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Impacted Application of Water-Hyacinth-Derived Biochar and Organic Manures on Soil Properties and Barley Growth

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Abstract: The biochar application can improve the physiochemical properties of both sandy and clayey loam soils and is considered a potential adaptation tool toward climate change. Therefore, the current study is novel in combining water-hyacinth-derived biochar with organic manures as a suggested effective way of treating the soil with biochar under arid and semiarid conditions. Water hyacinth weeds were slow pyrolyzed at a temperature of 300 °C, which resulted in nonalkaline biochar with a pH value of 6.31, which is suitable for alkaline soils. A pot experiment was established to study the impact of the solo application of nonalkaline water-hyacinth-derived biochar (WHB) and its combined application with farmyard (WHB/FM) and poultry manure (WHB/PM) at a rate of 1.5 and 3%, respectively, on some chemical and physical properties of sandy and clay loam soils and some barley's growth parameters. WHB, WHB/FM, and WHB/PM significantly affected the soil pH at different application rates (1.5 and 3%) in sandy soil. A considerable alteration in water-stable aggregates (WSA), dispersion ratio (DR), available water content (AWC), and cation ratio of soil structural stability (CROSS) index resulted from combining manures (FM and PM) with biochar better than the solo application of biochar. WHB/PM treatments had a superior effect in improving barley's growth. Relative increases were by 37.3 and 11.0% in plant height and by 61.6 and 28.5% in the dry matter in sandy and clayey loam soils, respectively. Under the conditions of this study, we can conclude that treating the soil with WHB/PM at a rate of 1.5 and 3% is the most effective application. The current study may have a vital role in Egyptian agriculture sustainability by enhancing the soil characteristics of the old agricultural and the newly reclaimed lands.

Keywords: biochar; farmyard manure; poultry manure; CROSS; barley

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1. Introduction

Climate change and improper soil management threaten soil organic carbon and agriculture sustainability in the Mediterranean semiarid and arid regions [1–3]. Therefore, the addition of biochar may be considered as a potential adaptation tool for climate change in vulnerable regions by enhancing soil quality and agriculture productivity [4]. The old agricultural land of the Nile delta with heavy soil texture suffers from poor drainage and high soil salinity, which caused a reduction in soil suitability for various strategic crop production [5–7]. Contrary, the newly reclaimed land suffers from excessive drainage due to the coarse soil texture and high demand for irrigation water [8,9]. The Egyptian agricultural activities consume about 85% of Egypt's water resources, and the water availability represents a challenge for Egypt, particularly under water scarcity (<550 m^3 per capita per year) and arid conditions [8,10].

Biochar can be defined as a carbon-rich product, produced when biomasses such as woods, manures, or leaves are heated in a closed container with little or no oxygen available [11]. Biochar has many possible benefits: Applying biochar as a soil amendment plays a role in soil carbon sequestration; it improves moisture retention, which may reduce crop water demand and make cropping more secure; boosts plant growth; increases and sustains crop yields; and also helps improve problematic nutrient-poor soils [12–16]. Biochar, in the last 10 years, has been widely investigated for agricultural purposes in sandy soils under arid conditions by way of considering it as a soil amendment and improving the soil's physical, chemical, and biological properties [17–19]. Biochar plays a vital role in altering soil hydrology and is considered as a soil amendment to improve drainage in both sandy and clay soils [20]. Among many beneficial characteristics of biochar for acidic soils, its high pH value has an influence on elevating the pH of these soils, which is known as the liming effect [21–24]. On the contrary, the alkaline-pH biochar is a problem in alkaline soils, so it is preferable to convert the plant residues into biochar at relatively low temperatures to produce nonalkaline biochar [25,26].

Since ancient times, the Egyptian farmer has used livestock and poultry residues as organic fertilizers or organic soil amendments [27]. Through scientific research, it has been proven that organic fertilizers, such as farmyard manure and poultry manure, have many positive effects on the physical, chemical, and biological properties of the soil and, hence, on soil quality and crop productivity [28,29]. Adding animal manures to soils is a well-established method for enhancing the stability of aggregates, raising organic matter content, increase water-holding capacity, and reducing erosion as well as for boosting soil fertility [30,31]. Multiple initiatives in Egypt have attempted to improve soil organic matter levels by incorporating agricultural wastes, sewage effluent, and farmyard manures into the soil [32].

Simultaneous biochar application with manures has little research attention, particularly its effects on soil structural stability [33]. The corncob biochar co-applied with farmyard manure and NPK in sub-Saharan Africa showed improvements in the soil's chemical properties [34]. The solo application of biochar produced in local kilns in Nigeria showed a nonsignificant improvement in radish yield, particularly in the first year [35]. Thus, it was recommended to co-apply poultry manure with biochar [36]. Improvements were observed in soil fertility, water-holding capacity, and soil structural stability under laboratory and field conditions by applying biochar with compost or co-composted biochar [37–40].

Converting plant residues and/or weeds into biochar is a solution for several problems in agriculture and environment. On the one hand, it disposes of tons of agricultural waste, which may be subject to being burned and thus pollute the environment, or weeds, such as water hyacinths, and the problems they cause for irrigation canals. On the other hand, it is an inexpensive source [41]. Water hyacinth plants (*Eichhornia crassipes*) are considered one of the worst weeds in the world, as reported by the International Union for Conservation of Nature [42]. In Egypt, water hyacinths were recorded in the 19th century [43]. The agricultural sector suffers from water hyacinth plants because of the high water consumption of these weeds and the possibility of clogging irrigation canals [25]. One of the most recent management strategies is producing biochar from water hyacinths [44].

The objectives of this research were to investigate the impact of nonalkaline biochar produced from water hyacinth plants and its combinations with two different manures on soil physical properties, and to predict some soil physical properties by using a newly suggested soil structural-stability indicator which is based on soluble cations. The investigated hypothesis was that the integration between nonalkaline biochar derived from water hyacinths and manures, such as farmyard and poultry manure, would be more effective in improving soil physical properties than individual biochar applications in two soils of different textures in Egypt. How are barley's growth parameters affected by such a way of biochar application?

2. Materials and Methods

2.1. Collection and Characterization of Samples

In this study, two soils were used both from the top layer (0–20 cm) at two different locations: (i) Samallute district in El-Minia Governorate (28°18′16′′ N, 30°34′38′′ E) (soil-1), and (ii) from the Scientific Experimental farm (soil-2), Faculty of Agriculture, Minia University, El-Minia Governorate, (28°7′12′′ N and 30°43′28′′ E), Egypt.

Water hyacinth weeds were used as a feedstock to produce biochar. Firstly, water hyacinth plants were cut into pieces and oven-dried at 40 °C for 48 h. Biochar was produced by slow pyrolysis from the water hyacinth at 300 °C, with a duration time of 30 min. Water hyacinth biochar (WHB) was crushed to particles of <2 mm and stored in plastic bags until used. Farmyard and poultry manures (FM and PM) were collected from nearby farms, then air-dried at room temperature and finely ground to pass through a 2 mm sieve. The chemical and physical properties of the investigated soils and the characteristics of the biochar and the manures are presented in Table 1. Field emission scanning electron microscopy images (FE-SEM) of WHB surface morphology were taken at various magnifications (from 50+ to 4000+) using a Sigma-300 variable pressure microscope operated with an accelerating voltage of 15 kV [45].

Table 1. Some chemical and physical characteristics of soil, biochar, poultry, and farmyard manure.

Characteristic	Soil-1	Soil-2	Biochar (300 °C)	Farmyard Manure	Poultry Manure
Coarse sand (%)	48.3	21.2	—	—	—
Fine sand (%)	38.7	9.8	—	—	—
Silt (%)	3.9	28.8	—	—	—
Clay (%)	9.1	39.2	—	—	—
Texture class	Sand	Clay loam	—	—	—
pH (water) *	8.3	8.15	6.31	7.91	6.76
EC_w (dSm^{-1}) *	1.98	1.43	3.58	3.2	5.81
CEC (cmol (+) kg^{-1}) *	6.8	47.56	45.27	35.62	39.17
OC% *	0.19	0.91	27.58	25.83	31.19
$CaCO_3$%	2.8	1.96	—	—	—
D_p Mg m^{-3} *	2.62	2.55	—	—	—
D_d Mg m^{-3} *	1.57	1.26	—	—	—
Total N% *	—	—	1.03	1.05	2.95
Total P% *	—	—	0.37	0.41	1.62
Total K% *	—	—	0.68	0.98	2.21
Total Ca% *	—	—	0.95	2.01	2.63
Total Mg% *	—	—	0.38	0.38	0.51
Total Na% *	—	—	0.07	0.62	0.69

* pH (water) and EC_w for soil was at 1:2.5 and for organic amendment at 1:10; CEC: cation exchange capacity; OC%: organic carbon percentage; D_p is the soil particle density; D_d is the soil bulk density; Total N%: total nitrogen percentage; Total P%: total phosphorus percentage; Total K%: total potassium percentage; Total Ca%: total calcium percentage; Total Mg%: total magnesium percentage; Total Na%: total sodium percentage.

