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Minimizing hazard impacts of soil salinity and water stress on wheat plants by soil application of vermicompost and biochar

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Abstract

Soil water and nutrient status are two of the most important factors for plant development and crop yield. Vermicompost and biochar are supposed to amend soil attributes and increase the productivity. However, little is known about their mixture application on soil quality and nutrient uptake under natural conditions. The aim of this investigation was to understand the impact of soil amendments (control, vermicompost, biochar, and vermicompost + biochar) on yield, soil quality, physiological and biochemical attributes, as well as nutrient uptake of wheat plants grown at different irrigation water treatments (50%, 75%, and 100% of field capacity [FC]) in saline sodic soil. Vermicompost improved wheat growth and yield. Biochar-treated plants had higher growth performance and yield than control plants in all traits and than vermicompost in some cases, thus confirming its potential for enhancing soil quality and increasing nutrient uptake, which stimulates soil chemical properties. When vermicompost was added in combination with biochar, further enhancement in the growth and yield was recorded, highlighting the beneficial effect of vermicompost on plant yield. Vermicompost–biochar mixture application followed by biochar as a singular application caused significant improvements in relative water content, chlorophyll content, stomatal conductance, cytotoxicity, leaf K^+ content with respect to nutrient uptake (N, P, and K), while reducing oxidative stress (i.e., activities of catalase [CAT] and ascorbate peroxidase [APX], and expression levels of *CAT*, *APX*, and *Mn-SOD* genes), leaf Na^+ content, and proline content. This resulted in increases in yield-related traits and productivity owing to the enhancement in soil chemical characteristics and soil moisture content. Grain yield and nutrient uptake attained the highest values at 75% FC in wheat plants treated by the combination of vermicompost and biochar. In summary, this investigation revealed that the synergistic effect of vermicompost and biochar can not only enhance crop production but also eliminates the detrimental effects of soil salinity and water stress.

Abbreviations: AAS, atomic absorption spectrophotometer; APX, ascorbate peroxidase; BD, bulk density; CAT, catalase; DW, dry weight; EC, electrical conductivity; ESP, exchangeable sodium percentage; FC, field capacity; FW, fresh weight; g_s, stomatal conductance; PCR, polymerase chain reaction; PWP, permanent wilting point; ROS, reactive oxygen species; RWC, relative water content; SAR, sodium adsorption ratio; TW, turgid weight; VC, vermicompost; WFC, gravimetric soil-water content (%) at field capacity; WPWP, gravimetric soil-water content (%) at permanent wilting point.

1 | INTRODUCTION

With the change in global climate, growth and productivity of crops are negatively affected by abiotic stresses (Osakabe *et al*., 2014; Parihar *et al*., 2015). Among the abiotic stresses, soil salinity and drought are two of the utmost threat influencing agrarian zones, derived from the intensifying use of saline water and unsuitable agronomic practices. At the world level, approximately 800×10^6 Mha of land is influenced by salt with an annual raise of approximately 1%–2% (FAO Land and Nutrition Management Service, 2008; Munns and Tester, 2008). Among saline soils, saline-sodic soils are extremely nonproductive which might be due to the impact of both sodicity and salinity on soil characteristics (Rehman *et al*., 2016). Soils with high salt concentrations disrupt plants' physiological and biochemical attributes (Qadir *et al*., 2014). Saline soils diminish the microbial activity and biomass (Ramlow *et al*., 2019). The lower productivity of saline soils could be attributed not only to their salt toxicity but also arising from the low availability of organic matter and minerals, particularly N, P, and K (Ramlow *et al*., 2019). Concerns about the risks of salinity, eco-friendly quality, and productivity of agro-ecosystems have highlighted the requirement to develop management cultural practices that conserve soil resources. Attaining an appropriate moderator or stress relievers allowing plants to grow better on saline soil is crucial.

Water deficit affects plant yield and growth (Bodner *et al*., 2015). It reduced photosynthesis, nutrients uptake, leaf water content, and growth of plants (Tardieu *et al*., 2014; Noman *et al*., 2015; Siddiqui *et al*., 2015). Water deficit causes oxidative stress via the overproduction of reactive oxygen species (ROS) (Abbasi *et al*., 2017; Anjum *et al*., 2017). Currently, various physiological and molecular genetic approaches are being used to cope with water deficit (El-Esawi and Sammour, 2014; El-Esawi *et al*., 2016, 2018, 2019; El-Esawi, 2017; Vwioko *et al*., 2017). However, those strategies are labor-intensive, time-consuming, and costly (Hafez *et al*., 2014; Chandra *et al*., 2018). Therefore, using organic compounds as soil amendment is a developing practice.

Application of organic fertilization amends soil structure and augments the availability of mineral elements, increasing the soil productivity and quality, and is also cheaper than synthetic fertilizers (Ayyobi *et al*., 2014). A well-known strategy to enhance the health of degraded soils is vermicompost (VC) amendment. Vermicomposting is resulting from the decomposition process of organic material by earthworms (Song *et al*., 2014) and it is giving a soil with a good physical structure in a form easily taken by plants (Doan *et al*., 2014). Recently, studies revealed that vermicomposting amendments could improve soil quality and production by enhancing the chemical traits of the soil, augmenting the amount of plant-available nutrients, improving soil biological activities, and boosting crop yield (Goswami *et al*., 2017).

Biochar is a carbon-rich organic material generated from biological matter pyrolysis under low oxygen conditions or no supply of oxygen (Gul *et al*., 2015). It is an organic matter conditioner able to enhance carbon sequestration and organic and inorganic pollutants immobilization (Akoto-Danso *et al*., 2019), and constitutes an important way of soil regeneration (Luo *et al*., 2017). Biochar also facilitates increasing mineral supply and soil organic matter content, resulting in soils with higher nutrients content (Agegnehu *et al*., 2017; Alvarez-Campos *et al*., 2018). Moreover, biochar promotes microbial growth and soil enzymes' activity (Lehmann *et al*., 2011; Zhao *et al*., 2013). Previous studies revealed that biochar effectively promoted the growth and yield of salt-stressed wheat plants (Oppong *et al*., 2019) and also enhanced the yield of numerous crops grown in water-deficit conditions, including sweet melon, soybean, and maize (Shah *et al*., 2017; Ramlow *et al*., 2019). Nevertheless, due to the low labile nutrients content in biochar, VCs can be utilized as complementary materials. Hence, the co-application of biochar and VC synergistically affects the structure of microbial communities and soil nutrients. Previous researches also revealed that biochar can be utilized with VC to enhance its stability and decrease the solubility of organic matter (Doan *et al*., 2013).

Wheat (*Triticum aestivum* L.) represents the most important cereal used in human nutrition. Wheat production requires additional irrigations for getting the optimum yield in arid and semi-arid regions (Wang *et al*., 2015; Tari, 2016). Water deficit represents a bottleneck for the production of wheat in these areas (Zhang *et al*., 2017). To overcome water resources scarcity, water-saving scheduling was used to enhance wheat production under limited water conditions. Additionally, soil degradation due to the effect of salinity is increasing in arid and semi-arid areas (Tari, 2016), which adversely affect wheat production.

In light of these considerations, little information is available on the integrative application of biochar in the presence of VC as valuable soil amendments relieving plants from water-induced stresses and alleviating the soil degradation due to salinization. The investigation is based on the hypothesis that the synergistic use of biochar and VC ameliorates water stress by improving soil chemical attributes, and physiological and biochemical traits in wheat plants. To the best of our knowledge, no experiments have investigated the integrative impacts of VC and biochar on soil chemical properties, physiological and biochemical attributes as well as nutrients uptake of wheat under water-stress condition in saline sodic soil. Therefore, this study was carried out to prove this hypothesis and fill this knowledge gap. The results of this study will open new research prospects to maintain a good yield despite the environmental stressors in the climate change scenario.

2 | MATERIALS AND METHODS

2.1 | Experimental site and growth conditions

The experiment was conducted in a lysimeter to test the effect of water stress and soil salinity on grain yield, nutrient uptake, and soil properties in wheat (cultivar “Misr 1”). The experiment was conducted in 2018/2019, from 27 November to 24 April and repeated in 2019/2020, from November 29 to April 28 at Sakha Agricultural Research Station, Kafr El-Sheikh Government (30°3′N latitude, 31°3′E longitude), Egypt. During the wheat growth cycles from November to April, the meteorological results were received from the agrometeorological station adjacent to the experimental locations and are shown in Table 1.

TABLE 1 Sakha station meteorological data during the growing seasons of 2018–2019 and 2019–2020

Year	2018/2019				2019/2020			
	Temperature (°C)				Temperature (°C)			
Month	Max	Min	Rainfall (mm)	RH (%)	Max	Min	Rainfall (mm)	RH (%)
Dec	24.5	13.2	1.10	35.1	23.2	12.4	0.54	32.7
Jan	22.3	10.3	3.10	46.2	20.3	11.1	3.32	42.4
Feb	21.4	9.7	6.40	44.3	20.6	10.7	6.85	43.1
Mar	23.7	13.8	0.50	43.8	22.5	12.5	0.63	44.8
April	24.8	14.9	0.00	52.7	25.7	16.6	0.00	52.5
May	29.2	16.5	0.00	62.9	28.8	17.8	0.00	64.3

Abbreviation: RH, relative humidity.

