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Biochar production from wastewater sludge for application in sustainable lettuce plant cultivation and climate change mitigation †

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Abstract: Compared with conventional soil additives, biochar has found successful application as an organic soil amendment to improve crop productivity coupled with climate change mitigation via carbon sequestration. This study investigated the synthesis of biochar from wastewater sludge, followed by its application for lettuce plant growth. Biochar was added to the soil at three rates of 2.5%, 5%, and 10% (w/w) using pot experiments under greenhouse conditions. Biochar application demonstrated an economic feasibility scenario with a payback period of 0.89 years. Hence, the study outcomes would contribute to eco-friendly crop management, soil conservation, and combat climate change, providing a reliable strategy for achieving targets of SDG 2 "Zero hunger," SDG 13 "Climate action," and SDG 15 "Life on land."

Keywords: CO_2 sequestering; Economic feasibility; Pyrolysis; SDGs; Soil amendment

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1. Introduction

Sludge is an unavoidable by-product of wastewater physico-chemical treatment [1]. This sludge primarily contains a matrix of organic and inorganic hazardous substances [2]. Hence, its uncontrolled disposal introduces persistent residual pollutants into the environment. Moreover, due to environmental concerns, most countries have limited conventional sludge disposal methods based on direct application in agricultural land, landfilling, incineration, and ocean dumping [3]. Therefore, recycling wastewater sludge is essential for protecting the environment and climate change mitigation.

Biochar is a solid, carbon-rich product derived from the thermochemical conversion of biomass (e.g., animal manures, agricultural wastes, wastewater sludge, and other waste products) under oxygen-limited conditions via pyrolysis [4]. Biochar contributes to carbon sequestration, reducing greenhouse gas (GHG) emissions, improving soil properties, and adsorbing organic and heavy metal pollutants [5]. In recent years, biochar has attracted significant attention as a material for soil amendment due to its several benefits, such as nutrient and water retention and soil fertility improvement [1]. It has also been reported that biochar application could improve soil's structural and physicochemical properties, such as nutrient and water-holding capacity, bulk density, cation exchange, and pH, which is beneficial for plant growth, especially in acidified soils [5].

Lettuce is an essential herbaceous plant used as a food salad and in traditional medicines [6]. Lettuce accounts for a large proportion of short-cycle leafy vegetables produced in greenhouses worldwide. The plant contains vitamins such as A, B, C, and E and a large amount of fiber and iron, which are well known for physiological importance, such as antioxidants and anti-inflammatory [4]. Despite scientific investigations on the application of biochar derived from various waste residues as a soil amendment agent for lettuce growth [6]; a research gap exists in the literature regarding the recycling of coagulation sludge for biochar preparation and application for lettuce cultivation.

Therefore, this study aimed to assess the potential of biochar derived from wastewater sludge as a soil amendment agent for lettuce plant cultivation to allow for "zero-waste-discharge" and "waste-to-wealth" frameworks. Precisely, the objectives of this study are threefold: (1) investigate the effects of biochar application to soil on the growth of lettuce plants, (2) determine the environmental and economic feasibility of the proposed farming practice, and (3) determine the sustainability of implementing the proposed practice in terms of the achievable sustainable development goals (SDGs).

2. Materials and methods

2.1. Wastewater sludge and biochar production

Sludge obtained from the coagulation of automobile service station wastewater was used as the feedstock for biochar production [2]. The raw sludge was dried in an oven at 100 °C for 24 h. Dried sludge was then pyrolyzed at 500 °C for 1 h in a muffle furnace (ASH AMF-25 N, Japan) with a heating rate set at 5 °C/min to produce biochar. The produced biochar sample was then passed through a 2-mm sieve. The surface morphology, main elemental composition, and the pore size distribution of the prepared biochar have been reported in our previous study [2]. The biochar's pH and electrical conductivity (EC) were determined by a digital meter (Jenway 3510 pH meter, USA) after mixing the biochar sample with ultrapure water in a ratio of 1:10.

2.2. Soil sampling and analysis

The surface soil (taken at a depth of 0-20 cm) samples used in this study were collected from Borg El-Arab City, Alexandria, Egypt. The samples were oven-dried at 105 °C for 24 h, ground, and passed through a 2 mm sieve. The pH and EC were measured similarly to the biochar samples, but the soil-to-ultrapure water mixing ratio was 1:5 (w/v). The moisture content, total organic matter, and ash contents were measured, following standard procedures of the American Society for Testing and Materials [7]. The soil texture was classified following a criteria by the U.S. Department of Agriculture soil taxonomy based on hydrometer analysis. Cation exchange capacity (CEC) was determined using barium chloride following a procedure reported by Carter et al. [6].

