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Assessment of Water Hyacinth Biochar as a Soil Amendment for Sandy Soils

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ABSTRACT

Soil application of water hyacinth biochar as a source of nutrient- and carbon-rich biomass may be an effective ploy to eradicate this invasive aquatic weed. Incubation trial was conducted to assess effects of water hyacinth biochar addition on some sandy soil biochemical and biological properties and potential carbon sequestration at different application rates and methods. Results demonstrated that pyrolysis of water hyacinth at temperature of 300 °C and 30 min furnace residence time produced biochar with coveted physicochemical properties. Field emission scanning electronic microscopy (FE-SEM) images obtained for water hyacinth biochar showed major macroscopic changes caused by substantial changes in pore structure, surface area and surface morphology due to insufficient carbonization. Soil biochemical and microbiological characteristics after incubation exposed obvious significant improvements at all rates compared to control and varied markedly between addition of biochar as incorporation and broadcasting. Among different treatments, biochar addition as incorporation at the rate of 3% resulted in higher significant increases in most tested soil parameters. Water hyacinth biochar provided nitrogen and carbon immediately via SOC, DOC and DON in treated sandy soils providing energy for microbial biomass compared to control and this reflected by increases in soil values of $C_{\text{-MIC}}$ $N_{\text{-MIC}}$ and $P_{\text{-MIC}}$. In addition, water hyacinth biocharring would greatly improve sandy soil carbon sequestration at high application rates. It could be concluded that water hyacinth transformation into biochar represents a sustainable strategy for managing these weeds and thus become a valuable organic source for sandy soils and will boost carbon sequestration.

Keywords: Hyacinth Biochar, Carbon Sequestration, Pyrolysis, Incubation Trial.

INTRODUCTION

Egypt suffers from a continuous population growth and a deterioration in the natural resources of water and soil. This population growth has created and will continue to create unprecedented pressures on the limited soil and water resources to produce more food, fibre, housing and raw materials. Egypt's population (104 million in 2020) is concentrated in the Nile Valley and Delta which are dominated by alluvial fertile soils and are intensively cultivated for food production while they constitute less than 5% of the country total area (Hammam and Mohamed, 2018; Abd El-Azeim *et al*., 2020). The other 95% dominated by sandy soils, with coarse texture, low fertility and low organic matter (less than 0.5%). Reclamation of these sandy soils by addition of organic matter in order to solve the problems of food and housing for the ever-increasing population, is critical for Egypt's future. In addition, management strategies used for making newly reclaimed sandy soils functionally productive on a long-run basis must be economically viable and also in harmony with the environment. Food production is paramount to human well-being, and the global demand for food productivity is expected to grow by 59–98% by 2050 (FAO, 2017). Global food production is further threatened through water scarcity because of increasing population, pollution and climate change, requiring improved agricultural water use efficiency (Gao *et al*. 2020).

Moreover, the increase in population in Egypt has led to an increase in agricultural activities and thus the production of large quantities of agricultural organic biomass waste. In addition to rising demand for the constructions of more irrigation and drainage canals that infested with aquatic weeds of water hyacinth under improper maintenance. The disposal of these aquatic weed has become an increasing problem and a growing expense for the country, farmers and agricultural authorities, especially in the light of further water scarcity and climate change (Allam *et al*., 2020; Gaurav *et al*., 2020). Organic biomass in general are valuable resources when properly managed and applied to soils, both as a fertilizer and as a soil amendment. Organic biomass can improve soil physical properties (e.g., water retention, aggregate stability), soil chemical properties (e.g., CEC, pH, EC, soil nutrient status) and the biological properties (Stratton, *et al*., 1995). In specific, water hyacinth aquatic weeds recover a large biomass yield of around 120 t/ha/year, contain worthy nutrients for plant growth and are therefore a potential source for staple organic matter in sandy soil reclamation projects (Allam *et al*., 2020; Gaurav *et al*., 2020). Transformation of this huge biomass into biochar would boost biocarbon stability and sequestration and support long term biocarbon storage in soils (Jeffery *et al*., 2011; Masto *et al*., 2013).

The aquatic weed water hyacinth (*Eichhornia crassipes)* is one of the most pernicious invasive weeds owing to its speedy proliferation rate, ecological adaptability and survival strategies and deleterious impact on environment and water resources and socio-economic development. It was itemized as one of the world's top 10 worst weeds by International Union for Conservation of

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Nature (Sharma and Aggarwal, 2020). Many serious threats to the agroecosystem such as blocking irrigation and drainage canals, high water consumption, acting as channels for greenhouse gas emissions from watercourses and destruction of native biodiversity are posed by water hyacinth (Masto *et al*. 2013; Hoko and Toto 2020). Water hyacinth (WH) biomass is cellulosic in nature and when it is disposed or dumped into soils, the carbon in biomass will readily decompose due to high biodegradation (Masto *et al.* 2013; Gaurav *et al*., 2020). Due to their redundancy, low density and weight, low cost, recyclability and biodegradable properties, a sustainable strategy to manage these weeds are to convert water hyacinth into biochar and apply it in agriculture (Ahmed *et al.* 2018; Allam *et al*., 2020; Bottezini *et al*., 2021).

In addition, water hyacinth aquatic plants grow intensively in drainage water and anyway in highly polluted water assimilating nutrients, metal ions, and organic compounds (Rezania *et al.* 2015; Bottezini *et al*., 2021). This aquatic plant has also rapid proliferation and can widely infest fresh water bodies as it is the case in the Nile River. Existing control methods for water hyacinth have been insufficient to control its aggressive propagation in nutrient-rich water bodies (Abdel Shafy *et al*., 2016; Hoko and Toto 2020). As attempts to control water hyacinth population in water bodies have not been completely successful, the best lenitive measure is to find alternative usages of this aquatic plant. The most feasible uses of water hyacinth include production of biogas (Gupta *et al.* 2012; Gaurav *et al*., 2020), bio-sorbent for pollution treatment, animal fodder, wastewater treatment (Kamna, 2013); and also, application in agriculture through converting into biochar (Ahmed *et al.* 2018). In the developing countries, there has been an emphasis on converting these aquatic weeds into useful resources, including animal feed, compost or for biochar production via pyrolysis process (Abdel Shafy *et al*., 2016; Allam *et al*., 2020; Khan *et al*., 2020).

In general, biochar nowadays is considered for carbon sequestration and delivering different soil ecosystem services (Blanco-Canqui, 2021). Biochar is a porous carbonaceous solid material having a relatively high degree of aromatization and strong anti-decomposition ability (Blanco-Canqui, 2021; Bottezini *et al*., 2021). Biochar is generated by pyrolysis of plant biomass or animal wastes at elevated temperatures (350 °C to 1000 °C), under a limited supply of oxygen (Wu *et al.* 2017; Ahmed *et al.* 2018). Biochar is one of the stable forms of carbon and it is rapidly gaining popularity in the last few decades due to the improvement in agricultural productivity, environmental remediation and for carbon sequestration (Das *et al*., 2016; Blanco-Canqui, 2021). Biochar exhibits a great potential in maintaining soil fertility, deactivating pesticides over abiotic degradation and accelerating pesticide biodegradation (Ding *et al*., 2017). Biochar is a suitable soil amendment to provide long-lasting carbon enrichment of infertile sandy soils while enhancing water retention (Litvinovich *et al*., 2016; Hammam and Mohamed, 2018; Mohamed and Hammam, 2019; Safian *et al.* 2020; Khadem *et al*., 2021); to enhance macro- and micro-nutrient retention and soil microbial and enzymatic activity (Pokharel *et al.* 2020; Khadem *et al*., 2021). Biochar achieves these benefits due to its highly porous carbonaceous structure, wide range of functional high negative charged groups (Lam *et al*., 2020; Foong *et al*., 2020), large cation exchange capacity (CEC) (Pradhan *et al*., 2020; Khadem *et al*., 2021). Also, water hyacinth biomass is highly suitable for pyrolysis and biochar production due to their high lignocellulosic content (Sakhiya *et al*., 2020). The pyrolysis temperature and the specific feedstock employed are the primary factors influencing water hyacinth biochar (WHB) yields and characteristics (Pradhan *et al*., 2020; Bottezini, *et al*., 2021).