2.2 | Experimental design and agronomic practices

The randomized complete experimental design (plots of 0.455 m^2 area and 0.6 m depth with 0.1 m gravel filter) consisted of water stress treatments by irrigation at 50%, 75%, and 100% of field capacity (FC) from the depth 0–30 cm, as well as soil amendments including control, VC, biochar, and VC + biochar. Each plot contained 10 plants, and three plots for each treatment were provided (representing each a biological replicate). Plants were randomly picked in every plots for all analyses described below. VC (4% W:W of soil; about 3.95 kg/plot) and biochar (1% W:W of soil; about 0.95 kg/plot) as well as their interactions were mixed with the soil in the top 20-cm layer before wheat sowing. Seeds were planted at a seeding rate of 142.8 kg ha^{-1}. Phosphorus fertilizers were applied during the soil preparations in a super phosphate form (15% P_2O_5) at 35 kg P_2O_5 ha^{-1} rate. Potassium fertilizers were also applied directly before the first irrigation in a potassium sulfate form (48% K_2O) at 57 kg K_2O ha^{-1} rate. Nitrogen fertilizers were applied directly before the first and second irrigations in a urea form (46.5% N) at 180 kg N ha^{-1} rate. Other agronomic approaches such as the protection of wheat plants from diseases or weeds were achieved in a timely manner.

2.3 | VC characterization

VC was made in vermicomposting bins (100 × 120 × 50 cm). Crop residues (rice and maize straw) were utilized as materials for VC. Cow manure and green waste were used as worm feeds. The earthworm species (*Eisenia fetida* and *Dendrobaena veneta*) were inoculated (Joshi *et al.*, 2015). VC was brought from the Agricultural Research Center, Giza, Egypt. The moisture content was maintained at 80% (volume) through the vermicomposting process (2 months). The prepared VC had an organic matter content of 42%, electrical conductivity (EC) 3.8 dS m^{-1}, total N 2.1%, total P 7.8%, total K 0.5%, pH 7.4, and polyphenol 8.4%; water holding capacity 150 ± 12.23; and C 18.3 ± 1.36%. The VC was applied to the soil at the rate of 10.0 ton ha^{-1}. Neither the control treatments nor the individual biochar treatments received VC.

2.4 | Biochar characterization

The biochar used in the present study was prepared through the slow pyrolysis of corn stalk and rice husk (1:1) at 350°C under oxygen-depleted conditions with a mean residence time of 3 h (Odesola and Owoseni, 2010). The characteristics of biochar are: EC (1:5 biochar: water extract) 2.05 ± 0.01 dS m^{-1}; pH (1:5 biochar: water extract) 7.90 ± 0.02; specific surface area 37.0 ± 2.13 m^2 g^{-1}; $CaCO_3$ 1.4 ± 0.03%; bulk density (BD) 0.20 ± 0.03 g cm^{-3}; moisture content 11.4 ± 1.09%; water holding capacity 139 ± 12.23%; P 2.2 ± 0.83%; N 1.9 ± 2.91%; and K 2.9 ± 1.42%. Prior to its application, the prepared biochar was ground and sieved through ~2 mm mesh. One week prior to planting and during the tillage process, biochar was broadcasted to each plot and mixed thoroughly with the soil (0–20 cm depth) at a rate of 1 kg biochar m^{-2}, which is equivalent to 10 ton ha^{-1}. Neither the control treatments nor the individual VC treatments received biochar.

2.5 | Soil physicochemical properties

Prior to seed sowing, soil samples were collected at 0–30 cm depth using an auger to document the physicochemical properties of the experimental soil. Soil samples were air-dried and passed through a 2-mm sieve for physicochemical properties analysis as shown in Table 2. Soil samples were taken from the surface layer in each plot before planting and after harvesting. EC (dS m^{-1}) and soluble ions were determined in soil extract according to Page (1982). Soil BD was determined before experiment and at the end of the experiment for each treatment using the core method according to Klute (1986). Soil moisture constants before planting in the growing seasons 2018–2019 and 2019–2020 are indicated in Table 3. At wheat harvest, soil samples were collected at 0–30 cm depth using an auger. Soil samples were air-dried and passed through a 2-mm sieve for chemical characteristics analyses. The concentration (meq L^{-1}) of K^+, Na^+, Mg^{2+}, and Ca^{2+} ions was estimated in the soil paste extract using atomic absorption spectrophotometer (AAS; Perkin Elmer 3300) (Sparks et al. 1996). Exchangeable sodium percentage (ESP) was estimated following the formula suggested by Seilsepour and Rashidi (2008):

$$ESP = 1.95 + 1.03 \times SAR \left(R^2 = 0.92\right)$$

where SAR (sodium adsorption ratio) was estimated using the following equation as described by (United States Department of Agriculture, 1954):

$$SAR = [Na^+]/\sqrt{\frac{([Ca^{2+}] + [Mg^{2+}])}{2}}$$

where Na^+, Ca^{2+}, and Mg^{2+} were expressed in meq L^{-1}.

TABLE 2 Experimental soil physicochemical characteristics before planting in 2018–2019 and 2019–2020 growing seasons

Character	2018/2019	2019/2020
pH (1:2.5 soil : water suspension)	8.15 ± 0.02[a]	8.08 ± 0.03
Electrical conductivity (EC, dS m^{-1})[b]	4.33 ± 0.01	4.12 ± 0.02
Soil organic matter (g kg^{-1})	11.6 ± 0.03	11.8 ± 0.05
ESP[c] (%)	20.20 ± 0.42	17.49 ± 0.32
Particle size distribution (%)		
Sand	27.22 ± 1.88	27.17 ± 1.98
Silt	25.23 ± 2.02	25.55 ± 1.99
Clay	47.55 ± 2.32	47.28 ± 2.03
Texture grade	Clayey	Clayey
Soluble cations (meq L^{-1})[b]		
Ca^{2+}	8.62 ± 0.94	9.89 ± 0.87
Mg^{2+}	3.87 ± 1.11	4.05 ± 1.32
Na^+	23.36 ± 2.06	21.25 ± 3.08
K^+	0.48 ± 0.02	0.51 ± 0.02
SAR (%)	9.34 ± 0.30	8.05 ± 0.29
Soluble anions (meq L^{-1})[b]		
CO_3^{2-}	nd	nd
HCO_3^-	3.44 ± 0.56	3.65 ± 0.68
Cl^-	26.75 ± 1.11	22.75 ± 1.15
SO_4^{2-}	17.35 ± 3.03	13.63 ± 3.04
Available macronutrients (mg kg^{-1})		
N	10.65 ± 0.91	11.55 ± 1.71
P	9.74 ± 1.33	9.98 ± 1.54
K	355 ± 26.42	394 ± 24.33

Abbreviation: SAR, sodium adsorption ratio, nd, not detected
[a]Standard deviation.
[b]Measured in soil paste extract.
[c]Exchangeable sodium percentage.

2.6 | Soil moisture constants

From the soil depth 0–30 cm, the volume of water deposited in the rhizosphere between FC and the permanent wilting point (PWP) is indicated in Table 3. ASW was determined using the following equation:

$$ASW = (WFC - WPWP) \times Bd \times V$$

where WFC and WPWP are the gravimetric soil-water content (%) at FC and PWP, respectively. Bd indicates the value of soil BD (g cm^{-3}) and V refers to the soil layer volume (m^3) at the depth of the root zone which was estimated to be different three times (i.e., June, July, and August) during 2018–2019 and 2019–2020 growing seasons as reported by Garcia (1978) and Klute (1986).

2.7 | Biochemical analysis and Na^+ and K^+ ions in wheat leaves

Ascorbate peroxidase (APX) and catalase (CAT) enzyme activities were determined following the procedures mentioned by Nakano and Asada (1981) and Rao *et al.* (1997). Enzyme activity was expressed as μM H_2O_2 min^{-1} g^{-1} fresh weight (FW). The cytotoxicity of aqueous leaf extracts and cell viability were determined using the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl-2H-tetrazolium bromide (MTT) method as reported by El-Esawi *et al.* (2017). Na^+ and K^+ contents were estimated using AAS (Perkin Elmer 3300) according to Cottenie (1980) and Temmingho and Houba (2004). All parameters were measured in three biological replicates.