2.2. Soil and Organic Amendments Analyses

Particle-size analysis of the studied soils was carried out using the pipette method [46]. The pH and electrical conductivity (EC) were determined at 1:2.5 w/v for soil and 1:10 w/v for organic amendments using a pH meter (Jenway, 3020 pH meter) and an EC meter (Jenway, 470 cond. meter). Cation exchange capacity (CEC) was determined using 1 M sodium acetate pH 8.2. WHB and manures were analyzed for organic carbon using the combustion method [47] and total nitrogen using the Kjeldahl method [48]. Concentrations of phosphorus, potassium, calcium, magnesium, and sodium were determined using the inductively coupled plasma mass spectrometry (Thermo ICP-MS model iCAP-RQ) according to the methods outlined in [49–51].

2.3. Experimental Setup and Procedure

Layouts and abbreviations of the applied treatments are presented in Table 2. Water hyacinth biochar (WHB) and manure mixtures were prepared before application to soil at a dry weight ratio of 2:1 for WHB/FM and WHB/PM. The trial consisted of 42 pots filled with either WHB alone or WHB/manure mixtures at rates of 0.0%, 1.5%, and 3.0%, thoroughly mixed with 10 kg of soil (<2 mm fraction) and maintained under greenhouse conditions at field capacity for 30 days before barley cultivation.

Table 2. Abbreviations of the applied treatments.

No.	Soil	WHB * (%)	WHB/FM * (%)	WHB/PM * (%)	Abbreviation
1	Sand	0	0	0	SCtrl.
2	Sand	1.5	0	0	SWHB1.5
3	Sand	3	0	0	SWHB3
4	Sand	0	1.5	0	SWHB/FM1.5
5	Sand	0	3	0	SWHB/FM3
6	Sand	0	0	1.5	SWHB/PM1.5
7	Sand	0	0	3	SWHB/PM3
8	Clay loam	0	0	0	CLCtrl.
9	Clay loam	1.5	0	0	CLWHB1.5
10	Clay loam	3	0	0	CLWHB3
11	Clay loam	0	1.5	0	CLWHB/FM1.5
12	Clay loam	0	3	0	CLWHB/FM3
13	Clay loam	0	0	1.5	CLWHB/PM1.5
14	Clay loam	0	0	3	CLWHB/PM3

* WHB: water hyacinth biochar; WHB/FM: water hyacinth biochar and farmyard manure mixture; WHB/PM: water hyacinth biochar and poultry manure mixture.

The whole experiment was maintained under greenhouse conditions with day and night temperatures ranging between 25 °C (day) and 15 °C (night). Barley (*Hordeum vulgare* L.) was sown after 30 days of mixing organic mixtures with soils to study the effectiveness of the organic waste mixture in promoting changes in the soil properties. Each pot received 10 seeds, and seedlings were thinned to 5 plants per pot after 10 days of sowing. Irrigation was applied when the moisture in the pot reached 70% below the field capacity [52]. The plant height (cm) was measured just before cutting barley plants above the soil surface 60 days after sowing. Firstly, plants were air-dried, then oven-dried at 65 °C, and the dry weight per pot was measured.

After removing barley plants, pots were left for two months, covered with black polyethylene, and watered once a week to decompose the barley roots before the soil's physical properties were analyzed. Pots were air-dried for 15 days before the determination of water-stable aggregates, dispersion ratio, and moisture retention capacity were carried out.

Rings of 5 cm in height and 5 cm in diameter were used to measure water-holding capacity in the pots. At matric potentials of −0.01 MPa, −0.03 MPa, and −1.5 MPa, moisture contents in samples were determined. The water content was measured using a pressure-plate device with a working pressure of 5 and 15 bar [53]. The difference in water content (wt. %) between 0.3 and 15 bar was calculated to compute the available water content (AWC).

Aggregate stability was evaluated by the single-sieve water stability technique [54]. Ten grams of soil or soil-organic mixture were presoaked on a 0.25 mm sieve for 10 min before being helicoidally oscillated 20 times at a rate of 1 oscillation per second along a 4 cm stroke. The resistant aggregates were oven-dried at 105 °C for 24 h, weighed, and corrected for sand fraction to obtain the mass of the true aggregates [55], using the following formula: $WSA = \left(\frac{Mra}{TMs}\right) * 100$, where WSA is the water-stable aggregate (%), Mra is the mass of the resistant aggregates, and TMs is the total mass of soil used (g).

The procedure described by Gee and Bauder [56] was used to determine the dispersion ratio. The dispersion ratio (DR%) measures the potential of the individual aggregates to resist breakdown upon contact with water molecules. Higher values indicate lower resistance. Ten grams of the sample aggregates was soaked in either distilled water or sodium hexametaphosphate (5% Calgon) followed by end-over-end shaking. Then, by determining the percent of silt and clay in water-dispersed samples (L) and that in sodium-dispersed samples (H), the dispersion ratio is calculated as: $DR = \left(\frac{L}{H}\right) * 100$.

Soluble cations Na^+, K^+, Ca^{2+}, and Mg^{2+} (mol m^{-3}) in the extracted soil solutions (1:5 soil:water) were determined using atomic absorption (Agilent, AA 240). The suggested soil structure stability index by Rengasamy and Marchuk [57], "cation ratio of soil structural stability" (CROSS) expressed in (mol $m^{-3})^{0.5}$, was then calculated as:

$$\text{CROSS} = \frac{\text{Na}^+ + 0.56\text{K}^+}{\left(\frac{(\text{Ca}^{2+} + 0.6\text{Mg}^{2+})}{2}\right)^{0.5}} \quad (1)$$

2.4. Statistical Analysis

The experimental design was randomized complete-block design (RCBD) with three factors (two soil textural classes, three treatment types, and three application rates). Each treatment was replicated three times. Three-way ANOVA test was preformed, followed by Duncan's multiple-range tests at a significance level of 5%, using IBM SPSS statistics version 20 (Armonk, North Castle, NY, USA) to measure the significant differences among different averages under each studied factor. The correlation matrix for all variables, regressions, and their validations between DR, WSA, AWC, and CROSS was applied using Microsoft Excel 365 add-ins with XLSTAT (2021). The number of observations for each variable was 42.

3. Results

3.1. Surface Morphology of Water Hyacinth Biochar (WHB)

Field emission scanning electron microscopy was used to illustrate the materials' surface morphologies. The FE-SEM images of WHB surface morphology are shown in Figure 1 at magnifications "500+", "1000+", and "3500+" using a Sigma-300 variable pressure microscope, operated with an accelerating voltage of 15 kV. The FE-SEM images of WHB show the porosity structure (honeycomb-like pores structure) at a magnification "3500+", formed under conditions of water hyacinth slow pyrolysis at 300 °C.