In Egypt, due to the negative impacts of water hyacinth on water courses beside that the large amount of money spent for their removal it becomes very important to find better solutions for the utilization of this aquatic plant (Gaurav, *et al*., 2020; Mohamed and Rashad, 2020). A number of weed control methods including physical/mechanical removal, chemical methods and biological control agents have been used in Egypt to eradicate or manage water hyacinth. Nevertheless, because of various environmental and financial challenges associated, none of these strategies or their combinations has been effective in completely eliminating this harmful weed. In contrast, water hyacinth has demonstrated its potential in various applications like bioremediation and bio-adsorption of heavy metal from polluted aquatic environment; bioenergy production; means of carbon sequestration; as animal and fish feed; as carbon source for microbial growth; composting, vermicomposting and biocharring (Allam, *et al*., 2020; Hussain *et al*., 2020).

Transformation of the abundant water hyacinth biomass in the Nile River into biochar and then adding this biochar to the vast areas of sandy soil existed in Egypt so far can turn these aquatic weeds into a valuable organic matter resource for improving sandy soil physical, chemical and biological properties. Hence, this research presents an overview of the physicochemical properties of water hyacinth and their potential after converting into biochar as a soil fertilizer and/or conditioner for newly reclaimed sandy soils. The scientific aim of this research was to evaluate impacts of water hyacinth biochar addition on some sandy soil biochemical and biological properties and a method of carbon sequestration at different application rates and methods. The hypotheses tested were therefore (1) the conversion of water hyacinth to biochar would improve soil biochemical properties and carbon sequestration potential, (2) soil addition of water hyacinth biochar would increase sandy soil microbial activity and fluoresceine diacetate hydrolysis (FDA) soil activity; and (3) soil incorporation addition of water hyacinth biochar would be greater than soil broadcasting on sandy soil biochemical parameters and carbon sequestration potential.

MATERIALS AND METHODS

After soil incubation with biochar, the estimated sandy soil biochemical properties that affected by water hyacinth biochar addition were soil organic C (SOC), dissolved organic carbon (DOC), and dissolved organic nitrogen (DON). In addition, the microbiological sandy soil properties that were analyzed for are microbial biomass counts of bacteria and fungi (cfu), soil microbial biomass and enzymatic activity by fluorescein diacetate (FDA) hydrolysis, soil microbial biomass carbon (C_{-MIC}), microbial biomass nitrogen (N_{-MIC}), and microbial biomass phosphorus (P_{-MIC}).

Experimental Materials and Design.

Experimental Procedure, design and incubation conditions.

Incubation trial was conducted in a complete randomized block design with factorial treatment combinations of 2 × 4 × 3 as two biochar application methods (incorporation and broadcasting) and four biochar application rates (0.0%, 1%, 2%, 3%) with three replicates, resulting in a total number of 24 observation pots. These application rates were chosen for an attempt to raise organic matter of the investigated sandy soil by up to 1% as prevalent in these soils under arid conditions.

The experimental treatments included therefore were as following:

1- (Control 0.0%) = Untreated sandy soil.
2- (Inc. 1%) = Treated sandy soil with biochar by incorporation at 1% rate.
3- (Inc. 2%) = Treated sandy soil with biochar by incorporation at 2% rate.
4- (Inc. 3%) = Treated sandy soil with biochar by incorporation at 3% rate.
5- (Bro. 1%) = Treated sandy soil with biochar by broadcasting at 1% rate.
6- (Bro. 2%) = Treated sandy soil with biochar by broadcasting at 2% rate.
7- (Bro. 3%) = Treated sandy soil with biochar by broadcasting at 3% rate.

The investigated sandy soil was air dried, sieved to <2 mm and one-kilogram of fine earth was packed into each of 24 pots. These pots were placed in an incubator at 25 ^{0}C for 3 days at 60% of field capacity to achieve stable soil conditions (Rowell, 1994). After 3 days, pots were treated with water hyacinth biochar (WHB) at four application rates (0.0, 1%, 2%, 3%) and incubated for 60 days under the same conditions. Soil moisture content was maintained at 60% of water holding capacity by deionised water to achieve stable moisture and aeration conditions, which is in the optimum range of water contents and temperature for maximum possible soil microbial and enzymatic activities. Moisture content of each pot was maintained by daily weight analysis and dropwise deionised water applications. Pots were arranged in a complete randomized block design (3 blocks of 8 pots). Soil samples (10 g) were taken on day 0 and 20 further intervals until day 60 (three replicates of each treatment and control pots) for analyses of changes in some soil biochemical and microbial biomass counts of fungi and bacteria.

The investigated soil.

The investigated sandy soil detailed in Table (1) was congregated at depth of 30 cm from a private farm at the Eastern Desert (28° 06′ 35.57″ N and 30° 45′ 1.08″ E), El-Minia Governorate, Egypt. The soil is designated as sand in texture and consists of fine and coarse sand (32.54% and 60.22%), with 2.43% silt content and 4.81% clay content. In addition, this sandy soil was chosen as its range of physical and chemical properties were similar to most sandy soils that spread throughout Western and Eastern deserts in Egypt.

Prior to initiation of the incubation study, soil was air dried, sieved to < 2.0 mm, and moisture content was adjusted at 15 % before addition of biochar combinations. At the end of incubation period, sub-samples of dried and sieved soil were used to determine soil physical and chemical properties using standard methods of Avery and Bascomb, (1982); Page *et al*., (1982); and methods of soil analysis by Black, (1965).

Table 1. Physical and chemical properties of the investigated soil.

Soil Property	**Value**			
Particle Size Distribution %	Coarse Sand	Fine Sand	Silt	Clay
	32.54	60.22	2.43	4.81
Texture grade	Sand	CEC cmol$_c$ kg^{-1} soil		4.22
F.C %	17.75	O.M g kg^{-1}*		4.67
PWP %	4.78	SOC g kg^{-1}		2.68
WHC %	19.88	EC dS m^{-1} at 25 $^{\circ}$C		1.73
A.V(F.C – PWP) %	12.97	Total N g kg^{-1}		0.38
A.V(WHC – PWP) %	15.10	C/N Ratio		7.05
Bulk Density g/cm^3	1.64	Total P g kg^{-1}		0.19
Particle Density g/cm^3	2.61	Total K g kg^{-1}		3.22
pH (1-2.5 water)	8.41	$CaCo_3^-$ g kg^{-1}		88.76
Soluble Cations and Anions				
Na^+		5.28		
Ca^{++}		14.65		
Mg^{++}		4.48		
K^+	(cmol$_c$ kg^{-1})	2.28		
HCO_3		12.57		
Cl^-		5.59		
$SO_4^=$		7.47		

*** Organic matter by Loss on ignition method.**

Water Hyacinth Biochar Preparation and Characteristics.

Biochar illustrated by Figure 1 and detailed in Table 2 was made from water hyacinth (*Eichhornia crassipes)* aquatic weeds collected from the Nile River in March 2019. All the required water hyacinth weeds were collected from the same place of the Nile River to avoid any genetic variations. The collected water hyacinth weeds were dried in air and cut into smaller pieces of 4 to 8 cm then grinded into powder (Figure, 1). Water hyacinth biomass was converted into biochar by pyrolysis process in a muffle furnace at 300 ºC temperature with residence time of 30 minutes.

Figure 1. Water hyacinth preparation for pyrolysis and the resulting biochar.

Water hyacinth biochar in its loose condition was stored in unsealed plastic bags at 4 ^{0}C before addition to the experiments. Sub-samples of biochar were used to determine some physiochemical properties such as particle size distribution, moisture, heavy metals and total nutrients. Most of the methods employed are of a standard laboratory practice as per the procedures described by Avery and Bascomb, (1982) and Bird *et al*., (2017). Standard methods have also been derived from (Page *et al*., 1982); and methods of soil analysis (Black, 1965). Water hyacinth biochar was then added to the investigated sandy soil alone at the rates of 0.0, 1%, 2%, 3%, on a dry weight basis at the same rates by two methods of application (Broadcasting and incorporating) in both experiments.