2.8 | Chlorophyll and carotenoid content

According to the procedures of Mousa *et al.* (2007), 0.1 g of fresh leaf tissue representing one leaf per plant per replicate was ground with

TABLE 3 Constants of soil moisture before planting in 2018–2019 and 2019–2020 growing seasons

Year	Soil depth (cm)	FC (%)	PWP (%)	ASW (%)	BD (g cm^{-3})	TP (%)
2018/2019	0–20	40.15 ± 0.02	20.76 ± 0.02	19.39 ± 0.02	1.41 ± 0.02	47.00 ± 1.70
	20–40	37.27 ± 0.06	20.21 ± 0.01	17.06 ± 0.01	1.45 ± 0.04	45.00 ± 1.47
	40–60	36.45 ± 0.02	19.76 ± 0.01	16.69 ± 0.05	1.48 ± 0.03	44.00 ± 0.70
2019/2020	0–20	43.01 ± 0.05	17.43 ± 0.02	25.58 ± 0.04	1.37 ± 0.05	48.00 ± 2.77
	20–40	42.33 ± 0.02	18.65 ± 0.02	23.68 ± 0.05	1.40 ± 0.03	47.00 ± 2.50
	40–60	42.32 ± 0.02	19.21 ± 0.04	20.67 ± 0.02	1.44 ± 0.02	46.00 ± 1.86

Abbreviations: ASW, available soil water; BD, bulk density; FC, field capacity; PWP, permanent wilting point; TP, total porosity.

5 ml acetone 80% then centrifugated at 13,000 rpm for 10 min. The absorbance of the supernatant was read at 645, 663, and 470 nm to estimate the contents of chlorophyll *a*, chlorophyll *b*, total chlorophyll, and carotenoid. These parameters were measured in three biological replicates.

2.9 | Free proline content, stomatal conductance, and leaf relative water content

Free proline content in leaves was estimated following the procedures of Bates *et al*. (1973) and was expressed as μmol proline g^{-1} FW. Stomatal conductance (g_s) was determined on fully expanded flag leaves (one leaf per plant per replicate) from the abaxial surface as mmol H_2O m^{-2} s^{-1}. FW, turgid weight (TW), and dry weight (DW) of leaves were estimated. Leaf relative water content (RWC) was then estimated using the following equation; all parameters were measured in three biological replicates (Barrs and Weatherly, 1962):

$$\text{Leaf RWC}\,(\%) = ([\text{FW}-\text{DW}]/[\text{TW}-\text{DW}]) \times 100$$

2.10 | Yield and yield components

At the maturity stage, out of each experimental plot, 10 plants were randomly chosen and used for counting the number of grains per spike and number of spikes per m^2 as well as for estimating 1000-grain weight. Additionally, at the physiological maturity, the plants of each plot were manually harvested. The biological yield was calculated by weighting the whole harvested plants of the plot. Grain yield weight was also measured. Straw yield was estimated by subtracting the weight of grain yield from the weight of biological yield. Harvest index was estimated as the ratio of grain yield to biological yield, and then the value was multiplied with 100 to be expressed as percent. Uptake of N, P, and K in grains was also determined. Nitrogen was estimated using macro-Kjeldahl technique according to Association of Official Agricultural Chemists (1975). Sodium, potassium, and phosphorus were estimated using the flame photometer following the procedures of Jackson (1958). All parameters were measured in three biological replicates.

2.11 | Transcriptional analysis

Quantitative real-time polymerase chain reaction (PCR) analysis was used to estimate the expression levels of the antioxidant genes (*CAT*, *APX*, and *Mn-SOD*) in wheat plants subjected to water stress conditions. RNA and cDNA were isolated from plant leaves (one leaf per plant per replicate) using Qiagen kits. QuantiTect SYBR Green PCR kit was used for the PCR. Primers used, PCR reactions, and amplification conditions were assayed as mentioned by El-Esawi *et al*. (2019). *ACTIN* served as a reference housekeeping gene. The relative genes expression levels were assayed following the $2^{-\Delta\Delta Ct}$ method. The anaylsis was performed in three biological and three technical replicates.

2.12 | Data analysis

ANOVA was calculated for the data using MSTAT-C Statistical Software package following Gomez and Gomez (1984). Means were compared using Tukey's multiple range test and ANOVA revealed significant differences at $P < 0.05$.

3 | RESULTS

In the present study, synergistic application of VC and biochar improved soil chemical properties, soil moisture contents, plant growth, physiological traits, biochemical traits, nutrient uptake, and wheat yield in comparison to their sole application during 2018/2019 and 2019/2020 growing seasons.

3.1 | Soil physicochemical properties

Stress water treatments and organic amendments significantly affected soil chemical properties compared to the initial soil characteristics at presowing stage (Table 4). Soil irrigation at 50% FC increased soil pH compared to that at 75% or 100% FC (Table 4). Untreated plants (control) increased soil pH, the application of organic amendments reduced it. The addition of VC, biochar, or their combination in the soil during wheat plant growth greatly decreased the pH (Table 4). Likewise, irrigating wheat plants at 50% FC augmented the EC compared to 75% or 100% FC. However, compared to the value EC before sowing, the application of VC and biochar alone or in combination notably declined EC of the soil solution irrespective of the level of irrigation at the harvest in both years under study, that is, 2018/2019 and 2019/2020 (Table 4). Furthermore, the sole biochar addition exhibited a better positive impact on EC than the sole addition of VC under the three levels of irrigation water (50%, 75%, and 100% FC) in both years. In addition, the soil cations (i.e., Na^+, K^+, Ca^{2+}, and Mg^{2+}) and ESP were affected upon treating wheat plants with VC, biochar, or their combination, irrespective of the level of the irrigation water (Table 4). As shown in Table 4, it was found that lower levels of irrigation (50% and 75% FC) integrated with the combination of VC and biochar decreased ESP more than with higher level of the irrigation (75% and 100% FC) without application of soil amendments (untreated plants) in the successive years.

3.2 | Soil moisture

Soil moisture constants (i.e., FC, BD, and available soil water) were measured in pretrial soil (Table 3) and post-trial soil (Table 5) in the

TABLE 4 Soil chemical characteristics at the harvesting of wheat plants irrigated with 50%, 75%, or 100% of field capacity in saline sodic soil treated with vermicompost and biochar

Year	Water treatments	Soil treatments	pH[a]	EC[b](dS m^{-1})	ESP[c](%)	Na^{+}[d] (meq L^{-1})	K^{+} (meq L^{-1})	Ca^{2+} (meq L^{-1})	Mg^{2+} (meq L^{-1})
2018/2019	50%	Control	8.18 ± 0.01a	4.89 ± 0.06a	22.93 ± 0.23a	27.44 ± 0.98a	0.33 ± 0.02 g	6.80 ± 0.12 h	6.08 ± 0.02 h
		VC[e]	8.14 ± 0.02b	4.41 ± 0.05b	17.49 ± 0.35b	23.64 ± 0.88b	0.35 ± 0.01 fg	8.08 ± 0.18gh	6.39 ± 0.03 g
		BC[f]	8.13 ± 0.01bc	4.33 ± 0.03c	16.92 ± 0.24bc	21.84 ± 0.75c	0.36 ± 0.03f	9.16 ± 0.23 g	6.54 ± 0.0.08f
		VC + BC	8.11 ± 0.02 cd	4.09 ± 0.08de	15.19 ± 0.15 cd	19.94 ± 1.05de	0.38 ± 0.02e	11.24 ± 0.25f	6.62 ± 0.07e
	75%	Control	8.12 ± 0.03c	4.12 ± 0.07d	15.93 ± 0.36c	20.55 ± 1.08d	0.37 ± 0.00ef	10.57 ± 0.15fg	6.59 ± 0.09e
		VC	8.10 ± 0.03d	3 93 ± 0.04e	13.05 ± 0.35d	18.78 ± 1.07e	0.39 ± 0.01d	12.35 ± 0.18e	6.82 ± 0.06d
		BC	8.09 ± 0.02de	3.85 ± 0.05ef	12.87 ± 0.24e	18.23 ± 0.99ef	0.39 ± 0.82d	13.45 ± 0.08d	6.97 ± 0.05 cd
		VC + BC	8.07 ± 0.01ef	3.52 ± 0.02 fg	10.91 ± 0.15 fg	16.57 ± 0.87fg	0.41 ± 0.03c	15.85 ± 0.07c	7.02 ± 0.08c
		Control	8.08 ± 0.00e	3.70 ± 0.03f	11.83 ± 0.22f	17.77 ± 0.85f	0.40 ± 0.02 cd	14.88 ± 0.05 cd	6.98 ± 0.04 cd
	100%	VC	8.05 ± 0.01f	3.45 ± 0.06 g	9.27 ± 0.12 g	15.92 ± 1.05g	0.42 ± 0.05bc	16.70 ± 0.09bc	7.09 ± 0.03bc
		BC	8.04 ± 0.01 fg	3.30 ± 0.04 h	9.01 ± 0.33 h	15.84 ± 0.02g	0.43 ± 0.04b	17.49 ± 0.18b	7.18 ± 0.02b
		VC + BC	8.02 ± 0.01 g	3.14 ± 0.08i	8.54 ± 0.11i	13.24 ± 0.11gh	0.46 ± .03a	19.32 ± 0.22a	7.31 ± 0.01a
2019/2020	50%	Control	8.17 ± 0.02a	4.83 ± 0.02a	21.71 ± 0.25a	26.03 ± 0.74a	0.33 ± 0.02 h	6.81 ± 0.17 h	6.18 ± 0.02j
		VC	8.14 ± 0.02b	4.46 ± 0.04b	18.14 ± 0.36b	23.21 ± 0.86b	0.35 ± 0.01 g	8.85 ± 0.16 g	6.49 ± 0.05i
		BC	8.13 ± 0.01bc	4.23 ± 0.01c	17.54 ± 0.34bc	22.69 ± 0.95bc	0.38 ± 0.01f	9.72 ± 0.14f	6.64 ± 0.06 h
		VC + BC	8.10 ± 0.03 cd	3.96 ± 0.03de	15.08 ± 0.25 cd	19.75 ± 0.98 cd	0.41 ± 0.02e	11.35 ± 0.25e	6.79 ± 0.08fg
	75%	Control	8.11 ± 0.01c	4.05 ± 0.04d	15.69 ± 0.21c	20.15 ± 1.05c	0.40 ± 0.02ef	10.82 ± 0.09ef	6.80 ± 0.07fg
		VC	8.08 ± 0.01d	3.88 ± 0.05e	13.28 ± 0.14d	18.87 ± 1.09d	0.42 ± 0.01de	11.66 ± 0.05e	6.87 ± 0.04f
		BC	8.07 ± 0.02de	3.79 ± 0.07ef	13.03 ± 0.15d	18.68 ± 1.08d	0.43 ± 0.02d	12.24 ± 0.08d	7.03 ± 0.09e
		VC + BC	8.05 ± 0.01ef	3.57 ± 0.08 fg	11.67 ± 0.18e	15.17 ± 1.05ef	0.46 ± 0.02c	13.92 ± 0.99c	7.09 ± 0.05d
		Control	8.06 ± 0.02e	3.69 ± 0.09f	12.23 ± 0.19de	16.05 ± 1.12e	0.45 ± 0.01 cd	12.28 ± 1.08 cd	7.07 ± 0.02d
	100%	VC	8.04 ± 0.01f	3.35 ± 0.06 g	10.54 ± 0.22f	14.18 ± 1.13fg	0.47 ± 0.01bc	13.94 ± 1.11bc	7.13 ± 0.01c
		BC	8.03 ± 0.02fg	3.32 ± 0.04 h	10.44 ± 0.25 fg	14.42 ± 1.09f	0.48 ± 0.01b	14.06 ± 1.23b	7.33 ± 0.03b
		VC + BC	8.01 ± 0.03g	3.09 ± 0.05i	8.30 ± 0.24g	12.86 ± 1.07g	0.50 ± 0.01a	15.27 ± 1.05a	7.50 ± 0.06a
F-test									
Treatment			***	***	***	***	***	***	***
Year			***	***	***	***	***	***	***
Treatment × year			***	***	***	ns	ns	ns	***