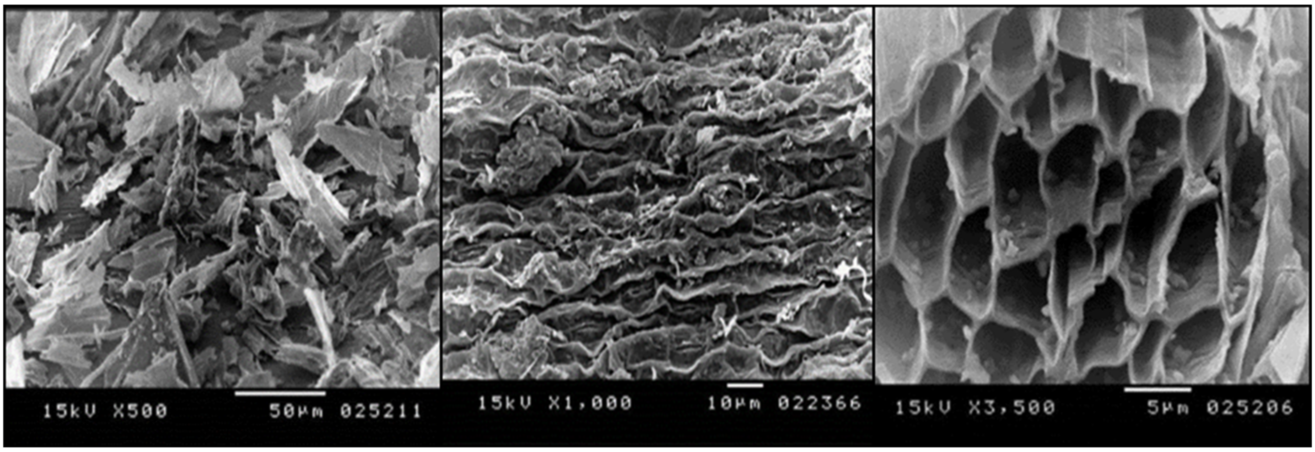

Figure 1. Surface morphology of WHB at magnifications of "500+", "1000+", and "3500+".

3.2. Effect of Biochar and Its Combined Application with FM and PM on Soil pH

Slow pyrolysis of water hyacinth plants at a temperature of 300 °C resulted in non-alkaline biochar with a pH value of 6.31, which was suitable for both investigated soils. Soils were characterized by pHs of 8.3 and 8.15 for the sandy and the clayey loam soils, respectively (Table 1). Duncan's analysis showed a significant ($p < 0.05$) decrease in the sand soil pH, as affected by the application of WHB and its integration with either FM or PM at both rates (1.5 and 3%). However, there were no significant differences between SCtrl and treatments on the clay loam soil pH (Table 3).

Table 3. Effects of water hyacinth biochar (WHB), water hyacinth biochar and farmyard manure mixture (WHB/FM), and water hyacinth biochar and poultry manure mixture (WHB/PM) on soil pH, soluble cations, cation ratio of soil structural stability (CROSS), dispersion ratio (DR%), and water-stable aggregates (WSA) of the investigated soils.

Treatments	pH	Soluble Cations (mol m^{-3})				CROSS	DR%	WSA%
		Na^+	K^+	Ca^{++}	Mg^{++}	(mol m^{-3})$^{0.5}$		
SCtrl	8.25 ^{a} ± 0.04	10.00 ^{c} ± 0.22	6.03 ^{b} ± 0.40	29.00 ^{e} ± 0.38	9.00 ^{e} ± 0.63	3.23 ^{a} ± 0.06	92.0 ^{a} ± 1.73	4.15 ^{e} ± 0.19
SWHB1.5	8.20 ^{bc} ± 0.02	10.13 ^{c} ± 0.18	6.42 ^{b} ± 0.27	35.21 ^{d} ± 0.55	12.62 ^{d} ± 0.45	2.97 ^{c} ± 0.05	85.9 ^{b} ± 1.63	6.74 ^{c} ± 0.13
SWHB3	8.18 ^{bcd} ± 0.02	10.26 ^{bc} ± 0.17	7.68 ^{a} ± 0.17	41.55 ^{b} ± 0.91	13.94 ^{c} ± 0.45	2.91 ^{c} ± 0.02	86.7 ^{b} ± 2.08	7.32 ^{b} ± 0.15
SWHB/FM1.5	8.21 ^{b} ± 0.02	10.11 ^{c} ± 0.16	7.32 ^{a} ± 0.14	39.58 ^{c} ± 0.47	11.79 ^{d} ± 0.51	2.94 ^{c} ± 0.02	80.0 ^{c} ± 1.76	6.26 ^{d} ± 0.21
SWHB/FM3	8.14 ^{d} ± 0.01	10.52 ^{b} ± 0.14	7.45 ^{a} ± 0.29	40.55 ^{bc} ± 0.59	14.28 ^{bc} ± 0.37	2.96 ^{c} ± 0.04	74.3 ^{d} ± 3.51	7.55 ^{ab} ± 0.19
SWHB/PM1.5	8.19 ^{bcd} ± 0.02	10.94 ^{a} ± 0.13	7.68 ^{a} ± 0.47	40.58 ^{bc} ± 0.40	14.94 ^{b} ± 0.65	3.06 ^{b} ± 0.06	77.0 ^{cd} ± 3.00	6.41 ^{d} ± 0.11
SWHB/PM3	8.16 ^{cd} ± 0.03	10.49 ^{b} ± 0.19	7.84 ^{a} ± 0.31	42.89 ^{a} ± 0.90	16.00 ^{a} ± 0.30	2.90 ^{c} ± 0.06	73.7 ^{d} ± 1.66	7.67 ^{a} ± 0.13
CLCtrl	8.13 ^{a} ± 0.03	8.53 ^{c} ± 0.09	4.55 ^{e} ± 0.37	48.00 ^{e} ± 0.58	35.00 ^{f} ± 0.71	1.89 ^{ab} ± 0.05	44.8 ^{a} ± 1.76	36.42 ^{e} ± 0.11
CLWHB1.5	8.11 ^{a} ± 0.02	8.79 ^{abc} ± 0.07	4.93 ^{de} ± 0.46	55.85 ^{d} ± 0.66	38.87 ^{d} ± 0.70	1.84 ^{b} ± 0.06	34.3 ^{b} ± 1.29	40.07 ^{cd} ± 0.17
CLWHB3	8.10 ^{a} ± 0.04	9.03 ^{ab} ± 0.16	5.13 ^{cde} ± 0.28	65.47 ^{b} ± 0.72	36.55 ^{e} ± 0.67	1.80 ^{b} ± 0.05	32.1 ^{bc} ± 1.47	42.27 ^{a} ± 0.28
CLWHB/FM1.5	8.11 ^{a} ± 0.02	9.18 ^{a} ± 0.22	5.50 ^{bcd} ± 0.39	63.58 ^{c} ± 0.70	40.21 ^{c} ± 0.55	1.85 ^{ab} ± 0.05	34.1 ^{bc} ± 1.30	39.34 ^{d} ± 0.16
CLWHB/FM3	8.09 ^{a} ± 0.03	8.98 ^{ab} ± 0.36	5.77 ^{bc} ± 0.27	64.02 ^{c} ± 1.00	41.1 ^{c} ± 0.39	1.83 ^{b} ± 0.03	32.2 ^{bc} ± 1.69	39.21 ^{d} ± 0.21
CLWHB/PM1.5	8.12 ^{a} ± 0.02	9.01 ^{ab} ± 0.30	5.91 ^{b} ± 0.28	55.24 ^{d} ± 0.68	42.55 ^{b} ± 0.55	1.94 ^{a} ± 0.05	31.43 ^{c} ± 1.61	40.57 ^{bc} ± 0.45
CLWHB/PM3	8.11 ^{a} ± 0.02	8.63 ^{bc} ± 0.17	6.93 ^{a} ± 0.51	67.50 ^{a} ± 0.54	44.89 ^{a} ± 0.68	1.82 ^{b} ± 0.06	27.97 ^{d} ± 1.08	41.29 ^{ab} ± 0.57

Different letters indicate significant differences among means of treatments for each soil, separately, according to Duncan's test at $p < 0.05$. Mean is the average of 3 replicates ± standard deviation (SD).

3.3. Effect of Different Treatments on the Stability of Soil Structure

3.3.1. Dispersion Ratio (DR)

The presented data in Table 3 show the impact of WHB, WHB/FM, and WHB/PM on the DR of the two soils differentiated by soil texture class. All treatments improved the soil structure stability, as a significant decrease in DR was obtained ($p < 0.05$). However, no significant differences in DR were observed for SWHB/FM3, SWHB/PM1.5, and SWHB/PM3 treatments. The CLWHB/PM3 treatment was the most effective in decreasing the DR of soil with clay loam texture.