Experimental pilot studies conducted to optimize the pyrolysis process to transform this abundant biomass carbon into biochar have specified that stable biocarbon increased but biochar yield decreased with increasing pyrolysis temperature. A number of Known weights of air-dried water hyacinth weeds was put in stainless-steel cylinder with lid into a muffle furnace at different temperatures for different times to get maximum staple organic matter and optimal biochar characteristics for improving sandy soil quality parameters. The resulting water hyacinth biochar (WHB) was analyzed for organic carbon (OC) using a modified Walkley and Black method (Nelson and Sommers, 1996) to assess the labile organic carbon fraction in water hyacinth biochar. By contrast, biochar staple total organic matter was determined using loss on ignition (LOIOM) method by burning dry water hyacinth weeds in a muffle at 650 °C for six hours in an open silica crucible (Page *et al*., 1982). Biochar stable organic matter index was calculated as follows: BSOM = LOIOM– (OC × 1.724) while labile organic carbon index was calculated as OC/LOIOM ratio and stable organic matter biochar yield index (SOMBYI) after pyrolysis was determined as following: BSOMYI = (Water hyacinth biochar yield/ 100) × BSOM (Masto *et al*., 2013).

Table 2. Some physicochemical properties of the studied water hyacinth biochar (WHB).

Biochar property	**Value**	**Biochar property**	**Value**
pH (1 - ١0٠)	6.51	Total P g kg^{-1}	5.00
EC dS m^{-1} at 25 ^{0}C	3.31	N/P Ratio	2.00
CEC cmol$_{c}$ kg^{-1} soil	45.66	Water absorption capacity (%)	256.88
Dry Solids %	74.40	Bulk Density (BD) g cm^{-3}	0.25
Ash %	16.90	Total Ca^{+2} g kg^{-1}	9.00
Total Organic Matter g kg^{-1} (LOIOM)*	658.00	Total Mg^{+2} g kg^{-1}	3.3
Organic Carbon (OC) g kg^{-1}	265.00	Total K^{+} g kg^{-1}	6.60
Biochar Staple OM index (BSOMYI)* g kg^{-1}	136.77	Total Na^{+} g kg^{-1}	0.55
Labile Carbon Index (OC / LOIOM) Ratio	40.27	Total sulphur g kg^{-1}	0.25
Total N g kg^{-1}	10.00	Total Fe mg kg^{-1}	1757
C/N Ratio	26.50	Total Mn mg kg^{-1}	908
Staple Organic Matter g kg^{-1}	201.14	Total Cu mg kg^{-1}	845
Biochar yield (%)	68%	Total Zn mg kg^{-1}	645
Particle size distribution%			
Coarse sand%	0.00%		
Medium sand %	0.00%		
Fine sand % (o.5 – 0.05 mm)	18%		
Silt + Clay% (< 0.05 mm)	82%		

* LOIOM = Loss on ignition organic matter
* BSOMYI = Biochar staple organic matter index

FE-SEM morphology analysis of water hyacinth biochar.

To spectate water hyacinth biochar (WHB) surface morphology, field emission scanning electronic microscopy (FE-SEM) pictures were taken at different magnifications (15 kV × 500, 1000. 2000, 3500 and 5000) using a Sigma-300 (Zeiss) variable pressure operated with 10 to 15 kV accelerating voltage.

Zeta ζ-potential of water hyacinth biochar and soil-biochar mixtures measurements.

Zeta ζ-potential of water hyacinth biochar and soil-biochar mixtures at different application rates were measured via an automated Malvern electrophoresis apparatus, equipped with a microchip unit for statistical analyses. For zeta potential records, a 50mg sample was transported into aqueous solution was mixed consistently with a magnetic agitator. All zeta potential measurements were carried out at 100 mg/L concentration as that the ζ potential deviates to some extent and then remains always constant at concentration of 100 mg/L.

Analyses of some soil biochemical properties and carbon sequestration.

Once after incubation, soil samples were sieved (< 2mm) and then incubated for 10 days at 250C under 65% of soil field capacity. After incubation, soil samples for the determination of soil biochemical properties were sieved to pass a 0.5 mm mesh and reported means were calculated on soil oven dried bases (1050C). Walkley and Black method was used to determine soil organic C (SOC) (Nelson and Sommers, 1996), and steam distillation method using N analyzer (Kjeltech 2100, Foss) for mineral N (Mulvaney, 1996). Dissolved organic nitrogen (DON) and dissolved organic carbon (DOC) were determined by the method described by Smolander and Kitunen (2002) using multi-N/C Analyzer (Jena, Germany). After aerobic incubation, the chloroform fumigation-extraction method of 25 gm of moist soil (Dinesh *et al*., 2013) was used to determine soil microbial biomass carbon (C-MIC), microbial biomass nitrogen (N-MIC) using (multi-N/C 2100, analyzer Jena), and microbial biomass phosphorus (P-MIC) using *k*EC of 0.45, *k*EN of 0.54 and *k*EP of 0.40, respectively. Soil organic carbon (SOC) content of sandy soils amended with water hyacinth biochar divided by the corresponding SOC content of unamended soils was used to calculate carbon pool index (CPI) and to derive the carbon sequestration potentials resulting from water hyacinth biochar application in sandy soils reclamation projects (Calderón *et al*., 2015; Khadem *et al*., 2021).

Total counts of bacteria and fungi.

At the end of the incubation period, plate count technique in accordance with Alef (1995) was used to determine total counts of bacteria and fungi in soil samples after incubation. On nutrient agar, colony forming units (CFU) of total bacteria was counted, while colony forming units (CFU) of total fungi was counted on glucose agar media. To evaluate the effects of water hyacinth biochar addition on microbial population (Fungi and Bacteria) at different application rates and methods, 10 grams of the incubated soils were collected after 60 days of incubation and then were added to 95 ml of sterilized water, shaken for 5 min, then the solution was diluted (10^{-1} to 10^{-6}) and then the resulting solutions were plated directly onto the surface of nutrient agar medium for bacteria, and Martin (1950) medium for fungi and then incubated again at 25 ºC for 10 days under 65% of soil field capacity then, the colony forming units were counted (CFU).

The media used were as following.

- **Nutrient Agar:** Beef extract (3g)**,** Yeast extract (2g), Peptone (5g), Agar (15g), Distilled water to 1000 mL and pH (7.0).
- **Modified Czapek's – Dox Agar Medium:** Sucrose (30g)**,** $NaNO_3$ (3g), $MgSO_4.7H_2O$ (0.5g), KCl (0.5g), $FeSO_4.4H_2O$ (0.01g)**,** K_2HPO_4 (1g), Agar (12g)**,** Tap water to 1000 mL and pH 7.2.
- **Martin's Medium for Fungi:** Glucose (10g), Peptone (5g), KH_2PO_4 (1g), $MgSO_4.7H_2O$ (0.5g), Agar (20g), Distilled water to 1000 mL and Rose Bengal 1 part in 30.000 parts of medium. Streptomycin solution 30 µg mL^{-1} medium was added after sterilization just before plating.

Determination of soil microbial biomass and enzymatic activity by fluorescein diacetate (FDA) hydrolysis.

At the end of incubation, determination of fluorescein diacetate (FDA) hydrolysis as an indicator of microbial biomass and enzymatic activity in soils, is done by incubating the soil sample with buffer and FDA for 1 to 2 hours (Patle *et al*., 2018). The amounts of fluorescent color formation during the incubation are indicative of the enzymatic activity of the microbial community in the soil sample. The fluorescein diacetate (FDA, mg kg^{-1} soil h^{-1}) activity was then measured calorimetrically at wavelength of 490nm and compared to a standard curve to determine the relative microbial activity in soil samples using FDA (2 mg ml^{-1} acetone) as substrate according to the method described by Patle *et al.* (2018). Fluorescein diacetate is hydrolyzed by a number of different enzymes, such as protease, lipase, and esterase. The product of this enzymatic reaction is fluorescein, which can be envisioned within cells by fluorescence microscopy or measured by spectrophotometry (Patle *et al.* 2018; Khadem *et al*., 2021).

Statistical analysis

Analysis of variance was conducted on the experimental data using a completely randomised block design, with three replicates. The experimental data were computed using the procedures available in the (6.11, SAS Institute, 1996) package. Means comparison was done using Duncan's test at the probability level of 5%. Interrelationships between soil parameters was measured using Pearson's correlation coefficient.

