its water use efficiency affected by different plant populations under reclaimed soil conditions. ~ *126 ~ Journal of Medicinal Plants Studies*, *7*(5), 126–134. http://www.plantsjournal.com

Hasnain, M., Munir, N., Abideen, Z., Zulfiqar, F., Koyro, H. W., El-Naggar, A., Caçador, I., Duarte, B., Rinklebe, J., & Yong, J. W. H. (2023). Biochar-plant interaction and detoxification strategies under abiotic stresses for achieving agricultural resilience: A critical review. *Ecotoxicology and Environmental Safety*, *249*, 114408. https://doi.org/10.1016/j.ecoenv.2022.114408

Holm, G. (1954). Chlorophyll mutations in barley. *Acta Agriculturae Scandinavica*, *4*(1), 457–471.

Horneck, D. A., & Miller, R. O. (2019). Determination of total nitrogen in plant tissue. *Handbook of Reference Methods for Plant Analysis*, 75–83.

Hu, Q., Jung, J., Chen, D., Leong, K., Song, S., Li, F., Mohan, B. C., Yao, Z., Prabhakar, A. K., Lin, X. H., Lim, E. Y., Zhang, L., Souradeep, G., Ok, Y. S., Kua, H. W., Li, S. F. Y., Tan, H. T. W., Dai, Y., Tong, Y. W., … Wang, C. H. (2021). Biochar industry to circular economy. *Science of the Total Environment*, *757*. https://doi.org/10.1016/j.scitotenv.2020.143820

Ibrahim, M., Mahmoud, E., Gad, L., & Khader, A. (2019). Effects of biochar and phosphorus fertilizer rates on soil physical properties and wheat yield on clay textured soil in middle Nile Delta of Egypt. *Communications in Soil Science and Plant Analysis*, *50*(21), 2756–2766. https://doi.org/10.1080/00103624.2019.1679162

Islam, M. U., Jiang, F., Guo, Z., & Peng, X. (2021). Does biochar application improve soil aggregation? A meta-analysis. *Soil and Tillage Research*, *209*, 104926. https://doi.org/10.1016/j.still.2020.104926

Jackson, M. L. (1973). Soil chemical analysis, pentice hall of India Pvt. *Ltd., New Delhi, India*, *498*, 151–154.

Jain, S., Singh, A., Khare, P., Chanda, D., Mishra, D., Shanker, K., & Karak, T. (2017). Toxicity assessment of Bacopa monnieri L. grown in biochar amended extremely acidic coal mine spoils. *Ecological Engineering*, *108*, 211–219. https://doi.org/10.1016/j.ecoleng.2017.08.039

Jien, S.-H., Chen, W.-C., Ok, Y. S., Awad, Y. M., & Liao, C.-S. (2018). Short-term biochar application induced variations in C and N mineralization in a compost-amended tropical soil. *Environmental Science and Pollution Research*, *25*(26), 25715–25725. https://doi.org/10.1007/s11356-017-9234-8

Jien, S.-H., Wang, C.-C., Lee, C.-H., & Lee, T.-Y. (2015). Stabilization of Organic Matter by Biochar Application in Compost-amended Soils with Contrasting pH Values and Textures. *Sustainability*, *7*(10), 13317–13333. https://doi.org/10.3390/su71013317

Khalifa, D. M., & Elareny, I. M. (2020). Effect of Olive mill Wastewater and Biochar under Different NPK Rates on Sandy Soil Properties and Peanut productivity. *Middle East Journal of Agriculture Research*, *9*, 624–635.

Laird, D. A. (2008). The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, *100*(1), 178–181. https://doi.org/10.2134/agronj2007.0161

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota - A review. In *Soil Biology and Biochemistry* (Vol. 43, Issue 9, pp. 1812–1836). https://doi.org/10.1016/j.soilbio.2011.04.022

Li, Q. W., Liang, J. F., Zhang, X. Y., Feng, J. G., Song, M. H., & Gao, J. Q. (2021). Biochar addition affects root morphology and nitrogen uptake capacity in common reed (Phragmites australis). *Science of the Total Environment*, *766*. https://doi.org/10.1016/j.scitotenv.2020.144381

Liang, J. F., An, J., Gao, J. Q., Zhang, X. Y., Song, M. H., & Yu, F. H. (2019). Interactive effects of biochar and AMF on plant growth and greenhouse gas emissions from wetland microcosms. *Geoderma*, *346*, 11–17. https://doi.org/10.1016/j.geoderma.2019.03.033

Linder, D. H. (1944). A new rust of orchids. *Mycologia*, *36*(5), 464–468.