3.3.2. Cation Ratio of Soil Structural Stability (CROSS)

The new soil structural stability index, (cation ratio of soil structural stability) CROSS, suggested by Rengasamy and Marchuk [57], has been calculated to explore Na and K dispersive effects along with Ca and Mg flocculation powers. The presented data in Table 3 show the concentration of the soluble cations Na^+, K^+, Ca^{++}, and Mg^{++}, expressed in mol m^{-3} and calculated CROSS expressed in (mol m^{-3})$^{0.5}$. Treated sandy soil showed a significant decrease in CROSS compared to untreated soil (SCtrl) ($p < 0.05$), with no significant differences within treatments. Treatments had no significant effects on the CROSS values in the case of clay loam soil.

3.3.3. Water-Stable Aggregate (WSA)

Both studied soils, when treated with WHB, WHB/FM, and WHB/PM, showed significant increases in WSA compared to the untreated soil ($p < 0.05$). The presented results in Table 3 showed the treatment effect on WSA property in sand and clay loam soil. In the sandy soil (soil-1), a superior effect on WSA was noticeable with SWHB/PM3 and SWHB/FM3 treatments, followed by SWHB3 treatment. In clayey loam soil (soil-2), the more effective treatments were CLWHB/PM3 and CLWHB3, followed by CLWHB/PM1.5 and CLWHB1.5.

3.4. The Effects of Soil Texture, Amendment Type, and the Application Rate of Amendment on pH, CROSS, DR, and WSA

Data illustrated in Figure 2 show the effects of soil texture class on soil pH, CROSS, DR, and WSA. Soil pH, CROSS, and DR were higher in sand soil; however, WSA was higher in clay loam soil. In addition, from the statistical analysis, there are statistically significant differences between the values of attributes under each soil texture ($p < 0.05$).

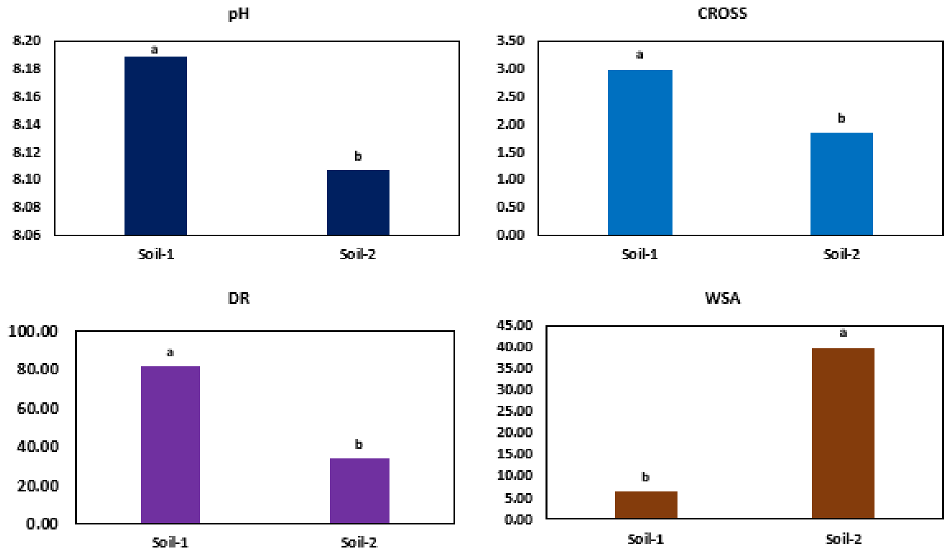

Figure 2. Effects of soil texture on pH, CROSS, DR, and WSA (columns with different letters indicate significant differences).

Figure 3 shows the effects of amendments (i.e., WHB, WHB/FM, and WHB/PM) on the soil pH, CROSS, DR, and WSA of the two studied soils. All treatments had a significant effect on the studied traits compared to the control ($p < 0.05$). There was not a statistically significant difference between the treated soils with WHB, WHB/FM, or WHB/PM. The integration between biochar and poultry manure was the most effective amendment in improving soil structure stability through decreasing the DR of the soil (Figure 3).

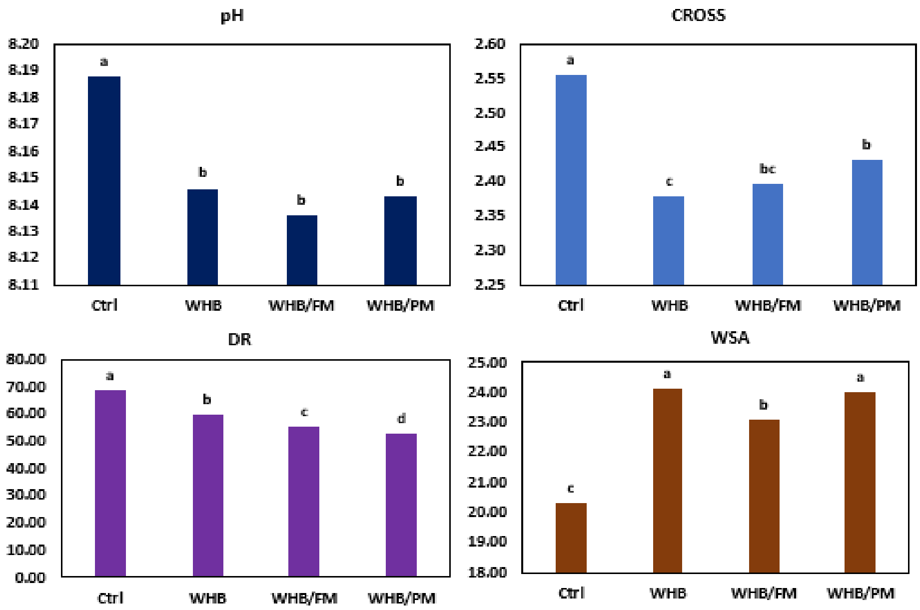

Figure 3. Effect of amendment type on pH, CROSS, DR, and WSA (columns with different letters indicate significant differences).

Soil pH significantly decreased as the rate of the applied amendment increased ($p < 0.05$) (Figure 4). The same pattern of the application rate effect was observed for CROSS. The integration between WHB and manures at a rate of 1.5% and 3.0% resulted in significant ($p < 0.05$) decreases in DR compared to WHB alone (Figure 4). Homogeneous subsets analysis, using a harmonic mean sample size = 18 ($p < 0.05$), generalized that the higher application rate (3%) was significantly the most effective in improving WSA on both studied soils (Figure 4).

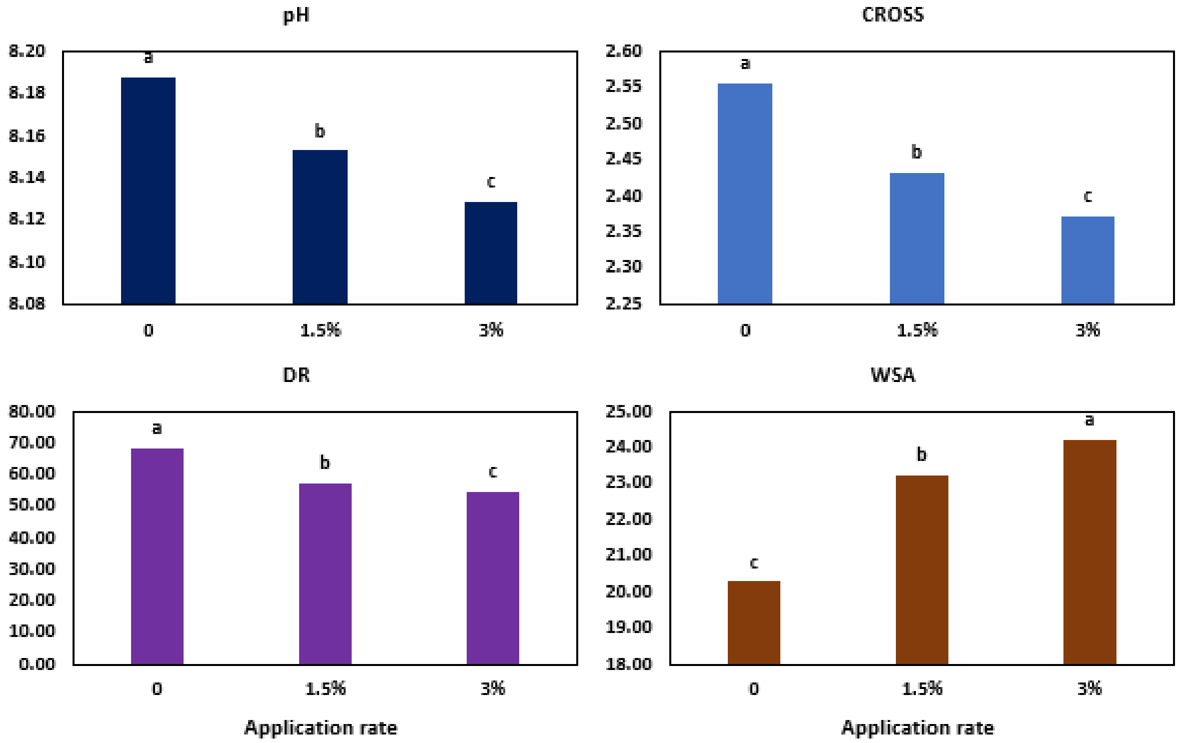

Figure 4. Effect of application rate on pH, CROSS, DR, and WSA (columns with different letters indicate significant differences).