RESULTS AND DISCUSSION

As a sustainable management strategy for sandy soil reclamation projects, water hyacinth biomass as feedstock was converted into biochar and as it has the potential for carbon sequestration and for improving soil physical, chemical and biological quality parameters. Hence, these results provide an overview of the physicochemical properties of water hyacinth biochar and their potential as a carbon sequestration means and soil fertilizer and/or conditioner for reclaiming pristine sandy soils.

Physicochemical characteristics of water hyacinth biochar (WHB).

Results of this research demonstrated that pyrolysis of water hyacinth biochar infested the Nile River and watercourses in Egypt at temperature of 300 °C produced biochar with desirable physicochemical properties for reclaiming sandy soil under arid conditions (Table 2). Pilot studies conducted to optimize the pyrolysis process for the transformation of this abundant biomass into biochar have determined that biochar stable biocarbon and clay plus silt size particles content increased but biochar yield decreased with increasing pyrolysis temperature. Total yield of organic carbon (265.0 g kg^{-1}) and clay + silt fractions (82%) in the resulting water hyacinth biochar was found to be optimal at a pyrolysis temperature 300 °C and a furnace residence time of 30 minutes. In addition, these pyrolysis circumstances have produced suitable biochar as a soil conditioner under arid conditions in terms of biochar physicochemical properties such as pH (6.51), biochar EC (3.31 d Sm^{-1}), CEC (45.6 $cmol_c$ kg^{-1}), bulk density BD (0.25 g cm^3), and water absorption capacity 256. 88%. Therefore, adding biochar with such physicochemical properties to the dominant sandy soils in Egypt can improve their physical, chemical and biological properties under arid conditions. This study demonstrated that biocharring of water hyacinth at low temperature of 300 °C is the dominant factor, suitable for slow pyrolysis, favoring optimum biochar physicochemical characteristics. Cornette *et al*., (2018) indicated that water hyacinth biochar yields negatively correlated (R^2 = 0.93) with increasing pyrolysis temperature. The highest yield of biochar (62.2%) was obtained at 300°C and declined to (35.9%) as the temperature augmented to 550°C. By contrast, Bottezini *et al*., (2021) reported that pyrolyzed water hyacinth biochar (WHCB) at 400 ◦C represents the greatest promising soil conditioner amongst different studied feedstocks, as deduced from its lower aromaticity and C/N ratio and highest P availability.

Literature has reported that biochar can improve soil physicochemical properties, increase soil microbial biomass, plant water and nutrients availability, crop yields, and carbon sequestrations and provide other appropriate agronomic benefits but has minor or no effects on erosion either by wind or water (Abd El-Azeim and Haddad, 2017; Sindhu *et al*., 2017; El-Naggar *et al*., 2019; Blanco-Canqui, 2021). These agronomic benefits induced by biochar rely on raw feedstocks characteristics, temperature range of pyrolysis process, resulted biochar physicochemical characteristics, rates and methods of application, climate, soil properties and other ecosystem aspects (Campos *et al*., 2020). For instance, biochar can improve crop yields more in deteriorated and infertile sandy soils than in fertile and fine-textured clay soils (Sun *et al*., 2020; Huang *et al*., 2021; Thi *et al*., 2021). Masto *et al*., (2013), reported that the ideal state for achieving maximum staple biocarbon by biocharring water hyacinth (WHB) is 300 to 350 °C temperature with 30 to 40 min residence time where water hyacinth biochar yield decreased with increased temperature and time, but biochar carbon stability increased with temperature.

These results indicated that water hyacinth biochar yield declined with the increase in pyrolysis temperature and furnace residence time as the standard biochar yield production (68%) was observed at 300 °C and biochar yield decreased sharply above 300 °C temperature and 40 minutes residence time. Higher pyrolysis temperature increases the rate of dehydration and release of volatile components of biomass, and the tendency to lose biomass through incineration increases with increasing pyrolysis duration (Cornette *et al*., 2018; Garg *et al*., 2020; Luo *et al*., 2020). By contrast, the stable organic carbon in water hyacinth biochar seems to increase with increasing pyrolysis temperature as indicated by the direction of oxidized carbon (OC) in water hyacinth biochar. Similar tendencies had been observed by (Masto *et al*., 2013; Najmudeen, *et al*., 2019; Hussain *et al*., 2020). Loss on ignition biochar organic matter (LOIOM) decreased with increasing temperature and time reflecting the increased ash content of WHB at higher pyrolysis temperatures and the ideal ash content (16.9 %) was observed at 300 °C. Carbon liability index (OC/LOIOM) of water hyacinth biochar (WHB) declined with increasing temperature and pyrolysis duration but stable organic matter (SOM) content of WHB increased with increasing temperature and time as SOM shows a peak at 300°C and subsequently decreased probably due to the increase in ash content.

The initial analysis of biochar elements discloses that it principally comprises carbon (C), oxygen (O), hydrogen (H), ash, and trace amounts of nitrogen (N) and sulphur (S) and most of these elements declined with an upsurge in pyrolysis temperature; attributed to loss of volatile components and dehydration of organic compounds (Gujre *et al*., 2021). By contrast, Biochar produced with higher temperatures of pyrolysis causes increase in the levels of insurgent biocarbon; suggesting maintenance of significantly higher stable biocarbon fractions in soils compared to biochar produced at low temperatures (Shen *et al*., 2019). In addition, biochar produced at high temperatures results in higher surface area and alkaline biochar enhances metal absorption capacities and uptake dynamics (Shen *et al*., 2019; Gujre *et al*., 2021).

Water hyacinth biochar (WHB) surface morphology.

To magnify raw water hyacinth and water hyacinth biochar (WHB) surface morphology, field emission scanning electronic microscopy (FE-SEM) pictures (Figures, 2 and 3) were taken. Field emission scanning electronic microscopy (FE-SEM) is a useful utensil to depict materials composition, surface topography structure, surface morphology, surface area, material porosity which expected to increase sandy soil water and nutrient retention, provide cavities for harboring microorganisms and boosting fertilizer use efficiencies (Allam *et al*., 2020; Bottezini *et al*., 2021). Figure 2 shows the surface topography and morphology of biochar produced from water hyacinth at temperature condition of 300 °C and a burning time of 30 minutes using images of field emission scanning electronic microscope (FE-SEM) at different magnifications (15 kV × 500, 1000 and 3.500). As can be seen by this figure, water hyacinth biochar produced under these conditions encompasses some vacuoles and honey-comb like pores structure which may be attributed to insufficient carbonization and probably catalyzed by biopolymers connected by biomolecular bonds in raw material cells. In addition, the SEM images for WHB displays a heterogeneous rough surface, many pores in honey-comb shape at 15kV × 3500 as well as pores in different shapes, size and depth at different magnifications.

In comparison with water hyacinth raw materials, FE-SEM images (Figure, 3) obtained at the same magnifications for water hyacinth biochar shows major macroscopic changes caused by substantial changes in pore structure, surface area and surface morphology due to insufficient carbonization at 300 °C temperature (Cornette *et al*., 2018; Gujre *et al*., 2021). By contrast, FE-SEM micrographs for water hyacinth powder displayed puffed nonconductive surfaces compared to resulting water hyacinth biochar having high porous surface area and porosity (Figure 3). Increases of biochar stable biocarbon content, fine particle size and surface functional groups (i.e., –OH, –COOH and –CO) had the major impacts on biochar characteristics, mainly allowing increases to soil CEC and ζ-potential of the investigated sandy soils (Lehmann *et al*., 2011; Masto *et al*., 2013; Cornette *et al*., 2018; Luo *et al*., 2020). Many small cavities were seen in corn biochar due to devolatilization at 600 °C and these cavities occur due to volatiles release and intermediate-size organics (Luo *et al*. 2018). After water hyacinth pyrolysis, created micropores on biochar surface is ascribed to release of volatile matters, but inside biochar micropores is owing to trapped volatiles expanding total biochar microstructure (Allam *et al*., 2020; Bottezini *et al*., 2021). These remarks are consistent with many other previous observations for water hyacinth biochar by Masto el al., (2013); Allam *et al*., (2020) and Bottezini *et al*., (2021).