2.3. Experimental design

The effect of biochar application on lettuce growth was investigated using pot experiments under greenhouse conditions (temperature 26±2°C, relative humidity 75-88%, and light:dark period 14:10 h) for 35 days. Lettuce seeds were sown in the seed tray for 14 days, after which each seedling was transplanted into a plastic pot (9 cm diameter, 9 cm depth). Soils in the pots were amended with biochar at different application rates (2.5, 5, and 10% w/w), while the control pots received no sludge biochar (i.e., 0% w/w). After transplanting, each pot was irrigated with 150 mL daily, depending on the prevailing weather conditions to avoid water stress.

2.4. Plant growth and quality investigation

The plant morphological analyses were executed weekly by measuring the main leaf parameters, including leaf number (LN) and plant height (PLH). Moreover, after 35 days of growth, yield parameters of the fresh and dry weight of roots and fresh and dry weight of shoot were measured on the harvest.

2.5. Statistical analysis

Data were analyzed by one-way analysis of variance (ANOVA) using SPSS (IBM SPSS Statistics version 19.0). A post hoc test was performed using Tukey's honestly significant difference (HSD) at the 5% significance level. A *p*-value < 0.05 was considered statistically significant.

3. Results and discussion

3.1. Biochar and soil characterization

The physico-chemical properties of wastewater sludge-derived biochar and soil samples are summarized in Table 1. These results indicated that the soil samples used in this experiment had low fertility. Hence, biochar with promising soil nutrient elements, surface morphology, CEC properties, and pore size distribution was applied to improve fertility.

Table 1. Physicochemical properties of biochar and soil samples before pot experimentation.

Biochar sample		**Soil sample**		
Parameter	Value	Parameter		Value
pH (1:10 H_2O)	7.8	Texture (%)	Sand	70
EC (dS/ m)	0.72		Silt	12
N-total (g/kg)	7.6 ± 0.3		Clay	18
P-total (g/kg)	14.1 ± 2.4	Water content (wt%)		20.8
C-total (g/kg)	766.8±11.5	pH (1:5 H_2O)		6.2
Alkalinity (%$CaCO_3$)	15.3 ± 0.9	EC (dS/m)		0.2
CEC (cmol/kg)	19.4 ± 1.3	Ash content (%)		90.8
		Organic matter (%)		1.1
		N-total (g/kg)		1.5 ± 0.1
		P-total (g/kg)		0.3 ± 0.0
		C-total (g/kg)		10.2±0.8
		CEC (cmol/kg)		29.8 ± 1.8

3.2. Effects of biochar on plant growth characteristics

From Figure 1a, the plant agronomic performance based on height was increased over the control as biochar application rates increased. Furthermore, the highest plant height was achieved with a biochar application rate of 10%. However, increasing the rate above 5% did not significantly improve ($p > 0.05$) the lettuce height.

Regarding the number of plant leaves, enhancing the biochar application rate resulted in an increased number of leaves (Figure 1b). For instance, with increasing levels of biochar from 2% and 3%, the leaf number increased sharply by 7 and 17.7% over the control. The most leaves were found at 10%, while the lowest was obtained in the control.

Other considered parameters used to assess the plant growth at the maturity stage maturity included fresh shoot weight, shoot dry weight, fresh root weight, and root dry weight (Figure 2). The shoot biomass for lettuce on both fresh (Figure 2a) and dry weight (Figure 2b) basis significantly increased with biochar addition to 5%. For instance, the shoot biomass of lettuce increased by 41% and 59% in the soil amended with biochar at 2.5% and 5%, respectively. Biochar addition at 10% showed no significant effect ($p > 0.05$) on the shoot biomass of lettuce. The fresh root weight was significantly enhanced ($p < 0.05$) with increasing levels of biochar addition (Figure 2c). The root dry weight reached a maximum at 5% biochar treatment and attained a constant value for 10% biochar addition (Figure 2d). In general, 5% biochar application to unfertile soil significantly impacted the agronomic properties of lettuce and would thus be applied on large-scale farms for commercial lettuce production.