3.5. Effect of Treatments on Available Water Content (AWC)

Soil water retention percentage at three different matric potentials (−0.01, −0.03, and −1.5 MPa) given in Table 4 indicated that the addition of water-hyacinth-derived biochar, alone or with FM and PM, resulted in significant ($p < 0.05$) increases in moisture-retention contents (MRC) at different matric potentials and AWC on two contrasting soils. In sand soil, top effects were observed with SWHB3 treatment, followed by SWHB/PM3 treatment and SWHB1.5, excluding moisture content at −0.01 MPa. In clay loam soil, SWHB1.5, SWHB3, and SWHB/PM3 treatments had a superiority effect on moisture content at a matric potential of −0.3 Mpa and −1.5 Mpa.

Clay loam soil showed a significantly higher AWC in comparison with sand soil ($p < 0.05$). Generally, all amendments (WHB, WHB/FM, and WHB/PM), whatever the effect of the application rate, significantly increased AWC. The impact of amendment type on AWC is arranged in descending order WHB > WHB/PM > WHB/FM. The application rate of 3% was significantly effective in increasing AWC (Figure 5). These findings revealed that the application of WHB alone at both application rates (1.5% and 3%) has superiority over the rest of the amendments in rising AWC (Figure 5).

Table 4. Effect of water hyacinth biochar (WHB), water hyacinth biochar and farmyard manure mixture (WHB/FM), and water hyacinth biochar and poultry manure mixture (WHB/PM) on water retentions and available water content (AWC) of the investigated soils.

Treatments	Moisture Retention Contents (MRC) (%) −0.01 (Mpa)	−0.03 (Mpa)	−1.5 (Mpa)	AWC * (%)
SCtrl.	26.4 ^{f} ± 0.44	17.1 ^{e} ± 0.25	5.7 ^{d} ± 0.20	11.4 ^{e} ± 0.10
SWHB1.5	30.9 ^{d} ± 0.76	21.1 ^{b} ± 0.25	6.9 ^{b} ± 0.13	14.2 ^{b} ± 0.30
SWHB3	35.6 ^{a} ± 0.53	22.9 ^{a} ± 0.19	7.3 ^{a} ± 0.14	15.6 ^{a} ± 0.29
SWHB/FM1.5	29.3 ^{e} ± 0.29	19.3 ^{d} ± 0.18	6.3 ^{c} ± 0.21	13.0 ^{d} ± 0.10
SWHB/FM3	33.2 ^{c} ± 0.36	20.5 ^{c} ± 0.24	6.7 ^{b} ± 0.18	13.8 ^{c} ± 0.08
SWHB/PM1.5	30.1 ^{d} ± 0.25	20.1 ^{c} ± 0.26	6.3 ^{c} ± 0.24	13.8 ^{c} ± 0.11
SWHB/PM3	34.2 ^{b} ± 0.27	21.1 ^{b} ± 0.17	6.8 ^{b} ± 0.15	14.3 ^{b} ± 0.28
CLCtrl.	35.2 ^{e} ± 0.12	28.5 ^{d} ± 0.20	8.2 ^{c} ± 0.20	20.3 ^{d} ± 0.36
CLWHB1.5	41.1 ^{c} ± 0.23	33.1 ^{a} ± 0.19	9.7 ^{ab} ± 0.20	23.3 ^{a} ± 0.35
CLWHB3	43.3 ^{a} ± 0.30	33.2 ^{a} ± 0.20	10.1 ^{a} ± 0.19	23.2 ^{a} ± 0.07
CLWHB/FM1.5	39.9 ^{d} ± 0.18	31.8 ^{c} ± 0.26	9.5 ^{b} ± 0.22	22.3 ^{bc} ± 0.47
CLWHB/FM3	41.6 ^{b} ± 0.17	31.6 ^{c} ± 0.27	9.6 ^{b} ± 0.22	22.1 ^{c} ± 0.43
CLWHB/PM1.5	40.1 ^{d} ± 0.28	32.6 ^{b} ± 0.35	9.5 ^{b} ± 0.27	23.1 ^{a} ± 0.08
CLWHB/PM3	41.9 ^{b} ± 0.30	32.8 ^{ab} ± 0.21	10.0 ^{a} ± 0.12	22.8 ^{ab} ± 0.32

* AWC = moisture content at 0.03 (Mpa) minus moisture content at 1.5 Mpa. Different letters indicate significant differences among means of treatments for each soil separately according to the Duncan test at $p < 0.05$. The mean is the average of 3 replicates ± standard deviation (SD).

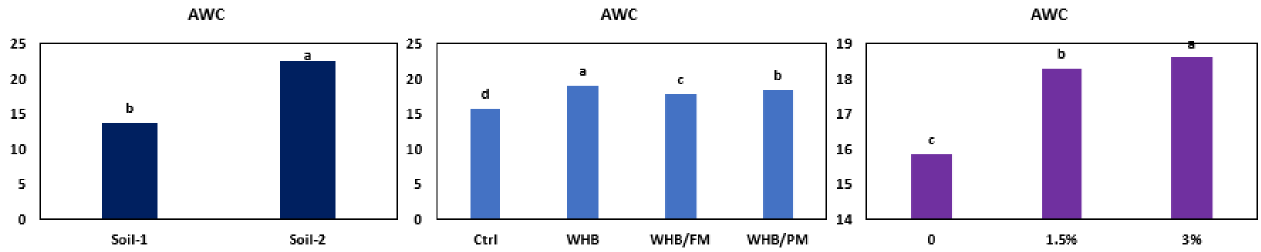

Figure 5. The effects of soil texture, amendment type, and the application rate of amendment on AWC (columns with different letters indicate significant differences).

3.6. The Effect on Barley's Growth Parameters

Data presented in Table 5 showed that plant height and dry matter of barley plants per pot in clay loam soil were higher than those in sand soil. All amendments caused a significant increase in barley's growth parameters, and the WHB/PM amendment had the best effect ($p < 0.05$). The higher the application rate, the higher the barley plant's height; however, there was no significant difference between application rates in the case of dry matter.

Regarding the interaction effects of soil texture, amendment type, and application rate, all treatments caused a significant increase ($p < 0.05$) in plant height and dry matter except for CLWHB1.5 treatment, as shown in Figure 6. The higher relative increases in plant height and dry matter were 39.1 and 64.9% in case of SWHB/PM3 treatment, and 11.7 and 31.2% in CLWHB/PM1.5 treatment, respectively.

Table 5. Effects of soil texture, amendment type, and the application rate of amendment on barley's growth parameters.

	Plant Height (cm)	Dry Matter per Pot (g)
Soil texture effect		
Sand soil	42.59 ^{b}	7.76 ^{b}
Clay loam soil	55.29 ^{a}	12.35 ^{a}
Amendment type effect		
Ctrl	43.23 ^{d}	8.16 ^{d}
WHB	47.20 ^{c}	8.99 ^{c}
WHB/FM	49.99 ^{b}	10.71 ^{b}
WHB/PM	52.49 ^{a}	11.40 ^{a}
Application rate effect		
0	43.23 ^{c}	8.16 ^{b}
1.5%	49.27 ^{b}	10.25 ^{a}
3%	50.52 ^{a}	10.48 ^{a}

Different letters indicate significant differences among means.