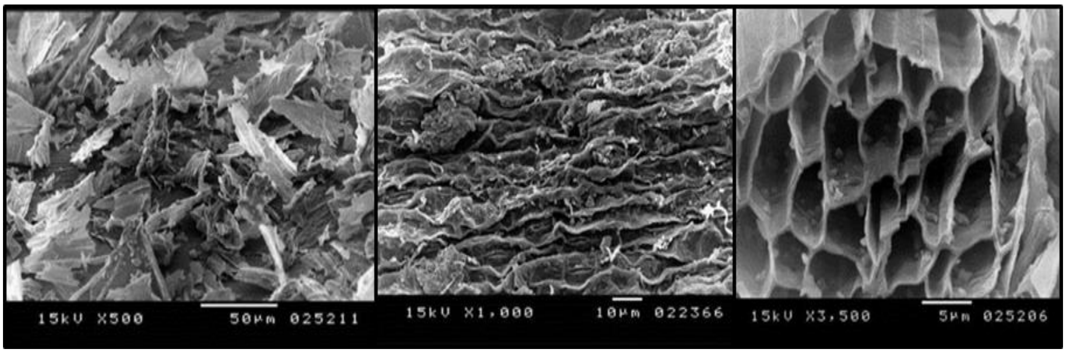

Figure 2. Morphology of water hyacinth biochar surface (SEM images) at different magnifications.

Garg *et al*., (2020) conducted analyses of FESEM and FTIR to understand the morphological structure of water hyacinth biochar. Images of FE-SEM revealed that water hyacinth biochar contains high porosity and specific surface area, while FTIR analysis indicates three major surface functional groups (i.e., –OH, –COOH and –CO) on the biochar particles. These functional groups indicate that the biochar produced from locally collected water hyacinth is porous and hydrophilic in nature.

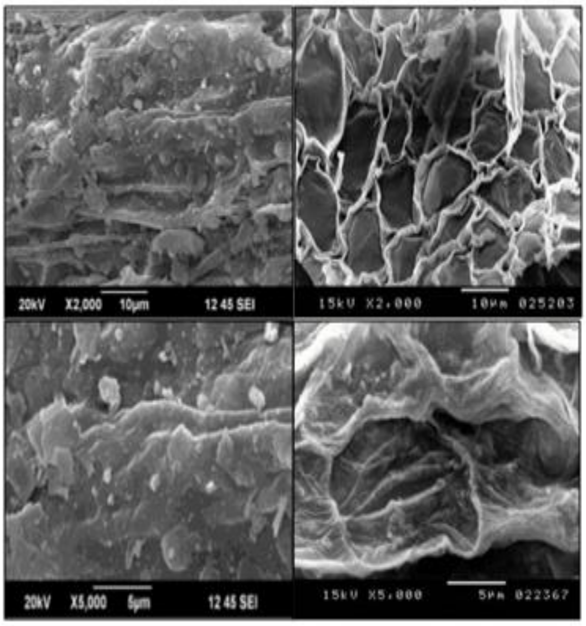

Figure 3. Comparison between raw water hyacinth powder and water hyacinth biochar using scanning electronic microscopy (SEM) images at the same magnifications.

Zeta ζ-potentials of sandy soil as affected by biochar addition.

In this study, sandy soil zeta potential peaks as affected by biochar addition either incorporated or broadcasting were determined (Figure 4). Results reported that zeta potentials of biochar addition to sandy soils showed similar trends and biochar addition produced higher negative zeta potentials than control. Sandy soil scale of zeta potential peaks of biochar incorporated addition was significantly higher than that of biochar broadcasting. There is inadequate data presented on how physicochemical parameters such as zeta potential (ζ) of a sandy soil changes in the company of biochar under arid conditions. As illustrated by figure (4), incorporation addition of biochar at 3% application rate vindicated sandy soils to have significant increases of negative zeta ζ-potential values (-18.7mV Figure 4C) compared to control (-8.5mV Figure 4A). Whereas, the scale of zeta ζ-potentials peaks somewhat decreased (-15.1mV Figure 4B) when biochar mulched over sandy soils. Changes in sandy soil zeta potentials can be described by mechanisms going on between soil particles and biochar functional surface groups leading to more negative zeta ζ-potential developments in treated sandy soils with water hyacinth biochar. As expected, since the application rate of biochar increases, zeta ζ-potential peaks of sandy soils become more negative. Also, soil reaction (pH) of the treated sandy soils is significantly decreased in the company of biochar and the increase in biochar rates alters the pH of the soil solutions during zeta potentials measurements.

Understanding soil zeta potential variations with biochar addition is important because it controls the magnitude of soil nutrients solubility, availability, leachability and sorption-ability, which plays an important part in sandy soil fertility. The practical implications of zeta potential measurements with various biochar rates will help to not only understand soil physicochemical reactions at the double layer interface but also to manipulate such interactions to improve sandy soil fertility. This is important to increase nutrient adsorption and to avoid leaching and precipitation of nutrients during fertigation process in sandy soils.

The incidence of biochar increased zeta ζ-potential of the investigated sandy soils making them more surface negative charged in comparison with the control treatments. Increases of biochar application rates as incorporating might increase stable soil biocarbon content, fine particle size and micropores. In addition, biochar surface functional groups for example, –CO, –OH and –COOH may have significant impacts on soil-biochar mixtures characteristics enabling increases in sandy soil CEC and zeta ζ-potential (Luo *et al*., 2018). However, adding biochar as broadcast has little effect on sandy soil zeta ζ-potential and other soil physicochemical characteristics probably due to incomplete mixing of biochar into soils and biochar tendency to float above the soil surface. Similar explanations were attained by Lehmann *et al*., (2011); Masto *et al*., (2013); and Luo *et al*., (2018) who found that the biochar additives to soils produced more negative zeta ζ-potential than untreated soils.

In conclusion, when applied to sandy soils under arid conditions, water hyacinth biochar will be exposed to harsh climate with numerous interactions, thus, the stability of organic matter in applied biochar is very critical. The maximum staple organic matter (SOM = 201.14 g kg^{-1}) with water hyacinth biochar (WHB) yield (68%) were observed at 300 °C and 30 min burning duration. Nevertheless, for organic carbon storage in sandy soils under arid conditions, stable organic matter yield is more critical than its total concentration in biochar. The biochar stable organic matter yield index (BSOMYI) increased up to 300°C, and then decreased with increasing temperature. In addition, calculated BSOMYI was decreased with temperature degrees above 300 °C and increasing pyrolysis duration. Highest biochar stable organic matter yield index of 136.77 g kg^{-1} was obtained at 300 °C. In addition, results indicated that the optimum biochar organic carbon content (265.00 g kg^{-1}) and biochar staple organic matter content (201.14 g kg^{-1}) tends towards reasonable pyrolysis conditions of 300 °C and 30 min burning duration.

As the goal behind biochar application to sandy soils under arid conditions is to improve soil fertility and organic matter content, the ideal conditions were found to be burning biochar at 300 °C for 30 min. Masto *et al*., (2013) recommended a low temperature moderate pyrolysis (300–350 °C, 30–40 min) conditions for production of water hyacinth biochar from water hyacinth biomass. Water hyacinth biomass pyrolytic to biochar is a renewable energy resource with many utilities and many marketable activated carbons and other fine materials at lower wholesale price compared to raw biomass. These utilities consist of high storability, hydrophobicity, ease of handling and transportation, and high millability. Biochar's applications are not limited to dense energy; they also comprise soil ecosystem services, water purification and pollutants decontamination (Liang *et al*., 2019; Amer *et al*., 2020; Pradhan *et al*., 2020; Huang *et al*., 2021).