Liu, L., Wang, S., Guo, X., & Wang, H. (2019). Comparison of the effects of different maturity composts on soil nutrient, plant growth and heavy metal mobility in the contaminated soil. *Journal of Environmental Management*, *250*. https://doi.org/10.1016/j.jenvman.2019.109525

Mahmoud, E., Ibrahim, M., Ali, N., & Ali, H. (2018). Spectroscopic analyses to study the effect of biochar and compost on dry mass of canola and heavy metal immobilization in soil. *Communications in Soil Science and Plant Analysis*, *49*(16), 1990–2001. https://doi.org/10.1080/00103624.2018.1492601

Marchese, J. A., & Figueira, G. M. (2005). The use of pre and post-harvest technologies and good agricultural practices in the production of medicinal and aromatic plants. *Revista Brasileira de Plantas Medicinais (Brazil)*.

Masmoudi, S., Magdich, S., Rigane, H., Medhioub, K., Rebai, A., & Ammar, E. (2020). Effects of Compost and Manure Application Rate on the Soil Physico-Chemical Layers Properties and Plant Productivity. *Waste and Biomass Valorization*, *11*(5), 1883–1894. https://doi.org/10.1007/s12649-018-0543-z

Mehdizadeh, L., Farsaraei, S., & Moghaddam, M. (2021). Biochar application modified growth and physiological parameters of Ocimum ciliatum L. and reduced human risk assessment under cadmium stress. *Journal of Hazardous Materials*, *409*. https://doi.org/10.1016/j.jhazmat.2020.124954

Monteith, J. L. (1965). Evaporation and environment. The stage and movement of water in living organisms. *19th Symp. Soc. Exp. Biol.*

Moosavy, M. H., Shahbazi, Y., & Shavisi, N. (2015). The combined effect of Mentha spicata essential oil and nisin against listeria monocytogenes. *Pharmaceutical Sciences*, *21*(4), 178–183. https://doi.org/10.15171/PS.2015.34

Mumivand, H., Izadi, Z., Amirizadeh, F., Maggi, F., & Morshedloo, M. R. (2023). Biochar amendment improves growth and the essential oil quality and quantity of peppermint (Mentha × piperita L.) grown under waste water and reduces environmental contamination from waste water disposal. *Journal of Hazardous Materials*, *446*. https://doi.org/10.1016/j.jhazmat.2022.130674

Munda, S., Nayak, A. K., Mishra, P. N., Bhattacharyya, P., Mohanty, S., Kumar, A., Kumar, U., Baig, M. J., Tripathi, R., Shahid, M., Adak, T., & Thilagam,

V. K. (2016). Combined application of rice husk biochar and fly ash improved the yield of lowland rice. *Soil Research*, *54*(4), 451–459. https://doi.org/10.1071/SR15295

Murphy, J., & Riley, J. P. (1962). A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta*, *27*, 31–36.

Najafian, S., & Zahedifar, M. (2018). Productivity, Essential Oil Components and Herbage Yield, of Sweet Basil as a Function of Biochar and Potassium-Nano Chelate. *Journal of Essential Oil-Bearing Plants*, *21*(4), 886–894. https://doi.org/10.1080/0972060X.2018.1510793

Netherway, P., Reichman, S. M., Laidlaw, M., Scheckel, K., Pingitore, N., Gascó, G., Méndez, A., Surapaneni, A., & Paz-Ferreiro, J. (2019). Phosphorus-Rich Biochars Can Transform Lead in an Urban Contaminated Soil. *Journal of Environmental Quality*, *48*(4), 1091–1099. https://doi.org/10.2134/jeq2018.09.0324

Niel, E. M. (2021). Effect of Organic and Nitrogen Fertilizers on Soil Fertility and Wheat Productivity in a Newly Reclaimed Sandy Soil. *Alexandria Science Exchange Journal*, *42*(3), 573–582. https://doi.org/10.21608/asejaiqjsae.2021.182596

Oram, N. J., Van de Voorde, T. F. J., Ouwehand, G. J., Bezemer, T. M., Mommer, L., Jeffery, S., & Groenigen, J. W. Van. (2014). Soil amendment with biochar increases the competitive ability of legumes via increased potassium availability. *Agriculture, Ecosystems and Environment*, *191*, 92–98. https://doi.org/10.1016/j.agee.2014.03.031

Ouertatani, S. (2021). Study of the Effect of the Biochar Amendment on the Physic-Chemical Properties of a Soil Cultivated in Green Mint (Mentha Viridis L.). In *Agriculture Productivity in Tunisia Under Stressed Environment* (pp. 173–192). Springer.