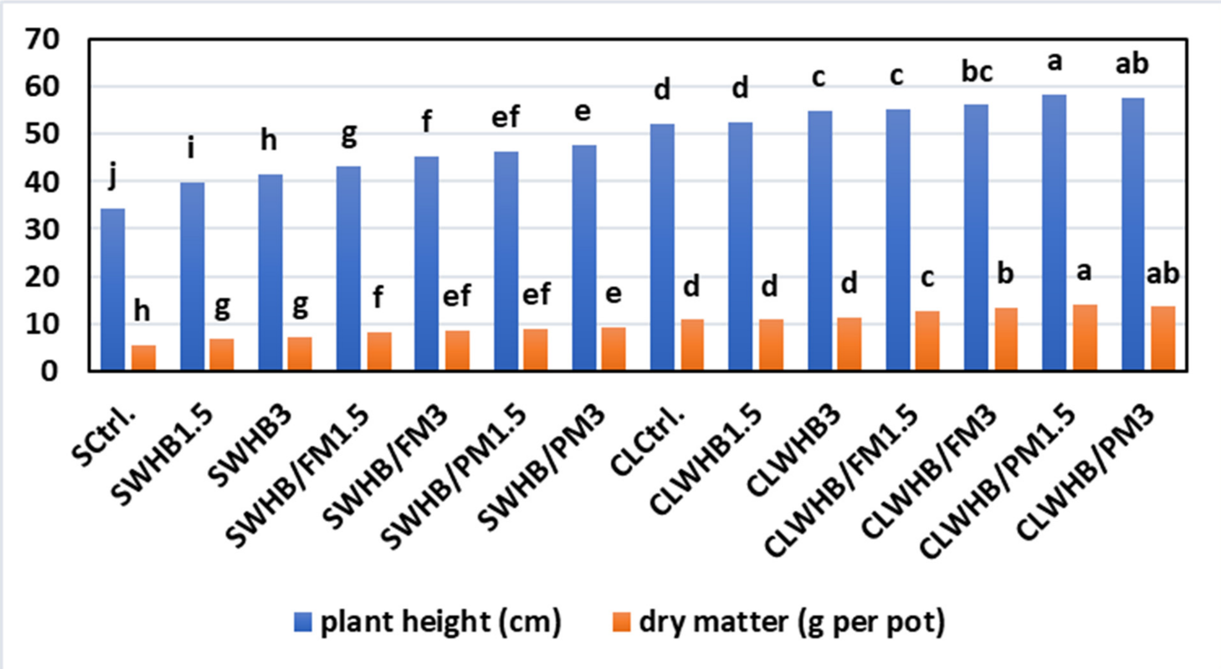

Figure 6. Effects of treatments on barley's growth parameters (columns with different letters indicate significant differences).

3.7. Statistical Findings

The correlation matrix (Pearson) for the studied soil properties detailed in Table 6 showed that *r* values were different from zero, with a significance level of alpha = 0.05. The simple correlations between K^+ (mol m^{-3}) and DR% or CROSS (mol $m^{-3})^{0.5}$ showed a positive relation with the *r* values 0.62 and 0.71, respectively. However, negative correlations were observed between K^+ and WSA or AWC (−0.71 and −0.65). These significant correlations with K^+ indicated the importance of using the equation suggested by Rengasamy and Marchuk [57]. CROSS showed highly significant *r* values with DR, WSA, or AWC (0.98, −0.99, −0.98).

Table 6. Correlation matrix (Pearson) for some studied soil properties.

Variables	pH	Na	K	Ca	Mg	CROSS	DR	WSA	MRC0.01	MRC0.03	MRC1.5	AWC
pH	1.00											
Na	0.66	1.00										
K	0.46	0.78	1.00									
Ca	−0.84	−0.74	−0.44	1.00								
Mg	−0.83	−0.88	−0.62	0.93	1.00							
CROSS	0.84	0.92	0.71	−0.92	−0.98	1.00						
DR	0.86	0.85	0.62	−0.94	−0.99	0.98	1.00					
WSA	−0.82	−0.91	−0.71	0.91	0.99	−0.99	−0.98	1.00				
MRC0.01	−0.86	−0.73	−0.45	0.95	0.90	−0.90	−0.91	0.90	1.00			
MRC0.03	−0.84	−0.86	−0.63	0.94	0.98	−0.98	−0.97	0.98	0.95	1.00		
MRC1.5	−0.84	−0.84	−0.58	0.95	0.96	−0.96	−0.95	0.96	0.96	0.99	1.00	
AWC	−0.83	−0.86	−0.65	0.93	0.98	−0.98	−0.97	0.98	0.94	1.00	0.98	1.00

Values in bold are different from 0, with a significance level alpha = 0.05.

Table 7 and Figures 7–9 show regressions between independent variables (DR, WSA, and AWC) and dependent variable (CROSS); and between independent variables (WSA and AWC) and dependent variable (DR). The simple linear regression was to predict DR based on the CROSS value, and a significant regression equation was found with a coefficient of determination, r^2, and an adjusted r^2 of 0.951 and 0.950, respectively. The validation for the regression is illustrated in Figure 7A1,C1. The regression equation confirms that the DR values could be predicted from CROSS values as DR = 41.193CROSS − 42.267 (Table 7). The comparison between measured DR and a predicted DR is obtained from the equation, as shown in Figure 7B1. In addition, using CROSS data to predict WSA and AWC showed high significance, as presented in Table 7. Figures 7–9 illustrate all models and validations.

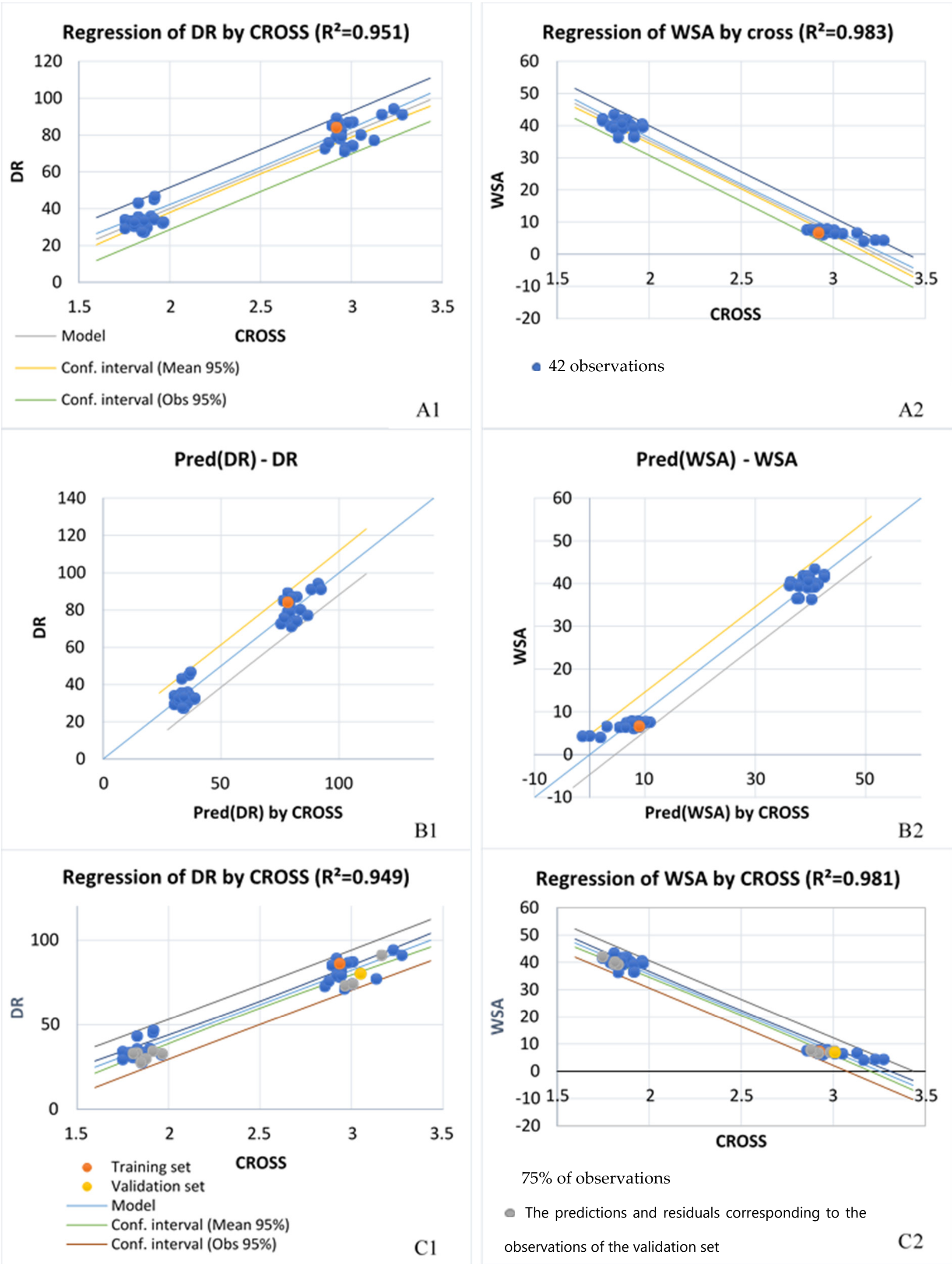

Figure 7. Regressions of DR and WSA against CROSS (**A1**,**A2**), their predictions (**B1**,**B2**), and validations (**C1**,**C2**), as affected by treating soil with biochar and its combined application with FM and PM.