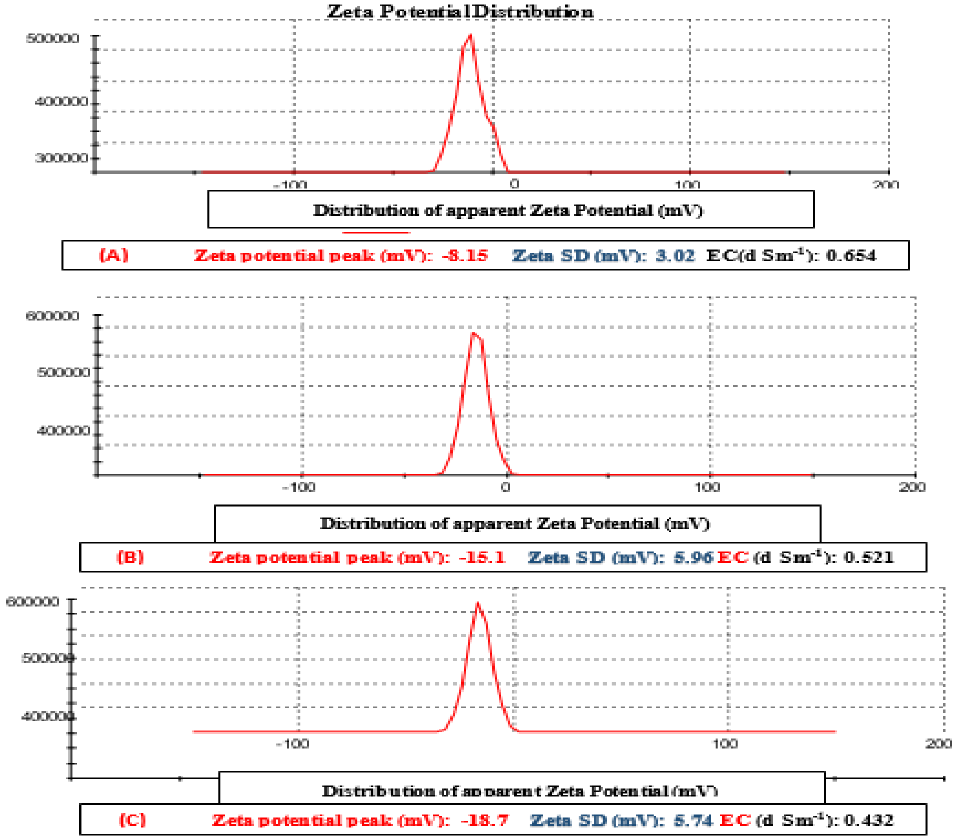

Figure 4. Sandy soil zeta potential peaks as affected by biochar addition. A). Control, B. Biochar broadcasting addition, C). Biochar incorporating addition.

Soil biochemical properties as affected by biochar addition.

Soil reaction (pH), electrical conductivity (EC), organic matter (O.M), cation exchange capacity (CEC), soil organic carbon (SOC), carbon pool index (CPI), dissolved organic carbon (DOC) and dissolved organic carbon (DON) were significantly ($P < 0.05$) affected by biochar incorporation or broadcasting additions (Table 3) compared to control. Generally, at a perusal of results represented in Table (3), a significant use impact of water hyacinth biochar was observed on the investigated sandy soil biochemical quality parameters compared to untreated soils. Soil biochemical characteristics of the investigated sandy soil after sort-term incubation exposed obvious significant improvements at all biochar treatments. The experimental results showed among different biochar application rates and methods of application, biochar addition as incorporation at the rate of 3% resulted in higher significant increases in most tested soil parameters compared to other treatments. Incorporation addition of water hyacinth biochar significantly decreased soil pH by 0.15, 0.29, 0.53 units, at the application rates of 1%, 2%, and 3%, respectively. Whereas, biochar addition as broadcasting at equal rates of 1%, 2%, and 3% decreased soil pH slightly but also significantly compared to control. By contrast, the slight decreases in sandy soil pH following biochar broadcasting addition are mainly due to most of biochar was floating above soil surface due to its low bulk density. The decrease in sandy soil pH by water hyacinth biochar addition either incorporating or broadcasting can be mainly attributed to incomplete raw water hyacinth burning, lower biochar pH and less ash contents in addition to low pH sandy soil buffering capacity.

Lehmann *et al*., (2011) reported that oxidation of biomass carbon forming carboxyl groups could also explicate the decrease in soil pH, while increases in soil pH were probably akin to the dissolution of alkaline cations in biochars rich with ashes. Naeem *et al*., (2018), reported decreases in soil pH with wheat straw biochar addition to a calcareous soil over 50 weeks incubation period (Naeem *et al*., 2018). Nevertheless, because of high pH Aridisols buffering capacity, biochar addition had no impact on Aridisols soil pH (Elzobair *et al*., 2016). Despite concerns about increasing soil pH by applying highly alkaline biochars, their effects on soil pH have been minimal (Blanco-Canqui, 2021; Thi *et al*., 2021). Transformation of water hyacinth to biochar signifies a standby sustainable strategy for managing this recalcitrant aquatic weeds. Biochar from water hyacinth biomass will boost carbon storage, soil fertility, and thus become a valuable organic resource for sandy soils reclamation projects (Jeffery *et al*., 2011; Thi *et al*., 2021).

Table 3. Some soil biochemical properties as impacted by water hyacinth biochar addition as incorporation and broadcasting.

Treatment		pH (1:2.5 water)	EC dS m^{-1}	O.M (g kg^{-1})	CEC ($cmol_c$ kg^{-1})	SOC (g kg^{-1})	Carbon pool index (CPI g kg^{-1})	DOC (mg kg^{-1})	DON (mg kg^{-1})	DOC: DON
Control		8.41a*	1.73a	4.67a	4.22a	2.68a	1a	18.34a	7.81a	2.34a
Incorporation	Inc. 1%	8.26b	2.01b	9.21b	6.44a	18.52e	6.47b	73.38e	18.68bc	3.93b
	Inc. 2%	8.12c	2.22b	9.10b	7.39ab	21.07cde	7.86bc	96.74f	22.77b	4.24b
	Inc. 3%	7.88e	2.66c	11.14b	9.08b	23.46b	8.75c	104.98f	24.21b	4.33b
Broadcasting	Bro. 1%	8.31b	1.88ab	5.64a	6.82a	19.69de	7.34bc	43.44b	11.78ad	3.68b
	Bro. 2%	8.24db	1.99ab	6.37a	7.44ab	20.99bcd	7.83bc	60.46bc	15.17d	3.98b
	Bro. 3%	8.05c	2.11ab	6.23a	8.03ab	22.56bc	8.41bc	76.31d	19.01c	4.01b

*** Figures in a Column followed by the same letters are insignificantly different (*P* < 0.05).**

Even though the addition of water hyacinth biochar (WHB) with either incorporation or broadcasting addition resulted in significant increases ($P < 0.05$) in the examined sandy soil EC; and that EC values increased with increasing application rates; these impacts were of trivial importance. Since the total pristine sandy soil EC value is less than 2.66 dS m^{-1} even at the higher water hyacinth soils incorporated with biochar at 3% application rate, which is much smaller than the edge of 4 dS m^{-1} between saline and un-saline soils. Soil addition of water hyacinth biochar increased sandy soil EC to only 2.66 and 2.11 dS m^{-1} at 3% application rate in both incorporation addition and broadcasting when compared with the control (1.73 dS m^{-1}).

Soil-incorporated water hyacinth biochar (WHB) plays a major role in the increase of sandy soil EC due to complete mixing of water-soluble alkaline cations compared to broadcasting-addition. Raised up sandy soil EC values with different biochar addition methods and application rates could be owing to biochar high content of alkaline cations and ash (29.9%) and then the dissolution and hydrolysis of basic cations in soil solution. Masto *et al.* (2013) reported that soil EC displayed slight elevations with water hyacinth biochar addition, which unexceed the critical level of 4 dS m^{-1} for EC in calcareous soils with relatively high $CaCO_3$ content and buffering capacity.

Given that the investigated sandy soil was alkaline (pH = 8.41), the resulting pH decreased to 7.88 in the case of biochar incorporated at 3% and 8.05 at the same rate as broadcasting, are likely to have a beneficial effect on sandy soil microbial activity, fertility and crop growth. Consequently, produced low-temperature water hyacinth biochars could be safely added to this sandy soil as an organic amendment without a serious threat for soil salinization or alkalinity. Nevertheless, soil pH and EC of biochar-amended soils are expected to increase for a measurable effect on plant and soil biota in the long-term with biochar aging and frequent addition (Backer *et al.* 2016). Further field research is required to establish longer term impacts of these biochars on the pH and EC of these calcareous sandy soils.