Notes: In the same growing season, means indicated with different letters show significant differences among treatments following Tukey's test ($P < 0.05$). Values represent means ± standard deviation ($n = 3$).
*** and ns indicate significance at $P < 0.001$ and nonsignificant, respectively.
[a]pH is determined in soil: distilled water suspension at 1:2.5 ratio.
[b]EC (electrical conductivity) is determined in soil:distilled water extract of 1:5.
[c]Exchangeable sodium percentage.
[d]Ions (Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+}) are estimated in soil:distilled water extract of 1:5.
[e]Vermicompost (VC) is applied at 1 kg m^{-2} rate.
[f]Biochar (BC) is applied at 1 kg m^{-2} rate.

TABLE 5 The soil moisture constants at the harvesting of wheat plants irrigated with 50%, 75%, or 100% of field capacity in saline sodic soil treated with vermicompost and biochar

Water treatments	Soil treatments	FC		BD		ASW	
		2018/2019	2019/2020	2018/2019	2019/2020	2018/2019	2019/2020
50%	Control	40.20 ± 1.25 h	40.80 ± 1.30 g	1.45 ± 0.02a	1.48 ± 0.02a	11.27 ± 0.98j	11.38 ± 0.15i
	VC[a]	43.63 ± 1.36 gh	42.05 ± 1.22 fg	1.42 ± 0.01b	1.43 ± 0.03b	14.06 ± 0.99i	16.31 ± 0.16 h
	BC[b]	44.34 ± 1.25 g	42.59 ± 1.25f	1.40 ± 0.03c	1.41 ± 0.02c	16.57 ± 1.10 h	23.87 ± 0.17 g
	VC + BC	46.74 ± 1.24f	43.46 ± 1.22e	1.36 ± 0.08de	1.36 ± 0.05e	20.65 ± 1.12 g	27.32 ± 0.15f
75%	Control	45.97 ± 1.22 fg	42.70 ± 1.20ef	1.37 ± 0.06d	1.39 ± 0.04d	19.42 ± 0.18gh	26.24 ± 0.14 fg
	VC	47.87 ± 1.18e	45.18 ± 1.18de	1.34 ± 0.05e	1.32 ± 0.02f	21.51 ± 0.19f	27.79 ± 0.15ef
	BC	48.07 ± 1.15d	45.98 ± 1.15d	1.33 ± 0.03ef	1.29 ± 0.01 g	22.43 ± 0.15e	28.09 ± 0.11e
	VC + BC	49.51 ± 1.16c	47.95 ± 1.16c	1.28 ± 0.04 fg	1.25 ± 0.05i	25.98 ± 0.14d	31.56 ± 0.12d
	Control	48.89 ± 1.19 cd	47.22 ± 1.14 cd	1.30 ± 0.02f	1.27 ± 0.06 h	24.13 ± 0.12de	30.15 ± 0.15de
100%	VC	49.96 ± 1.21b	49.46 ± 1.17bc	1.25 ± 0.01 h	1.20 ± 0.02j	27.81 ± 0.11c	32.31 ± 0.16c
	BC	49.81 ± 1.23bc	49.87 ± 1.25b	1.21 ± 0.03i	1.19 ± 0.03jk	29.77 ± 0.13b	34.41 ± 0.13b
	VC + BC	51.99 ± 1.25a	52.24 ± 1.22a	1.15 ± 0.05j	1.12 ± 0.03 k	33.48 ± 0.14a	36.09 ± 0.18a
F-test							
Treatment		***		***		***	
Year		**		**		***	
Treatment × year		ns		ns		ns	

Notes: In the same growing season, means indicated with different letters show significant differences among treatments following Tukey's test ($P < 0.05$). Values represent means standard deviation ($n = 3$). ***, **, and ns indicate significance at $P < 0.001$, $P < 0.01$, and non-significant, respectively.
Abbreviations: ASW, available soil water; BD, bulk density; FC, field capacity.
[a]Vermicompost (VC) is applied at 1 kg m^{-2} rate.
[b]Biochar (BC) is applied at 1 kg m^{-2} rate.

2 years under study. These constants were significantly affected by irrigation treatments and soil amendments in saline sodic soil. The addition of VC and biochar alone enhanced FC and available soil water, while it declined BD compared to the control (where neither VC nor biochar was applied). However, these traits were enhanced when VC was added in combination with biochar in both years. Besides, among the irrigation levels (50%, 75%, and 100% FC), the highest increases in FC, ASW, and the lowest decreases in BD were observed when plants were irrigated at 100% FC with the integrated treatment of VC and biochar. Meanwhile, wheat plants irrigated at 75% FC improved FC and ASW and decreased BD at harvest when treated with the combined application of VC and biochar.

3.3 | Biochemical assays

CAT and APX activities were measured in wheat plants grown in saline sodic soil during 2018/2019 and 2019/2020 (Table 6). Irrigation at 50% FC exhibited higher CAT and APX activities in wheat plants as compared to that reflected by irrigation at 75% and 100% FC. However, CAT and APX activities decrease in response to water stress (50% FC) when soil amendments, either VC or biochar or their combined treatment, are applied. In addition, the cytotoxicity assay revealed that the leaf extract of wheat plants significantly inhibited the growth of HepG2 cancer cells and exhibited higher cytotoxic effect when treated with the combined application of biochar and VC under water stress conditions, compared to the untreated plants in the 2 years (Table 6).