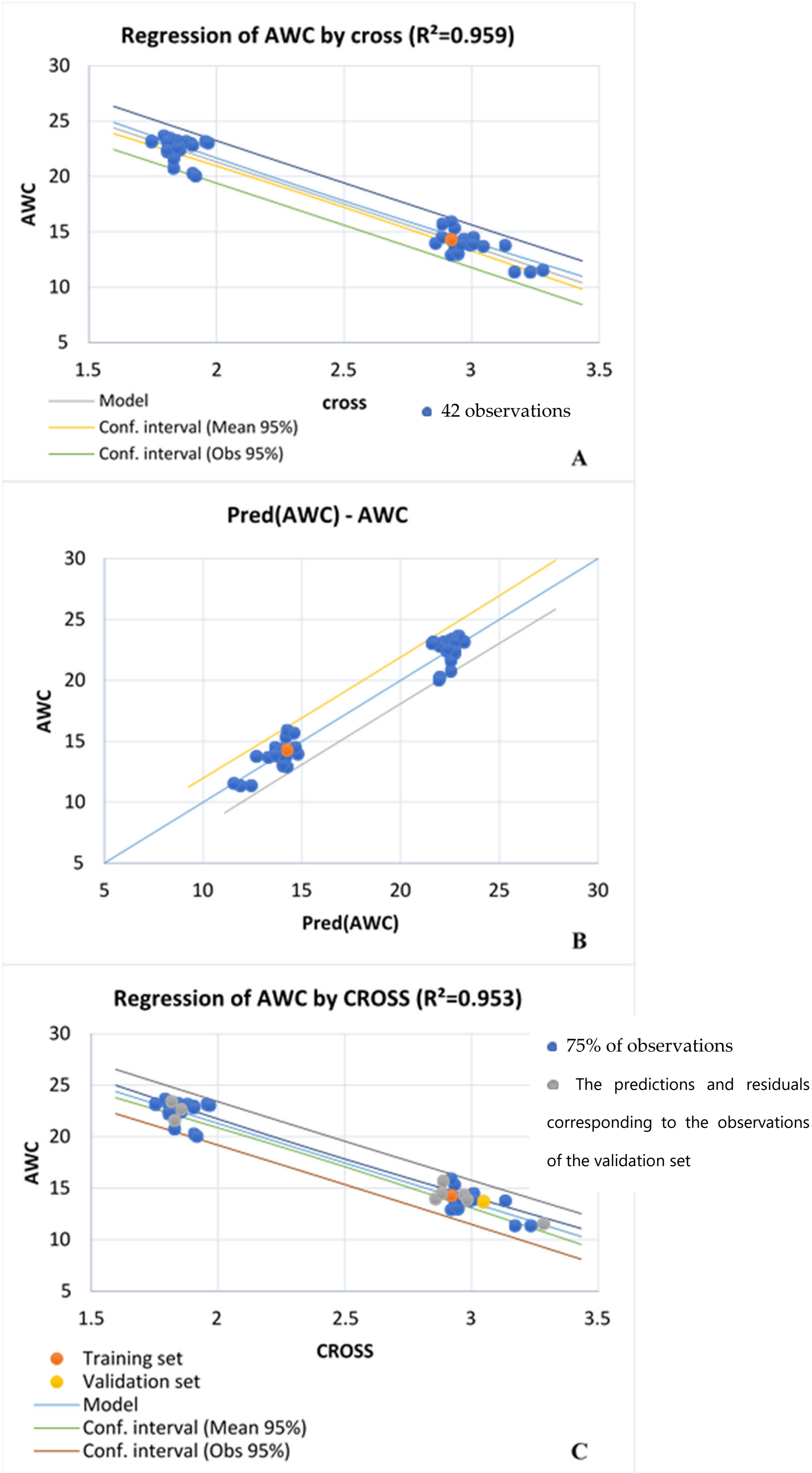

Figure 8. Regression of AWC against CROSS (**A**), its predictions (**B**), and validations (**C**), as affected by treating soil with biochar and its combined application with FM and PM.

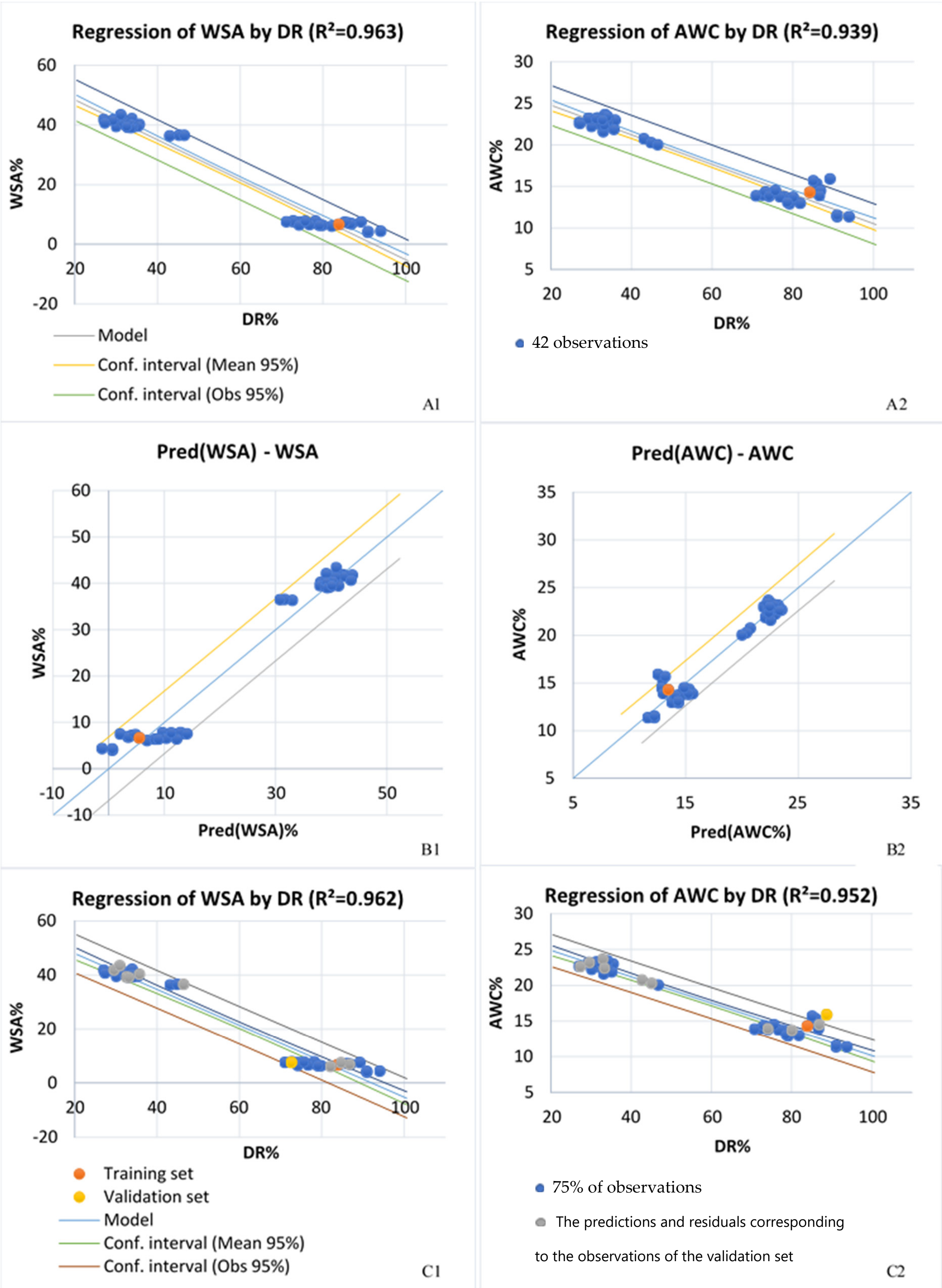

Figure 9. Regressions of WSA and AWC against DR (**A1**,**A2**), their predictions (**B1**,**B2**), and validations (**C1**,**C2**), as affected by treating soil with biochar and its combined application with FM and PM.