Impacts of water hyacinth biochar addition to sandy soil either incorporated or broadcasting at different application rates on some labile soil biochemical and biological properties were determined under incubation conditions (Table 3). Biochar application at different rates caused obvious significant changes in sandy soil OM, CEC, SOC, DOC, and DON compared to control. Levels of OM, CEC, SOC, DOC, and DON were significantly increased as the application rate increased as incorporation addition compared with broadcasting. Ratio of the studied microbial indicator namely DOC: DON followed the same trend as relative biochemical properties being greatest in biochar incorporation addition, broadcasting and minimal in control treatment.

In addition, sandy soil concentrations of organic carbon (SOC) and labile organic fractions such as dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) were significantly influenced by different application rates of water hyacinth biochar. Means of SOC ranged from 18.52 to 23.46 g kg-1 across different biochar treatments, where SOC levels were significantly greater in biochar treatment as incorporation (Inc 3%, 23.46 g kg-1) followed by biochar broadcasting (Bro. 3%, 22.52 g kg-1), and control (0.0%, 18.49 g kg-1). Whereas, means of dissolved organic carbon (DOC) ranged from 18.34 to 104.98 mg kg-1, recording obvious significant increases in biochar incorporating treatments over biochar broadcasting treatments.

Based on changes in soil organic carbon contents (SOC) between amended soils with water hyacinth biochar either incorporating or broadcasting and unamended control, a carbon pool index (CPI) was calculated as total SOC in amended soils divided by the corresponding SOC in the untreated soil (Calderón et al. 2015). The carbon pool index (CPI) indicates the significant effects of adding water hyacinth biochar on the accumulation of total organic carbon in sandy soils. Therefore, in this incubation trial, CPI is used to infer biochar potentials for carbon sequestration following biochar application to sandy soils under arid conditions.

Along with increasing sandy soil fertility and improving soil health under arid conditions, soil application of water hyacinth biochar is primarily aimed at increasing carbon sequestration to mitigate austere climate change. In both methods of application, the soil CPI values after biochar addition were significantly higher than those of control treatments, and tended to increase consistently from 1%, 2% to 3% biochar rates of application. These results indicated that water hyacinth biocharring would greatly improve soil carbon sequestration, especially at high application rates and coarse textured sandy soils. By contrast, high carbon sequestration potentials were found in biochar-amended soils also at higher application rates but at fine-textured clay soils more than coarse-textured soils (Khadem et al., 2021). Moreover, Khadem et al., (2021) reported a significant correlation between soil CPI values and pyrolysis temperatures as high temperature produced biochars with more stubborn and stable biocarbon nature related to their high aromatic concentration. Biochars with low atomic ratios of H/C and O/C has an essential advantage of increasing the sequestering capacity of soil carbon. It could be concluded from these results that water hyacinth biochar produced at 300 °C and 30 min residence time could have higher C sequestration potentials to mitigate climate change under arid conditions, particularly when incorporation applied at high application rates. In contrast, numerous studies revealed that biochars pyrolyzed at higher temperatures have more C sequestration potential than low-temperature biochars (Ouyang et al. 2014; Khadem *et al.*, 2021).

Biochar addition enhanced SOC, DOC and DON levels in sandy soil under investigation reflected in higher microbial and enzyme activities and these positive effects has been confirmed in many literature (Song *et al*., 2019; Bottezini *et al*., 2021). Biochar addition increased soil organic carbon (SOC), dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) and these increases are used as a labile substrate of C and N for soil microorganisms nutrition and plant uptake (Cornette *et al*., 2018; Garg *et al*., 2020; Luo *et al*., 2020).

Soil biological properties as affected by biochar addition.

After incubation, soil biological properties studied were microbial biomass counts of bacteria and fungi, soil fluoresceine diacetate (FDA) hydrolysis activity, microbial biomass-C ($C_{\text{-MIC.}}$), microbial biomass-N ($N_{\text{-MIC.}}$) and microbial biomass-P ($P_{\text{-MIC}}$). Impacts of different methods of water hyacinth biochar addition on sandy soil microbial biomass counting of bacteria and fungi at different application rates are displayed in Table (4). After soil incubation, means of bacteria or fungi counts were significantly higher in soils treated with biochar as incorporating compared to biochar broadcasting and control reflecting different soil microbial biomass activities. The levels and trends in total counts of bacteria and fungi among different treatments were in the order of biochar addition as incorporation at all rates of 1%, 2% and 3% > broadcasting at all application rates of 1%, 2% and 3% > untreated sandy soils. Obvious and significant observations were detected in sandy soil counts of bacteria and fungi due to different biochar application rates and methods. The increases in these soil biological parameters provided further evidence of healthier conditions for soil microbial biomass in biochar amended sandy soils (Khadem *et al*., 2021) compared to untreated sandy soils. The poor effects of adding water hyacinth biochar on sandy soil surface compared to mixing with soil on microbial and biological properties may be attributed to the buoyancy of biochar above sandy soil. By contrast, biochar incorporated caused rapid release, diffusion and dispersal of biochar components in sandy soil pores causing increases in soil microbial activities.

Microbial biomass carbon ($C_{\text{-MIC}}$) means ranged from 17.86 to 42.48 mg kg^{-1}, microbial biomass nitrogen ($N_{\text{-MIC}}$) ranged from 13.07 to 28.45 mg kg^{-1}, and microbial biomass phosphorus ($P_{\text{-MIC}}$) ranged from 8.11 to 21.75 mg kg^{-1}, reflecting apparent enhancements in between different biochar addition methods and rates (Table 4). The highest significant levels of $C_{\text{-MIC}}$, $P_{\text{-MIC}}$, and $N_{\text{-MIC}}$ were recorded in the incorporation treatment at 3%. After incubation, results of this research revealed that $C_{\text{-MIC}}$, $P_{\text{-MIC}}$, $N_{\text{-MIC}}$, soil bacterial and fungi counts values were relatively lower in treated sandy soils with biochar as mulching compared to incorporating. One conceivable reason to explicate why biochar addition on the studied sandy soil surface produces marked decreases in most biochemical and microbial properties. Existence of water hyacinth biochar above soil surface resulted in significant reductions in readily metabolizable carbon (SOC and DOC) needed by soil microorganisms to increase soil microbial biomass counts of bacteria and fungi and consequently enzyme activities and assuredly the reverse was happened in sandy soil-biochar mixtures. This proves that the most significant factors affecting soil microbial biomass activities in soils are the availability of dissolved organic substrates as reflected by strong intercorrelations between microbial biomass-C and -P with dissolved organic substrates in soils (Khadem *et al*., 2021).

Water hyacinth biochar provided immediate nitrogen and carbon via higher DON, SOC and DOC in sandy soil compared to control, and this yet provided energy for microbial biomass C, N and P that reflected by increases in soil values of $C_{\text{-MIC}}$ $N_{\text{-MIC}}$ and $P_{\text{-MIC}}$. Positive high significant intercorrelations ($P < 0.05$; $n = 24$) were obtained between $C_{\text{-MIC}}$, $N_{\text{-MIC}}$ and $P_{\text{-MIC}}$ vis-à-vis soil biochemical properties for instance $C_{\text{-MIC}}$ and SOC ($r = 0.87$), DOC ($r = 0.77$) and DON ($r = 0.67$); $P_{\text{-MIC}}$ and SOC ($r = 0.67$), DOC ($r = 0.75$) and DON ($r = 0.68$); $N_{\text{-MIC}}$ and SOC ($r = 0.81$), DOC ($r = 0.71$) or DON ($r = 0.69$).

Table 4. Total counts of bacteria and fungi, FDA hydrolysis activity and some soil biological properties as affected by water hyacinth biochar addition.