3.4 | Contents of Na^+, K^+, and K^+/Na^+ in leaves of wheat irrigated with 50%, 75%, or 100% FC

The K^+ content and K^+/Na^+ ratio in leaves of wheat significantly reduced (Table 6), whilst Na^+ augmented, when plants were irrigated with 50% and 75% FC compared to 100% FC under saline sodic soil during 2018/2019 and 2019/2020. There was a significant interaction between water treatments and soil amendments on K^+ and Na^+ content in leaves of wheat and subsequently K^+/Na^+ ratio (Table 6) in both years. Remarkably, the combination or individual addition of VC and/or biochar to wheat plants irrigated with either 50% and 75% or 100% FC significantly affected Na^+, K^+ and K^+/Na^+ in the leaves. These treatments significantly decreased Na^+ content and augmented K^+ and K^+/Na^+ (Table 6). However, the synergistic addition of VC and biochar had the highest effect, followed by the sole addition of biochar and VC. For example, the minimum Na^+ content and the maximum K^+ content and K^+/Na^+ ratio were perceived in plants treated with the combined application of VC and biochar upon irrigation with

TABLE 6 Activity of antioxidant enzymes and the percent of cell inhibition, Na^+, K^+ and K^+/Na^+ ratio in wheat leaves irrigated with 50%, 75%, and 100% of field capacity in saline sodic soil treated with vermicompost and biochar

			Enzymes activity			Leaves		
Year	Water treatment	Soil treatment	CAT (μM H_2O_2 min^{-1} g^{-1} FW)	APX (μM H_2O_2 min^{-1} g^{-1} FW)	Cell inhibition (%)	Na^+ (%)	K^+ (%)	K^+/Na^+
2018/2019	50%	Control	27.43 ± 0.85a	452.67 ± 3.45a	35.12 ± 0.98n	2.54 ± 0.01a	0.52 ± 0.01 h	0.20 ± 0.01 h
		VC[a]	23.27 ± 0.75b	439.33 ± 3.74b	54.23 ± 0.84j	2.43 ± 0.02b	0.66 ± 0.02 g	0.27 ± 0.01 gh
		BC[b]	22.76 ± 0.69bc	431.00 ± 3.78bc	56.11 ± 0.91i	2.39 ± 0.02bc	0.77 ± 0.02f	0.32 ± 0.01 g
		VC + BC	20.21 ± 0.65 cd	385.33 ± 3.41d	61.95 ± 0.88 g	2.22 ± 0.03 cd	0.84 ± 0.01e	0.38 ± 0.02f
	75%	Control	20.59 ± 0.85c	398.67 ± 3.52c	51.17 ± 0.94 k	2.29 ± 0.02c	0.81 ± 0.00ef	0.35 ± 0.01 fg
		VC	19.24 ± 0.74d	381.33 ± 3.63de	66.22 ± 0.89f	2.05 ± 0.02d	0.90 ± 0.01de	0.44 ± 0.01e
		BC	19.11 ± 0.36de	376.00 ± 3.14e	72.66 ± 0.91d	1.91 ± 0.03e	0.92 ± 0.02d	0.48 ± 0.01d
		VC + BC	17.36 ± 0.65e	345.67 ± 3.25 g	77.12 ± 0.88b	1.87 ± 0.03f	1.11 ± 0.02c	0.59 ± 0.01c
		Control	18.02 ± 0.45ef	368.00 ± 3.65f	60.25 ± 0.97 h	1.93 ± 0.01ef	0.98 ± 0.03 cd	0.51 ± 0.02 cd
	100%	VC	15.40 ± 0.68f	334.00 ± 3.31 h	71.18 ± 0.98e	1.66 ± 0.02 g	1.18 ± 0.02bc	0.71 ± 0.03bc
		BC	15.31 ± 0.74 fg	316.33 ± 3.36i	75.31 ± 0.93c	1.60 ± 0.01 gh	1.19 ± 0.01b	0.74 ± 0.02b
		VC + BC	11.94 ± 0.55 g	250.41 ± 3.25j	80.14 ± 0.89a	1.41 ± 0.02 h	1.29 ± 0.01a	0.92 ± 0.01a
2019/2020	50%	Control	27.75 ± 0.36a	458.27 ± 3.36a	35.88 ± 0.91n	2.75 ± 0.03a	0.60 ± 0.01j	0.22 ± 0.02 g
		VC	23.59 ± 0.65b	444.93 ± 3.34b	54.67 ± 0.92j	2.54 ± 0.01b	0.74 ± 0.02i	0.29 ± 0.01 fg
		BC	22.08 ± 0.45bc	439.60 ± 3.31bc	55.93 ± 0.88i	2.51 ± 0.02bc	0.85 ± 0.02 h	0.34 ± 0.01f
		VC + BC	20.53 ± 0.69 cd	399.93 ± 3.22d	62.07 ± 0.92 g	2.22 ± 0.01 cd	0.92 ± 0.02f	0.41 ± 0.01e
	75%	Control	20.91 ± 0.58c	414.27 ± 3.87c	51.88 ± 0.91 k	2.30 ± 0.01c	0.89 ± 0.01 g	0.39 ± 0.01ef
		VC	18.16 ± 0.74d	396.93 ± 3.54de	66.56 ± 0.92f	2.10 ± 0.02d	0.98 ± 0.02ef	0.47 ± 0.02de
		BC	17.43 ± 0.25de	381.60 ± 3.21e	72.81 ± 0.87d	2.07 ± 0.02de	1.00 ± 0.02e	0.48 ± 0.02d
		VC + BC	15.38 ± 0.24ef	351.27 ± 3.32 g	77.73 ± 0.81b	1.83 ± 0.03ef	1.19 ± 0.01c	0.65 ± 0.01c
		Control	16.64 ± 0.45e	363.60 ± 3.65f	60.61 ± 0.83 h	1.88 ± 0.02e	1.16 ± 0.01 cd	0.62 ± 0.01 cd
	100%	VC	12.72 ± 0.56f	339.60 ± 3.78 h	71.44 ± 0.91e	1.71 ± 0.02f	1.29 ± 0.02bc	0.75 ± 0.01bc
		BC	11.43 ± 0.98 fg	331.93 ± 3.12 hi	75.52 ± 0.90c	1.60 ± 0.01 g	1.30 ± 0.02b	0.81 ± 0.01b
		VC + BC	9.26 ± 0.75 h	256.01 ± 3.45i	80.89 ± 0.92a	1.46 ± 0.02 h	1.43 ± 0.02a	0.97 ± 0.01a
F-test								
Treatment			***	***	***	***	***	***
Year			***	***	***	***	***	***
Treatment × year			ns	***	***	***	***	***

Notes: In the same growing season, means indicated with different letters show significant differences among treatments following Tukey's test ($P < 0.05$). Values represent means ± standard deviation ($n = 3$).
*** and ns indicate significance at $P < 0.001$ and nonsignificant, respectively.
Abbreviations: APX, ascorbate peroxidase; CAT, catalase; FW, fresh weight.
[a]Vermicompost (VC) is applied at 1 kg m^{-2} rate.
[b]Biochar (BC) is applied at 1 kg m^{-2} rate.

either 50% and 75% or 100% FC compared to the individual addition or untreated plants grown in saline sodic soil during both years. Increasing FC from 50% and 75% to 100% increased the K^+ content and K^+/Na^+ ratio while declined Na^+ in both years (Table 6).

3.5 | Physiological traits

The content of chlorophyll *a*, chlorophyll *b*, total chlorophyll, carotenoids, RWC and g_s of wheat plants displayed significant differences with respect to different irrigation water treatments and soil amendments during both of the 2 years (Table 7). The content of chlorophyll *a*, chlorophyll *b*, total chlorophyll, carotenoids, RWC, and g_s of wheat plants grown under 50% and 75% FC were significantly ($P \leq 0.05$) declined relative to that of 100% FC (Table 7). However, treatment with VC, biochar and their combination augmented chlorophyll *a*, chlorophyll *b*, total chlorophyll, carotenoids, RWC, and g_s for the wheat plants grown under 50% and 75% FC conditions compared to those grown in the control (where neither VC nor biochar was applied) under saline sodic soil. On the other hand, the proline content was significantly increased ($P \leq 0.05$) for the plants grown under 50% and 75% FC compared to 100% FC in both years (Table 7). However, treatments with VC, biochar or their combination significantly ($P \leq 0.05$) reduced the proline content in the wheat plant grown under different irrigation water treatments compared to those grown in the control treatment (where neither VC nor biochar was applied). These findings designated that soil application of VC, biochar, and their combined application could ameliorate water deficit-induced negative impacts on wheat plants grown in saline sodic soil.

3.6 | Yield traits and productivity

The number of grains per spike, 1000-grain weight, grain yield, straw yield, and harvest index of wheat were significantly reduced with decreasing FC to 50% FC, compared to plants subjected to 100% FC (Table 8). The applications of VC, biochar or their combination has greatly improved wheat yield traits compared to control treatment (received neither VC nor biochar) at all irrigation water treatments (50%, 75%, or 100% FC) in both years.

3.7 | Nutrient uptake

Nitrogen, phosphorus, and potassium uptake were significantly influenced by irrigation water treatments and organic amendments in 2018/2019 and 2019/2020 and followed the same trend with higher values measured when organic amendments were used (Table 9). The interaction between the irrigation treatments and soil applications on N, P, and K uptake was significant during both years. It was found that more increment in nitrogen, phosphorus, and potassium uptake was detected when VC was added alongside with biochar at 100% FC as compared to their sole applications in both years (Table 9). Also, sole applications of either VC or biochar produced higher nitrogen, phosphorus, and potassium uptake compared to control treatment (neither VC nor biochar) at all irrigation water treatments (50%, 75%, or 100% FC) in both years. Among irrigation treatments, 50% FC greatly declined the nutrient uptake compared to 75% and 100% FC in both years. The combined amendments significantly ameliorated ($P \leq 0.05$) the negative effects of low irrigation (50% and 75% FC) in saline sodic soil during both years (Table 9). The highest N, P, and K uptake was recorded in wheat plants treated with the combined VC and biochar when irrigated with 75% or 100% FC during the 2 years (Table 9).