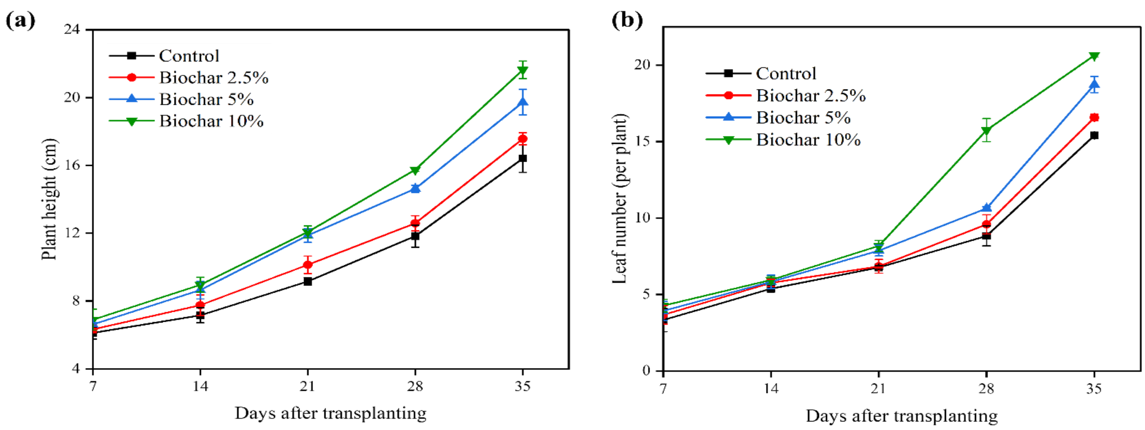

Figure 1. Effect of biochar application rates on (a) plant height, and (b) leaf number.

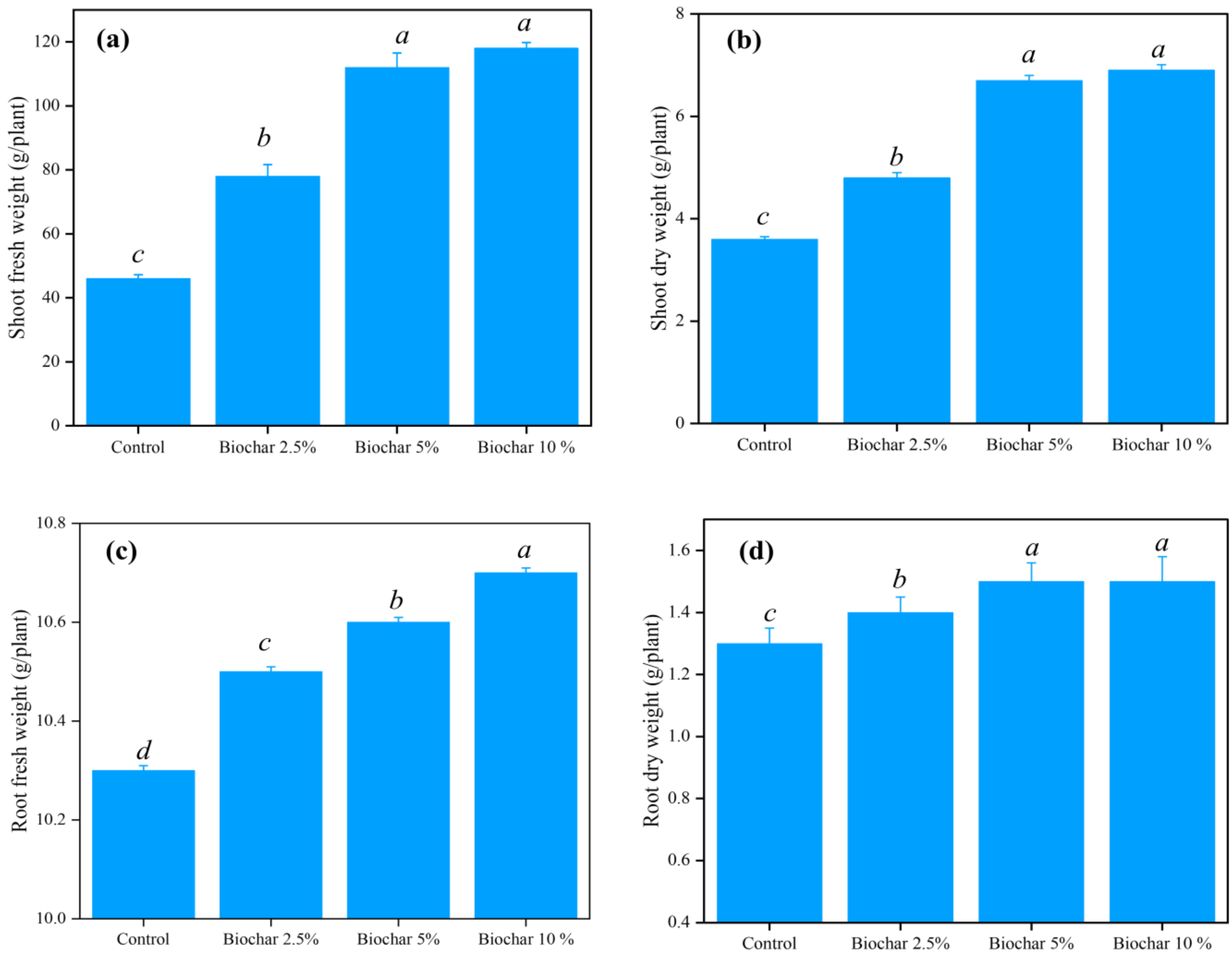

Figure 2. Effect of biochar application rates on (a) fresh shoot weight, (b) shoot dry weight, (c) fresh root weight, and (d) root dry weight. Different letters indicate a significant difference between the soil treatments ($p < 0.05$) based on one-way ANOVA followed by the Tukey post hoc test.