Treatment		Total Counts of Bacteria and Fungi, FDA and Soil Biological Properties					
		Total counts of Bacteria ($\times 10^{6}$ cfu g^{-1})	Total counts of Fungi ($\times 10^{4}$ cfu g^{-1})	FDA hydrolysis activity (mg kg^{-1} soil h^{-1})	$C_{\text{-MIC}}$ (mg kg^{-1})	$N_{\text{-MIC}}$ (mg kg^{-1})	$P_{\text{-MIC}}$ (mg kg^{-1})
Control		28.77^{e}	16.33^{e}	66.67	17.86f	13.07^{d}	8.11^{d}
Incorporation	Inc. 1%	47.24^{c}	38.77^{bc}	80.45	32.70de	24.13^{b}	17.44^{c}
	Inc. 2%	55.23^{b}	40.03^{abc}	109.75	39.99cd	27.62^{a}	18.74^{c}
	Inc. 3%	62.17^{a}	44.73^{ab}	143.25	42.48d	28.45^{a}	21.75^{b}
Broadcasting	Bro. 1%	44.60^{cd}	26.23^{d}	74.89	32.47bc	18.22^{c}	14.46^{a}
	Bro. 2%	46.33^{c}	33.97^{c}	89.25	34.75ab	19.11^{c}	15.48^{a}
	Bro. 3%	47.23^{c}	38.77^{bc}	91.56	34.44a	23.12^{b}	19.44^{b}

*** Figures in a Column followed by the same letters are insignificantly different (*P* < 0.05).**

Finally, water hyacinth biochar addition to sandy soils recorded significantly higher rates of $C_{\text{-MIC}}$, $P_{\text{-MIC}}$, microbial biomass activity (bacterial and fungal counts) and hydrolysis activities of FDA owing to the additive impacts of biochar. Biochar addition to sandy soils whether incorporating or broadcasting recorded higher rates of $C_{\text{-MIC}}$, $P_{\text{-MIC}}$, $N_{\text{-MIN}}$, SOC, DOC, bacterial and fungal counts, and FDA activities compared to control. Biochar soil addition as incorporating might espouse the positive effects of both effects on microbial activity as evidenced by the paralleled levels of soil biochemical and microbial biomass properties at all application rates compared to biochar addition as broadcasting. This indicated that biochar type, production conditions, application rates and methods affected these sandy soils properties in different ways probably due to changes in soil dissolved organic substrates and soil microorganism's growth environment.

After incubation, sandy soil fluoresceine diacetate hydrolysis activity (FDA) arraigned to biochar addition either incorporating or mulching (Table 4). The FDA hydrolysis activity values were significantly (P < 0.05) higher in biochar amended soils either incorporated or mulched at all application rates compared to control. These results indicated that biochar addition triggered the microbial activity in treated sandy soils compared to control with little organic substrates available for microbial degradation. Bhaduri *et al*., (2016) and Bottezini *et al*., (2021) reported similar results of soil FDA significant increases induced by significant increases in total SOC, labile DOC and labile DON, soil microbial biomass and improve soil physical properties. Soil FDA hydrolyzing activities were highly stimulated as the application biochar rate increased either incorporated or broadcasted over soil surface. Furthermore, soil FDA hydrolysis activity was significantly stimulated by biochar incorporating addition compared to biochar mulching. Similar results were obtained by Masto *et al*., (2013) reported that hydrolytic enzymes like FDA were increased in biochar added soils and the maximum FDA activity increase was 50% occurred at the highest water hyacinth rate of 20 g kg^{-1} soil. By contrast, Chintala *et al*., (2014) reported that maize biochar at application rates of 1 and 5% in a short-term incubation study declined soil FDA by 23% in clay and sandy loam soils, while Nielsen *et al*., (2014) reported no changes in FDA soil activity following biochar application under field conditions and attributed these results to recalcitrant nature of biochar and soil acidic conditions.

The increase in sandy soil microbial biomass and microbiological activities is partially ascribed to higher labile substrates of C and N availability as well as improved sandy soil physical properties conditions following water hyacinth biochar addition. The stimulating effect of water hyacinth biochar is supposed to be due to higher soil content of SOC, DOC, DON, C_{-MIC}, N_{-MIC}, P_{-MIC} compared to control. In addition, the large surface area and negative surface functional groups of biochar provided a favorable microenvironment conditions for microorganisms and more nutrients availability for microorganism's utilization. In general, these results confirmed the role of water hyacinth biochar as a source of labile organic substrates contributing to improvement in sandy soil biochemical and biological properties. Although, water hyacinth biochar contains high amounts of staple organic carbon resistant to microbial decay due to their high aromaticity, these results indicated that water hyacinth biochar is a nutrient-rich organic amendment providing some labile substrates for soil vigorous microbial and enzymatic activities and soil health improvements.

CONCLUSION

This study confirmed that transforming the abundant water hyacinth biomass in the Nile River into biochar and then adding this biochar to the vast areas of sandy soil existing in Egypt so far can convert these aquatic weeds into a valuable organic matter resource for improving sandy soil physical, chemical and biological properties. Yield of the stabilized organic carbon fraction in the resulting water hyacinth biochar was found to be optimal at a pyrolysis temperature of 300 °C and a furnace residence time of 30 minutes. Sandy soil biochemical and microbiological parameters were significantly increased at different water hyacinth biochar (WHB) application rates and varied markedly between addition of biochar as incorporation and broadcasting. All these soil parameters were significantly greater in sandy soils incorporated with biochar and biochar broadcasting compared to control treatment. Further research under field conditions is required to establish longer term impacts of these water hyacinth biochars on physicochemical properties of these sandy soils.

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تقييم الفحم الحيوي من ورد النيل كمحسن للأراضي الرملية

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يعتبر استخدام الفحم النباتي المنتج من نباتات ورد النيل كمحسن للتربة وكمصدر للمغذيات والكربون العضوي حيلة فعالة للقضاء على هذه الحشائش المائية ذات المضار الكثيرة والسريعة الانتشار. يهدف هذا البحث إلى تقييم آثار إضافة الفحم الحيوي لنباتات ورد النيل بمعدلات وطرق مختلفة على بعض الخصائص البيوكيميائية والبيولوجية للتربة الرملية وإمكانية مصادرة الكربون للتخفيف من حدة التغيرات المناخية. أظهرت النتائج أن التحلل الحراري لنباتات ورد النيل عند درجة حرارة ٣٠٠ درجة مئوية و٣٠ دقيقة داخل الفرن أدي الي انتاج الفحم الحيوي بالخصائص الفيزيائية والكيميائية المرغوبة. تُظهر صور المسح الإلكتروني (FE-SEM) التي تم الحصول عليها للفحم الحيوي لورد النيل تغييرات كبيرة ناتجة عن تغييرات كبيرة في البناء المسامي ومساحة السطح ومورفولوجيا السطح بسبب الكربنة غير الكافية. كشفت النتائج بعد التحضين أن الخصائص البيوكيميائية والمكروبيولوجية للتربة تحسنت بشكل ملحوظ وواضح عند جميع معدلات الإضافة من الفحم مقارنة بالكنترول وتفاوتت بشكل ملحوظ بين إضافة الفحم الحيوي بطريقة الخلط مع التربة عن الإضافة على السطح. من بين المعاملات المختلفة، أدت إضافة الفحم الحيوي بالخلط مع التربة بنسبة ٣٪ إلى زيادات معنوية أعلى مقارنة بمعظم معاملات التربة المختبرة. اضافة الفحم الحيوي للتربة الرملية ادي الي زيادات فورية في النيتروجين والكربون الميسر عبر الزيادات في DON وSOC وDOC مقارنة بالكنترول، وهذا يوفر الطاقة اللازمة للكتلة الحيوية الميكروبية للكربون والنيتروجين والفوسفور والتي تنعكس علي زيادة قيم التربة في N_{-MIC} C_{-MIC} وP_{-MIC}. بالإضافة إلى ذلك، فإن تحويل نباتات ورد النيل الي الفحم النباتي من شأنه أن يحسن بشكل كبير مصادرة الكربون ف ي التربة الرملية خصوصا عند استخدام معدلات الإضافة العالية. يمثل تحويل نباتات ورد النيل إلى الفحم الحيوي استراتيجية مستدامة لإدارة هذه الحشائش الضارة وبالتالي تصبح موردًا قيمًا للمادة العضوية في التربة الرملية وسيعزز من مصادرة الكربون.

الكلمات الدالة : الفحم الحيوي لورد النيل، مصادرة الكربون، الانحلال الحراري.