Pandey, V., Patel, A., & Patra, D. D. (2016). Biochar ameliorates crop productivity, soil fertility, essential oil yield and aroma profiling in basil (Ocimum basilicum L.). *Ecological Engineering*, *90*, 361–366. https://doi.org/10.1016/j.ecoleng.2016.01.020

Paneque, M., De la Rosa, J. M., Franco-Navarro, J. D., Colmenero-Flores, J. M., & Knicker, H. (2016). Effect of biochar amendment on morphology, productivity and water relations of sunflower plants under non-irrigation conditions. *Catena*, *147*, 280–287. https://doi.org/10.1016/j.catena.2016.07.037

Paradelo, R., Vázquez-Nion, D., Silva, B., González, Á., & Barral, M. T. (2016). Acidification of mixtures of granite powder and compost for reuse in plant production. *Compost Science and Utilization*, *24*(1), 1–10. https://doi.org/10.1080/1065657X.2015.1020399

Petruccelli, R., Bonetti, A., Traversi, M. L., Faraloni, C., Valagussa, M., & Pozzi, A. (2015). Influence of biochar application on nutritional quality of tomato (Lycopersicon esculentum). *Crop and Pasture Science*, *66*(7), 747–755. https://doi.org/10.1071/CP14247

Porra, R. J., Thompson, W. A. A., & Kriedemann, P. E. (1989). Determination of accurate extinction coefficients and simultaneous equations for assaying chlorophylls a and b extracted with four different solvents: verification of the concentration of chlorophyll standards by atomic absorption spectroscopy. *Biochimica et Biophysica Acta (BBA)-Bioenergetics*, *975*(3), 384–394.

Qian, S., Zhou, X., Fu, Y., Song, B., Yan, H., Chen, Z., Sun, Q., Ye, H., Qin, L., & Lai, C. (2023). Biochar-compost as a new option for soil improvement: Application in various problem soils. In *Science of the Total Environment* (Vol. 870). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2023.162024

Ramadan, A., & Maher Saad Saleh, M. (2018). *Sustainable management of deficit irrigation in sandy soils by producing biochar and adding it as a soil amendment*. https://www.researchgate.net/publication/323955307

Sakhiya, A. K., Anand, A., & Kaushal, P. (2020). Production, activation, and applications of biochar in recent times. In *Biochar* (Vol. 2, Issue 3, pp. 253–285). Springer Science and Business Media B.V. https://doi.org/10.1007/s42773-020-00047-1

Sanchez-Monedero, M. A., Cayuela, M. L., Roig, A., Jindo, K., Mondini, C., & Bolan, N. (2018). Role of biochar as an additive in organic waste composting. *Bioresource Technology*, *247*, 1155–1164. https://doi.org/10.1016/j.biortech.2017.09.193

Saric, M., Kastrori, R., Curic, R., Cupina, T., & Geric, I. (1967). Chlorophyll determination. *Univ. Noven Sadu Prakitikum Is Kiziologize Bilijaka Beogard, Haucna, Anjiga*.

Sarong, M., & Orge, R. F. (2015). Effect of rice hull biochar on the fertility and nutrient holding capacity of sandy soils. *OIDA International Journal of Sustainable Development*, *8*(12), 33–44.

Seilsepour, M., Rashidi, M., & Khabbaz, B. G. (2009). Prediction of soil exchangeable sodium percentage based on soil sodium adsorption ratio. *American-Eurasian Journal of Agricultural and Environmental Sciences*, *5*(1), 1–4.

Shiri, F., Aazami, M. A., Hassanpouraghdam, M. B., Rasouli, F., Kakaei, K., & Asadi, M. (2023). Cerium oxide- salicylic acid nanocomposite foliar use impacts physiological responses and essential oil composition of spearmint (*Mentha spicata* L.) under salt stress. *Scientia Horticulturae*, *317*. https://doi.org/10.1016/j.scienta.2023.112050

Singh, M. (2013). Influence of organic mulching and nitrogen application on essential oil yield and nitrogen use efficiency of rosemary (Rosmarinus officinalis L.). *Archives of Agronomy and Soil Science*, *59*(2), 273–279. https://doi.org/10.1080/03650340.2011.608157

Snyder, R. L. (2000). *BASIC IRRIGATION SCHEDULING (BIS)*. http://biomet.ucdavis.edu

Snyder, R. L., Orang, M., Bali, K., & Eching, S. (2004). Basic irrigation scheduling BISm [online].[Access 01.01. 2011] Available at: http://www. waterplan. water. ca. gov/land wateruse/wateruse/Ag/CUP. *California/CClimate_Data_, 10804*.