3.8 | Transcriptional analysis of antioxidant genes

The expression levels of antioxidant genes such as *CAT*, *APX*, and *Mn-SOD* were measured in wheat plants under saline sodic soil during 2018–2019 and 2019–2020 (Table 10). Plants exhibited significantly higher expression levels of *CAT*, *APX*, and *Mn-SOD* genes upon low soil water availability (50% FC), as compared to plants grown at 75% and 100% FC (Table 10). However, the application of soil amendments, either VC or biochar or their combined treatment, reduced the expression levels of *CAT*, *APX*, and *Mn-SOD* genes in all irrigation levels. The best effect was observed when VC and biochar were combined.

4 | DISCUSSION

Water stress is a serious factor that negatively affects plant growth and yield, particularly in salt-affected soils. Water stress and soil salinity are the two main restricting issues of sustainability of agricultural production, especially in arid and semiarid zones like Egypt. The current investigation was aimed at curtailing the detrimental effect of water stress and salt-affected soil on wheat by the sole and combined application of VC and biochar. The soil chemical properties and soil moisture constants, plant growth, physiological and biochemical attributes, as well as the yield and nutrient uptake were adversely influenced when the wheat plants were exposed to 50% and 75% FC in saline sodic soil during 2018/2019 and 2019/2020. However, this impact was reversed in plants treated with soil amendments, that is, VC, biochar, and their combination. The current study findings are in line with those of studies reporting that plant growth declined in saline soil combined or not with water stress (Bodner *et al*., 2015; Rehman *et al*., 2016).

Biochar is a carbon-rich organic material having multiple benefits for soil such as increased available nutrients, improved soil chemical properties, as well water retention in saline sodic soil (Dzvene *et al*., 2019; Hafez, Alsohim, *et al*., 2019), improved soil quality by mending ESP through discharging the mineral nutrients, especially K^+, Ca^{2+}, and Mg^{2+}. It was found that biochar is an applicable approach to counter water stress conditions thanks to the amelioration of soil hydrological conductivity (Omondi *et al*., 2016; Yu *et al*., 2017), which in turn get better plant physiological and biochemical responses. The

TABLE 7 Physiological measurements of wheat plants irrigated with 50%, 75%, or 100% of field capacity in saline sodic soil treated with vermicompost and biochar

Year	Water treatments	Soil treatments	Chlorophyll *a* (mg g^{-1} FW)	Chlorophyll *b* (mg g^{-1} FW)	Total chlorophyll (mg g^{-1} FW)	Carotenoids (μg g^{-1} FW)	Proline (μmol g^{-1} FW)	RWC (%)	g_s[a] (mmol H_2O m^{-2} s^{-1})
2018/2019	50%	Control	0.92 ± 0.02 k	0.21 ± 0.00 h	1.13 ± 0.05 k	0.32 ± 0.02i	11.39 ± 0.01a	71.11 ± 1.58 h	40.27 ± 1.02i
		VC[b]	1.05 ± 0.01j	0.27 ± 0.01 g	1.32 ± 0.03j	0.36 ± 0.02 h	8.46 ± 0.02b	74.45 ± 1.36 gh	43.85 ± 1.05 h
		BC[c]	1.09 ± 0.03i	0.34 ± 0.01f	1.43 ± 0.04i	0.47 ± 0.01 g	8.09 ± 0.03bc	75.38 ± 1.47 g	44.09 ± 1.09 g
		VC + BC	1.18 ± 0.01 h	0.43 ± 0.02e	1.61 ± 0.03 h	0.54 ± 0.03f	7.21 ± 0.02 cd	81.68 ± 1.65f	45.80 ± 1.08f
	75%	Control	1.13 ± 0.01 g	0.40 ± 0.00ef	1.53 ± 0.02 g	0.46 ± 0.02 fg	7.48 ± 0.02c	80.11 ± 1.48 fg	44.90 ± 1.12 fg
		VC	1.23 ± 0.02f	0.52 ± 0.01de	1.75 ± 0.03f	0.57 ± 0.01e	7.05 ± 0.01d	83.37 ± 1.95e	46.79 ± 1.13ef
		BC	1.26 ± 0.03e	0.56 ± 0.02d	1.82 ± 0.05e	0.66 ± 0.03d	6.98 ± 0.01de	83.55 ± 1.65e	47.05 ± 1.15e
		VC + BC	1.37 ± 0.02d	0.86 ± 0.03c	2.23 ± 0.04d	0.75 ± 0.01c	6.50 ± 0.00ef	85.75 ± 1.14c	49.07 ± 1.16d
	100%	Control	1.32 ± 0.02c	0.79 ± 0.03 cd	2.11 ± 0.04c	0.71 ± 0.02 cd	6.75 ± 0.03e	84.20 ± 1.54d	48.68 ± 1.18de
		VC	1.48 ± 0.04bc	0.97 ± 0.04bc	2.45 ± 0.03bc	0.81 ± 0.00b	6.22 ± 0.03f	84.80 ± 1.74bc	51.81 ± 1.02c
		BC	1.52 ± 0.05b	1.01 ± 0.04b	2.53 ± 0.04b	0.83 ± 0.01b	6.15 ± 0.02 fg	85.21 ± 1.65b	52.10 ± 1.05b
		VC + BC	1.68 ± 0.03a	1.27 ± 0.04a	2.95 ± 0.04a	0.91 ± 0.02a	6.02 ± 0.01 h	90.66 ± 1.85a	54.36 ± 1.22a
2019/2020	50%	Control	0.97 ± 0.01j	0.26 ± 0.01i	1.23 ± 0.02j	0.37 ± 0.03i	11.71 ± 0.03a	71.34 ± 1.74 h	41.48 ± 1.09i
		VC	1.10 ± 0.02i	0.32 ± 0.01 hi	1.42 ± 0.03i	0.41 ± 0.03 h	8.78 ± 0.03b	74.68 ± 1.85gh	43.56 ± 1.08hi
		BC	1.12 ± 0.02 h	0.39 ± 0.02 h	1.51 ± 0.04 h	0.52 ± 0.01 g	8.41 ± 0.04bc	75.61 ± 1.96 g	44.82 ± 1.05 h
		VC + BC	1.19 ± 0.03 g	0.52 ± 0.01 g	1.71 ± 0.04 g	0.59 ± 0.02f	7.43 ± 0.04 cd	81.36 ± 1.32f	46.66 ± 1.11 fg
	75%	Control	1.17 ± 0.03 gh	0.47 ± 0.03f	1.64 ± 0.02 gh	0.56 ± 0.02 fg	7.60 ± 0.02c	79.34 ± 1.12e	45.92 ± 1.12 g
		VC	1.28 ± 0.03f	0.67 ± 0.03e	1.95 ± 0.04f	0.61 ± 0.01e	7.17 ± 0.02d	85.60 ± 1.14ef	47.45 ± 1.15f
		BC	1.32 ± 0.02e	0.61 ± 0.04d	1.93 ± 0.03e	0.71 ± 0.03d	7.10 ± 0.01de	85.99 ± 1.85e	48.36 ± 1.14ef
		VC + BC	1.42 ± 0.02c	0.83 ± 0.04 cd	2.25 ± 0.04c	0.80 ± 0.04c	6.72 ± 0.02ef	88.05 ± 1.75c	51.40 ± 1.10d
	100%	Control	1.38 ± 0.01d	0.78 ± 0.04c	2.16 ± 0.03d	0.78 ± 0.03 cd	6.87 ± 0.04e	87.65 ± 1.95 cd	49.07 ± 1.05e
		VC	1.53 ± 0.03bc	0.92 ± 0.04b	2.45 ± 0.05bc	0.89 ± 0.02b	6.44 ± 0.03f	89.05 ± 1.45bc	53.17 ± 1.07c
		BC	1.57 ± 0.05b	0.99 ± 0.03ab	2.56 ± 0.04b	0.93 ± 0.02ab	6.37 ± 0.02 g	89.68 ± 1.65b	55.07 ± 1.13b
		VC + BC	1.73 ± 0.05a	1.22 ± 0.02a	2.95 ± 0.04a	0.96 ± 0.02a	6.09 ± 0.01 h	91.33 ± 1.53a	57.52 ± 1.11a
F-test									
Treatment			***	***	***	***	***	**	***
Year			***	***	***	***	***	***	***
Treatment × year			***	***	***	***	***	ns	ns

Notes: In the same growing season, means indicated with different letters show significant differences among treatments following Tukey's test ($P < 0.05$). Values represent means ± standard deviation ($n = 3$).
***, **, and ns indicate significance at $P < 0.001$, $P < 0.01$, and non-significant, respectively.
Abbreviation: FW, fresh weight; RWC, relative water content.
[a]Stomatal conductance.
[b]Vermicompost (VC) is applied at 1 kg m^{-2} rate.
[c]Biochar (BC) is applied at 1 kg m^{-2} rate.