Table 7. Regressions between dispersion ratio (DR), water stable aggregates (WSA), available water content (AWC), and cation ratio of soil structural stability (CROSS).

Soil	Y	X	Equation	R^2	Adjusted R^2	*p*-Value	Validation (75%)	
							R^2	Adjusted R^2
Both soils	DR	CROSS	$41.193x - 42.267$	0.951	0.950	<0.0001	0.949	0.948
	WSA		$-28.595x + 92.562$	0.983	0.982	<0.0001	0.981	0.980
	AWC		$-7.613x + 36.536$	0.959	0.958	<0.0001	0.953	0.951
	WSA	DR	$-0.670x + 61.834$	0.963	0.962	<0.0001	0.962	0.961
	AWC		$-0.178x + 28.346$	0.939	0.937	<0.0001	0.952	0.950

4. Discussion

Producing biochar from water hyacinth plants was one of the objectives of this study as a management strategy. Biochar pH is strongly related to pyrolyzing temperature, which affects all other biochar physicochemical properties. Production of biochar from different feedstocks at high temperatures increases biochar pH and the opposite with low pyrolyzing temperature [58,59]. In addition, using low pyrolysis temperature to produce biochar recorded the highest yield of biochar (converted portion of feedstock) [60]. Biochar with high pH values have a liming effect, which is favorable for acidic soils in humid regions. In Egypt, soils are characterized by pH values higher than 8; therefore, converting water hyacinth to biochar at 300 °C was practical for such conditions. The pH of sand soil was decreased, either with WHB application alone or with its mixtures with manures, contrary to the change of pH in clay loam soil, which is explained by its higher buffering capacity. Soils with a high degree of base saturation and heavy particle size distribution have a high buffering capacity against changes in soil reaction (pH) [61]. Results obtained in [62] indicated that applications of biochar alone or combined with PM resulted in significant improvements in soil physical and chemical properties in a tropical Alfisol.

The soil structure stability was represented by some physical parameters, such as DR%, CROSS, and WSA. The percentage of dispersible clay is a good indicator of soil structure stability. The high DR values indicate poor resistance to soil erosion [63,64]. All treatments improved structure stability for both soil types by decreasing the DR%. Generally, biochar and organic amendments, such as manures, have a high specific surface with negative charges, which play an important role with cations in forming bridges with clay particles [65]. The CROSS indicates the impact of cations such as Na, K, Ca, and Mg on soil structure. The higher the CROSS values, the lower the soil structural stability [57]. All treatments improved sandy soil structure stability through decreasing CROSS value; however, clayey loam soil had no significant effect. The reason behind the decrease in CROSS in sandy soil was the effect of the chemical compositions of WHB, FM, and PM. In arid areas, Ca^{+2} and K^{+} are flocculating agents, but Na^{+} is a dispersion agent. The decrease in CROSS values for treated sandy soil revealed an improvement in aggregate stability through the increase in flocculating agent evidence rather than dispersion agents [11].

Water-stable aggregate (WSA) is one of the soil structure stability indices. Both soils, when treated by WHB, WHB/FM, and WHB/PM showed an increase in WSA, in contrast to the untreated soils. This could be attributed to the stabilizing effect of WHB, FM, and PM. These results were in a good agreement with [66]. It was reported that biochar can increase the water aggregate stability in sandy soil more than in clayey loam soil [67]. The increase in WSA suggested that the application of WHB to soil improved soil aggregation by providing an organic binding agent. All applied organic amendments, characterized by their high content of organic carbon, improved WSA and soil structure quality [25,29,62].

Sandy soils in Egypt suffer from several problems, foremost of which is their low ability to retain irrigation water. This is reflected in the required irrigation frequency, and thus the volume of water needed for irrigation. Although water-holding capacity problems in the soils of the Nile Valley do not exist, there is an urgent need to reduce irrigation water consumption. The specific surface area of biochar has many advances in that it is mostly similar to or higher than clay; therefore, it increases the total soil-specific surface area when added as soil amendment [68]. WHB alone or mixed with FM or PM enhanced the available water content for both contrasting soils. Biochar increases water retention in soils because it has a high surface area and a large amount of macro- and micropores, in which water can be retained by capillarity [69]. In addition, biochar improves soil porosity and raises the soil water content, reducing the mobility of the water and decreasing water stress in plants. The WHB/PM at the higher application rate was more effective than the rest of the treatments in raising AWC. The positive effect of WHB and its integration with PM comes from their high water-holding capacity, their honeycomb-like pore structure, and their improvements in soil structural stability, as mentioned above.

Water-hyacinth-derived biochar, alone or combined with FM or PM, induced a pronounced effect on soil structure stability and water-holding capacity, and, consequently, AWC, which improved the soil potential in providing plants with their water and nutrition needs [61]. Barley, in the treated sand soil, responded clearly to the positive changes in soil physical properties brought by the treatments mentioned above, which was reflected in a high relative increase in plant height and dry matter. Biochar has a relatively low nutrient content, so the combination of biochar with FM or PM is supposed to increase the fertility of the treated soil. The latter was the reason behind the effectiveness of WHB/PM in improving barley growth. It was reported that water hyacinth biochar, applied to tropical soil at a rate of 10 tons ha^{-1} with recommended mineral fertilizers doses, increased rice yield in a pot experiment [70]. The combination of biochar and PM (30 + 7.5 Mg ha^{-1}) in degraded tropical sandy soil increased cocoyam yield more than the solo application of biochar [36]. The carrot yield was increased because of improvements in soil physical properties, such as porosity, aggregate stability, and soil water content, as affected by combining the application of NPK, poultry manure, and biochar in a field experiment in Nigeria [71]. It has been stated that the co-application of bamboo biochar and organic fertilizers increased the yield of red pitaya in a field experiment in China by improving soil properties. In addition, the cotton roots were influenced positively by biochar combined with organic manure [72]. In a pot experiment, the combination of wheat straw biochar and chicken manure, at a rate of 20 g kg^{-1} each, caused the largest increase in maize growth and improve the soil productivity [73–76].

5. Conclusions

Producing biochar from the invasive aquatic weed (*Eichhornia crassipes*) has tangible ecological impacts and agricultural impacts. The pyrolyzing process at 300 °C produced biochar from water hyacinth weeds with nonalkaline pH, which will be very valuable for improving Egyptian soils, having a pH > 8.0. Significant improvements in soil physical properties have been observed for both sandy and clayey loam soils. The solo applications of WHB and its combination with poultry manure (WHB/PM) were more effective in altering physical properties than WHB combined with farmyard manure (WHB/FM). Usually, these applications lead to increases in moisture retention contents (MRC), available water content (AWC), and water-stable aggregate (WSA), and cause a decrease in the dispersion ratio (DR). Consequently, the altering grades have been based on application type and rates (0.0%, 1.5%, and 3.0%). The impact of cations, such as Na^{+}, K^{+}, Ca^{++}, and Mg^{++}, on soil structure can be expressed by the cation ratio of the soil structural stability index (CROSS). Lower CROSS values mean higher soil structural stability and vice versa. Therefore, high significant correlations were observed between the determined soil physical properties (DR, WSA, and AWC) and CROSS. Barley growth showed progress, being affected when combining WHB with FM and PM rather than when applying WHB alone. Further studies under field conditions are highly needed.

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