Sohi, S., & Lopez-Capel, E. (2009). *Biochar, Climate Change and Soil: A Review to Guide Future Research Hydrologic impacts of deforestation View project INACH RT_06-17 View project*. https://www.researchgate.net/publication/228656328

Sun, C. X., Chen, X., Cao, M. M., Li, M. Q., & Zhang, Y. L. (2017). Growth and metabolic responses of maize roots to straw biochar application at different rates. *Plant and Soil*, *416*(1–2), 487–502. https://doi.org/10.1007/s11104-017-3229-6

Toundou, O., Pallier, V., Feuillade-Cathalifaud, G., & Tozo, K. (2021). Impact of agronomic and organic characteristics of waste composts from Togo on Zea mays L. nutrients contents under water stress. *Journal of Environmental Management*, *285*. https://doi.org/10.1016/j.jenvman.2021.112158

Vermeiren, L. (1984). *Localized irrigation*. FAO.

Wallace, D., Almond, P., Carrick, S., & Thomas, S. (2020). Targeting changes in soil porosity through modification of compost size and application rate. *Soil Research*, *58*(3), 268. https://doi.org/10.1071/SR19170

Wang, L., Sun, X., Li, S., Zhang, T., Zhang, W., & Zhai, P. (2014). Application of organic amendments to a coastal saline soil in north China: Effects on soil physical and chemical properties and tree growth. *PLoS ONE*, *9*(2). https://doi.org/10.1371/journal.pone.0089185

Wang, Q., Duan, C. jiao, Liang, H. xu, Ren, J. wei, Geng, Z. chao, & Xu, C. yang. (2023). Phosphorus acquisition strategies of wheat are related to biochar types added in cadmium-contaminated soil: Evidence from soil zymography and root morphology. *Science of the Total Environment*, *856*. https://doi.org/10.1016/j.scitotenv.2022.159033

Wen, Z., Chen, Y., Liu, Z., & Meng, J. (2022). Biochar and arbuscular mycorrhizal fungi stimulate rice root growth strategy and soil nutrient availability. *European Journal of Soil Biology*, *113*. https://doi.org/10.1016/j.ejsobi.2022.103448

Wolf, B. (1982). A comprehensive system of leaf analyses and its use for diagnosing crop nutrient status. *Communications in Soil Science and Plant Analysis*, *13*(12), 1035–1059.

Wu, H., Lai, C., Zeng, G., Liang, J., Chen, J., Xu, J., Dai, J., Li, X., Liu, J., Chen, M., Lu, L., Hu, L., & Wan, J. (2017). The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review. *Critical Reviews in Biotechnology*, *37*(6), 754–764. https://doi.org/10.1080/07388551.2016.1232696

Yuan, Y., Liu, Q., Zheng, H., Li, M., Liu, Y., Wang, X., Peng, Y., Luo, X., Li, F., Li, X., & Xing, B. (2023). Biochar as a sustainable tool for improving the health of salt-affected soils. *Soil & Environmental Health*, *1*(3), 100033. https://doi.org/10.1016/J.SEH.2023.100033

Zare Dehabadi, S., Asrar, Z., & Mehrabani, M. (2010). Biochemical changes in terpenoid compounds of Mentha spicata essential oils in response to excess zinc supply. *Iranian Journal of Plant Biology*, *2*(3), 25–34. https://ijpb.ui.ac.ir/article_18770.html

Zhang, C.-H. (2003). COMPOUND DECISION THEORY AND EMPIRICAL BAYES METHODS. In *The Annals of Statistics* (Vol. 31, Issue 2).

Zhang, X., Xu, S., Li, C., Zhao, L., Feng, H., Yue, G., Ren, Z., & Cheng, G. (2014). The soil carbon/nitrogen ratio and moisture affect microbial community structures in alkaline permafrost-affected soils with different vegetation types on the Tibetan plateau. *Research in Microbiology*, *165*(2), 128–139. https://doi.org/10.1016/j.resmic.2014.01.002

Zhou, H., Meng, H., Zhao, L., Shen, Y., Hou, Y., Cheng, H., & Song, L. (2018). Effect of biochar and humic acid on the copper, lead, and cadmium passivation during composting. *Bioresource Technology*, *258*, 279–286. https://doi.org/10.1016/j.biortech.2018.02.086

Zhou, S., Sun, H., Bi, J., Zhang, J., Riya, S., & Hosomi, M. (2020). Effect of water-saving irrigation on the N2O dynamics and the contribution of exogenous and endogenous nitrogen to N2O production in paddy soil using 15N tracing. *Soil and Tillage Research*, *200*, 104610. https://doi.org/10.1016/j.still.2020.104610

Zou, Z., Mi, W., Li, X., Hu, Q., Zhang, L., Zhang, L., Fu, J., Li, Z., Han, W., & Yan, P. (2023). Biochar application method influences root growth of tea (Camellia sinensis L.) by altering soil biochemical properties. *Scientia Horticulturae*, *315*. https://doi.org/10.1016/j.scienta.2023.111960