TABLE 8 Yield traits of wheat plants irrigated with 50%, 75%, or 100% of field capacity in saline sodic soil treated with vermicompost and biochar

Year	Water treatments	Soil treatments	Grains per spike	1000-grain weight (g)	Grain yield (ton/ha)	Straw yield (ton/ha)	HI (%)
2018/2019	50%	Control	40.26 ± 1.25 h	44.15 ± 0.50i	3.06 ± 0.06 h	6.69 ± 0.90i	31.38 ± 0.36 g
		VC[a]	43.24 ± 1.26gh	47.38 ± 0.65 h	3.76 ± 0.05 g	7.21 ± 0.85 h	34.27 ± 0.25f
		BC[b]	43.88 ± 1.22 g	47.33 ± 0.62 h	3.88 ± 0.02f	7.52 ± 0.87 g	34.03 ± 0.14 fg
		VC + BC	45.41 ± 1.25e	49.30 ± 0.84f	4.38 ± 0.01e	7.82 ± 0.95f	35.90 ± 0.65e
	75%	Control	42.78 ± 1.24 h	47.90 ± 0.22 g	4.25 ± 0.03ef	7.74 ± 0.88 fg	35.44 ± 0.45ef
		VC	44.73 ± 1.1.18f	51.49 ± 0.54ef	4.51 ± 0.07d	7.95 ± 1.02ef	36.19 ± 0.85de
		BC	44.81 ± 1.19ef	52.00 ± 0.48e	4.64 ± 0.08d	8.10 ± 1.03e	36.42 ± 0.74d
		VC + BC	47.79 ± 1.15c	54.50 ± 0.65c	5.08 ± 0.06c	8.62 ± 1.08c	37.08 ± 0.47c
	100%	Control	45.86 ± 1.21d	53.50 ± 0.75d	4.86 ± 0.04 cd	8.41 ± 1.08d	36.62 ± 0.58 cd
		VC	47.96 ± 1.20c	55.20 ± 0.84bc	5.83 ± 0.03bc	8.78 ± 1.02bc	39.90 ± 0.69b
		BC	48.13 ± 1.22b	55.85 ± 0.25b	5.99 ± 0.05b	8.84 ± 1.07b	40.39 ± 0.12ab
		VC + BC	49.20 ± 1.25a	56.98 ± 0.36a	6.33 ± 0.08a	9.32 ± 0.88a	40.44 ± 0.32a
2019/2020	50%	Control	40.75 ± 1.11i	45.94 ± 0.86 g	3.17 ± 0.07i	6.50 ± 0.75 h	32.78 ± 0.25i
		VC	43.60 ± 1.15 g	47.14 ± 0.47 fg	3.90 ± 0.06 gh	7.29 ± 0.95 g	34.85 ± 0.25 h
		BC	43.52 ± 1.18gh	47.49 ± 0.63f	4.02 ± 0.03 g	7.46 ± 0.65f	35.01 ± 0.15 g
		VC + BC	45.89 ± 1.19f	50.06 ± 0.54e	4.62 ± 0.02e	7.73 ± 0.45e	37.41 ± 0.16e
	75%	Control	44.25 ± 1.09 g	49.36 ± 0.25ef	4.36 ± 0.05f	7.59 ± 0.85ef	36.48 ± 0.14f
		VC	46.20 ± 1.05e	50.22 ± 0.14de	4.99 ± 0.04d	8.01 ± 0.99de	38.38 ± 0.12d
		BC	46.22 ± 1.07e	50.68 ± 0.23d	4.92 ± 0.01d	8.11 ± 1.02d	37.76 ± 0.14de
		VC+ BC	48.22 ± 1.18c	53.06 ± 0.65c	5.56 ± 0.05c	8.66 ± 1.07c	39.09 ± 0.22bc
	100%	Control	47.20 ± 1.17d	51.96 ± 0.74d	5.36 ± 0.06 cd	8.41 ± 1.08 cd	38.92 ± 0.11c
		VC	48.15 ± 1.14c	54.36 ± 0.48bc	5.83 ± 0.04bc	8.80 ± 1.10bc	39.84 ± 0.14b
		BC	48.89 ± 1.12b	54.87 ± 0.65b	5.99 ± 0.03b	8.97 ± 1.11b	40.04 ± 0.12ab
		VC + BC	50.16 ± 1.06a	56.36 ± 0.24a	6.40 ± 0.02a	9.36 ± 1.02a	40.61 ± 0.08a
F-test							
Treatment			***	***	***	***	***
Year			***	**	***	***	ns
Treatment × year			***	**	***	**	*

Notes: In the same growing season, means indicated with different letters show significant differences among treatments following Tukey's test ($P < 0.05$). Values represent means ± standard deviation ($n = 3$). ***, **, and ns indicate significance at $P < 0.001$, $P < 0.01$, and nonsignificant, respectively.
Abbreviation: HI, harvest index.
[a]Vermicompost (VC) is applied at 1 kg m^{-2} rate.
[b]Biochar (BC) is applied at 1 kg m^{-2} rate.

addition of biochar with VC obviously enhanced growth of wheat under water stress, while the individual addition of either VC or biochar improved the soil and physiological attributes as compared with control treatment (untreated plants) under water stress in both years.

The osmotic impact of salinity causes damage to plant development due to a reduced water absorption (Akoto-Danso *et al*., 2019). Moreover, the increased exposure of plants to salinity leads to ionic toxicity due to the absorption and accumulation of Na^+ and Cl^- in plant shoot tissues (Akoto-Danso *et al*., 2019). Likewise, higher Na^+ and Cl^- contents in soil solution adversely prevent the absorption of necessary minerals like K^+, Ca^{2+}, Mg^{2+}, and NO_3^- disturbs cellular ion balance and therefore causes nutritional disturbances (Alsaeedi *et al*., 2018). The increase of toxic ions constrains photosynthesis and enzyme activity and causes damages to chloroplast (Hafez and Seleiman, 2017). The nutritional disturbance occurs due to the competition between Na^+ and Cl^- and other ions; such as, higher Na^+ hinders Ca^{2+} absorption resulting in lack of CO_2 availability as well as net photosynthesis (Machado and Serralheiro, 2017). The improvement in soil quality and physiological traits of wheat plant grown under water stress was lower than those produced by the coupled application of VC and biochar in saline sodic soil. The improvement of soil chemical traits and physiological properties of wheat plants by the combined application of VC and biochar is ascribed to their synergetic impact on the mitigation of water stress (Oppong *et al*., 2019).

TABLE 9 Grains NPK uptake at the harvesting of wheat plants irrigated with 50%, 75%, or 100% of field capacity in saline sodic soil treated with vermicompost and biochar

		N uptake		P uptake		K uptake	
Water treatments	Soil treatments	2018/2019	2019/2020	2018/2019	2019/2020	2018/2019	2019/2020
50%	Control	43.84 ± 1.56 k	45.75 ± 1.63 k	19.06 ± 1.12j	20.60 ± 1.24j	75.05 ± 2.35 k	78.50 ± 2.65i
	VC[a]	57.37 ± 1.58j	50.79 ± 1.60jk	27.81 ± 1.22ij	28.69 ± 1.20i	96.07 ± 2.36i	97.82 ± 2.45hi
	BC[b]	57.52 ± 1.59j	51.09 ± 1.55j	29.49 ± 1.25i	29.65 ± 1.14 h	92.47 ± 2.45j	102.41 ± 2.75 h
	VC + BC	68.56 ± 1.58 h	56.01 ± 1.54 h	35.90 ± 1.24 g	39.43 ± 1.18f	110.21 ± 2.44 g	120.29 ± 2.45f
75%	Control	61.90 ± 1.44i	53.04 ± 1.47i	33.00 ± 1.23 gh	35.97 ± 1.17 g	105.37 ± 3.65 h	112.81 ± 2.36 g
	VC	70.94 ± 1.45 g	68.97 ± 1.56 g	37.92 ± 1.18f	41.80 ± 1.23ef	114.79 ± 2.36 fg	123.05 ± 2.24ef
	BC	74.06 ± 1.48f	75.64 ± 1.44f	38.78 ± 1.18f	43.76 ± 1.25e	116.58 ± 3.22f	127.02 ± 2.65e
	VC + BC	86.49 ± 1.52d	89.88 ± 1.58d	49.60 ± 1.19d	48.81 ± 1.24 cd	137.09 ± 3.45d	141.08 ± 2.15d
100%	Control	80.39 ± 1.53e	84.88 ± 1.69e	45.87 ± 1.15e	44.96 ± 1.21d	129.66 ± 2.74e	136.21 ± 2.45de
	VC	91.58 ± 1.57c	94.67 ± 1.45c	52.41 ± 1.14c	49.75 ± 1.19c	139.85 ± 2.95c	144.76 ± 2.65c
	BC	93.67 ± 1.66b	97.55 ± 1.55b	54.42 ± 1.22b	51.92 ± 1.18bb	141.42 ± 2.68b	149.46 ± 2.55b
	VC + BC	101.32 ± 1.62a	106.39 ± 1.89a	59.90 ± 1.25a	65.51 ± 1.18a	160.64 ± 2.11a	160.05 ± 2.85a
F-test							
Treatment		***		**		***	
Year		**		***		***	
Treatment × year		***		ns		**	

Notes: In the same growing season, means indicated with different letters show significant differences among treatments following Tukey's test ($P < 0.05$). Values represent means ± standard deviation ($n = 3$). ***, **, and ns indicate significance at $P < 0.001$, $P < 0.01$, and nonsignificant, respectively.
[a]Vermicompost (VC) is applied at 1 kg m^{-2} rate;
[b]Biochar (BC) is applied at 1 kg m^{-2} rate.

TABLE 10 Expression of the antioxidant enzymes-encoding genes in wheat leaves irrigated with 50%, 75%, or 100% of field capacity in saline sodic soil treated with vermicompost and biochar

		CAT		*APX*		*Mn-SOD*	
Water treatment	Soil treatments	2018/2019	2019/2020	2018/2019	2019/2020	2018/2019	2019/2020
50%	Control	2.91 ± 0.11a	2.88 ± 0.12a	3.03 ± 0.12a	3.00 ± 0.11a	2.85 ± 0.12a	2.81 ± 0.13a
	VC[a]	2.43 ± 0.13b	2.47 ± 0.11b	2.51 ± 0.13b	2.48 ± 0.12b	2.51 ± 0.11b	2.53 ± 0.11b
	BC[b]	2.27 ± 0.12bc	2.30 ± 0.11bc	2.33 ± 0.11bc	2.36 ± 0.13bc	2.41 ± 0.14bc	2.44 ± 0.11bc
	VC + BC	1.72 ± 0.11 cd	1.73 ± 0.12 cd	1.92 ± 0.11d	1.89 ± 0.12d	1.91 ± 0.12 cd	1.86 ± 0.12 cd
75%	Control	1.99 ± 0.13c	2.03 ± 0.11c	2.07 ± 0.12c	2.02 ± 0.11c	2.07 ± 0.14c	2.02 ± 0.11c
	VC	1.70 ± 0.13d	1.71 ± 0.12d	1.79 ± 0.11de	1.81 ± 0.12de	1.82 ± 0.12d	1.78 ± 0.11d
	BC	1.62 ± 0.12de	1.59 ± 0.12de	1.67 ± 0.12e	1.62 ± 0.11e	1.71 ± 0.11de	1.73 ± 0.12de
	VC + BC	1.41 ± 0.11e	1.40 ± 0.13e	1.50 ± 0.11 g	1.52 ± 0.12 g	1.52 ± 0.12e	1.54 ± 0.12e
100%	Control	1.50 ± 0.11ef	1.52 ± 0.13ef	1.55 ± 0.11f	1.57 ± 0.12f	1.61 ± 0.13ef	1.64 ± 0.12ef
	VC	1.40 ± 0.13f	1.38 ± 0.12f	1.43 ± 0.11 h	1.41 ± 0.13 h	1.47 ± 0.11f	1.50 ± 0.11f
	BC	1.32 ± 0.11 fg	1.31 ± 0.12 fg	1.36 ± 0.13i	1.33 ± 0.11i	1.38 ± 0.12 fg	1.37 ± 0.13 fg
	VC + BC	1.12 ± 0.11 g	1.15 ± 0.13 g	1.19 ± 0.12j	1.21 ± 0.13j	1.20 ± 0.12 g	1.18 ± 0.11 g

Notes: In the same growing season, means indicated with different letters show significant differences among treatments following Tukey's test ($P < 0.05$). Values represent means ± standard deviation ($n = 3$).
[a]Vermicompost (VC) is applied at 1 kg m^{-2} rate;
[b]Biochar (BC) is applied at 1 kg m^{-2} rate.

Wheat plants subjected to water stress resulted in a decline in RWC, chlorophyll, carotenoids, and g_s, which is attributed to a decrease in water uptake in response to a decrease in soil water availability (Alvarez-Campos *et al.*, 2018). An improvement in physiological properties such as RWC, chlorophyll, and g_s, but a decrease in proline content, were recorded in water-stressed wheat plants upon the sole or combined application of biochar and VC, compared to control plants (neither VC nor biochar). The synergistic effect of biochar and VC increased the available soil water, resulting in declining osmotic stress as well as avoiding losing turgor under water stress in saline sodic soil (Kheir *et al*., 2019).

It is observed that with the soil application of biochar, the FC and BD improved (Emami and Astaraei, 2012; Yu *et al*., 2017), which increased the soil available water leading to higher RWC, g_s, chlorophyll content, K^+ content, nutrient uptake (N, P, and K), CAT and APX activity (decreasing oxidative stress), as well as declining proline and Na^+ contents (Akhtar *et al*., 2014). In biochar-treated soil, the K^+ content in wheat plants was augmented while Na^+ content was reduced, resulting in an improved K^+/Na^+ ratio under water stress in saline sodic soil. Moreover, VC mitigates water stress (Di *et al*., 2019), enhances soil properties, and improves soil's available water in saline sodic soil (Ibrahim *et al*., 2015), leading to the improvement of physiological attributes and nutrient uptake under the combined application of VC and biochar (Doan *et al*., 2015).

Increases in the activity and expression of CAT and APX in response to water stress indicate a pivotal impact of these enzymes in protecting leaf tissues against oxidative damages (Anjum *et al*., 2017). The avoidance of ROS production during water stress is likewise an imperative strategy that allows plants to deal with water stress without massive damages, especially in saline sodic soil. In ecological stressors conditions (e.g., water stress), the high activities of CAT and APX enzymes are crucial for plants to cope with the increased level of ROS (Tardieu *et al*., 2014).

Grain yield and related traits, such as the number of grains per spike and 1000-grain weight of wheat plants grown under 50% and 75% FC were adversely impacted compared to that of 100% FC. A high number of grains per spike and 1000-grain weight leads to a high grain yield (Hafez, Omara, and Ahmed, 2019). A low to medium irrigation level (50% and 75% FC) integrated with high temperature may result in pollen infertility, low number of grains per spike, and reduced grain yield (Hafez and Gharib, 2016). These results could be attributed to the closure of stomata, decline RWC and chlorophyll content, which eventually result in reducing the photosynthesis rate and curtailed grain yield (Akoto-Danso *et al*., 2019). Nevertheless, in the current investigation, the addition of biochar, VC or their combination improved the number of grains per spike and 1000-grain weight as well as grain yield and harvest index under the different irrigation water treatments (50%, 75%, and 100% FC) in saline sodic soil during both years. The integration of biochar and VC had the highest positive effect on soil's available water, availability and absorption of nutrients compared to singular addition and control plants as reported by Luo *et al*., 2017. Therefore, the combinatory application of biochar and VC improved grain yield and harvest index under water stress (50% and 75% FC) in saline sodic soil conditions. The positive effect of VC or biochar application on soil physicochemical properties may be attributed to the enhancement in soil structure and soil particulates due to the excreted polysaccharides from microbial cells (Habib *et al*., 2016), resulting in an improvement in soil water-holding capacity, porosity, aeration, and infiltration occurs. These facilitate an easier penetration of plant roots into the deeper zone of the soil reaching potentially less saline layers (Deng *et al*., 2017).

The addition of biochar with VC as organic amendments to agricultural soil can increase the availability of N, P, and K in the soil, nutrient cycling in the soil, and increase the crop production (Ramzani *et al*., 2016). Biochar application to the soil can greatly increase nitrification (Li *et al*., 2019) by holding nitrogenous nutrients in the soil close to the root zone for an extended time (Kaya *et al*., 2006). Furthermore, the highest uptake of N, P, and K in wheat was attained from plants treated with the synergistic application of VC and biochar under the three irrigation levels compared to the two single amendments (Table 9 and Gul *et al*., 2015). This could be attributed to the high content of those minerals in biochar applied to the soil (Agegnehu *et al*., 2017). Our findings showed that the interactive application of biochar and VC augmented N, P, and K uptake more significantly than the sole treatment of them. In line with our findings, Doan *et al*. (2015) stated that biochar and VC have a key influence on the stabilization of soil aggregates under water stress and saline sodic soil.

5 | CONCLUSION

Water stress significantly reduced the growth and productivity of wheat plants by affecting the chlorophyll content, g_s, RWC, nutrient uptake, and yield traits of wheat grown in saline sodic soil. VC-treated soil slightly improved wheat growth and yield. However, the VC impact was more effective when coupled with biochar. The best improvement was recorded upon the synergistic application of biochar + VC and the second-best by the singular application of biochar. The modulation of the soil chemical properties improved wheat growth in response to water stress in saline sodic soil through the modulation of gene expression (*CAD*, *POD*, and *APX*), nutrient uptake, proline content, and Na^+ content. Therefore, the present study revealed the beneficial synergistic effect of VC and biochar on the enhancement of plant growth and yield as well as the reduction of the harmful effect of water stress and saline sodic soil.

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AUTHOR CONTRIBUTIONS

Emad M. Hafez, Mohamed A. El-Esawi, Alaa El Dein Omara, and Fahad A. Alhumaydhi have designed the study, conducted the experiments, analyzed the data, and wrote the manuscript. Mohamed A. El-Esawi has also carried out the molecular genetic analysis experiments. All the authors approved the final version of the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the authors.

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