The improved agronomic performance after biochar application could be assigned to the plant's uptake of inherent nutrients in char materials. In this study, the biochar produced from wastewater sludge contained several nutrients (N P K) essential for lettuce growth in the soil [8]. Moreover, the sludge-derived biochar was carbon-rich (C-content of 86.93%), which could enhance soil organic carbon (SOC), carbon sequestration, and soil microbial activity.

3.3. Climate change prospects and economic feasibility associated with the application of wastewater sludge-derived biochar for soil amendment

3.3.1. Climate change mitigation

The biochar's ability to slowly degrade in the soil helps the gradual rise of SOC over time. Biochar incorporation stores biogenic C in soil and offsets C emissions by burning fossil fuels. Organic C, being tightly bound to soil particles, leads to a relatively lower emission of CO_2 from soil to the atmosphere. Hence, adding biochar to agriculture helps decrease GHG emissions and climate change [3]. Incorporating biochar in the soil might become a C sink for long-term C storage [1]. Biochar contributes to building a refractory SOC pool and positively impacts SOC dynamics. Depending on management practices, agriculture can act as a net source/sink for GHGs [9]. Agricultural management practices that can foster soil C sequestration help mitigate climate change. It has been found that soil amendment imparts SOC protection from utilization. The incorporation of biochar minimizes CO_2 emissions from the soil by altering its characteristics and microbial diversity. Moreover, the emission of CH_4 could be reduced within the range of (45.2 - 54.9%) by biochar application [5].

3.3.2. Economic feasibility

The economic feasibility analysis for adding biochar to the soil was conducted based on the income received by farmers for lettuce plant cultivation and the potential for CO_2 fixation. The price of CO_2 fixation constantly varied after COP27, surpassing 90 EUR/t in March 2023 (https://uk.investing.com/commodities/).

The estimated monetary benefits from crop improvement can be calculated from Equation 1. The cost of biochar for soil amendment for each application rate and the value of CO_2 fixation (Equation 2) was used in the computation of the payback period (Equation 3).

$$\text{Income } (€/\text{ha}) = \text{Price } (€/\text{t}) \times \text{Productivity } (\text{t/ha}) \times \text{Improvement} \tag{1}$$

$$\text{CO}_2 \text{ value } (€/\text{ha}) = \frac{\text{CO}_2 \text{ Price } (€/\text{t})}{\text{CO}_2 \text{ Fixation}} \times \text{Biochar dosage (kg/ha)} \tag{2}$$

$$\text{Payback period (years)} = \frac{\text{Biochar cost } (€/\text{ha})}{\text{Income } (€/\text{ha}) + \text{CO}_2 \text{ value } (€/\text{ha})} \tag{3}$$

For the computation of income from crop improvement, the average price received by farmers for lettuce is considered 269.9 €/t (equivalent to 0.2699 €/kg) [9]. Considering 80000 plants (www. Starkeayres.co.za) per hectare and assuming that the improvement in yield is equivalent to the increase in mean fresh weight of lettuce plant, different benefits for each application rate were determined (see Supplementary Table S1).

Based on the average price in Egypt, the biochar cost was estimated at 800 €/t. An option to reduce the costs is to include the subsidized price of one ton of CO_2 that is no longer emitted on the farms or by reducing the cost of biochar (Table 2). According to Filiberto and Gaunt [10], one ton of biochar can fix 2.06 t of CO_2. Therefore, approximately 4.12, 8.24, and 16.48 t/ha could be fixed with biochar application rates of 2.5%, 5%, and 10% to the soil, respectively.

In all scenarios, assuming a similar improvement, the investment costs would be recovered in less than 1.5 years. The results showed no significant improvement in lettuce profitability when comparing the 2.5% and 10% biochar application rates. Therefore, applying the 5% dose would be more appropriate to optimize the project benefits since it would return the investment cost in a short period (approximately 10.7 months). These results indicate that applying sludge-derived biochar lettuce cultivation could be an economically profitable practice when implemented.

Table 2. Computation of payback period and the contribution price of CO_2 from biochar application.

Application rate (%)	CO_2 fixation value (€/ha)	Crop income + CO_2 value (€/ha)	Biochar cost (€/ha)	Payback period (Years)
2.5	185.4	875.91	800	0.91
5	370.8	1795.18	1600	0.89
10	741.6	2295.79	3200	1.39

3.4. Sustainable development goals (SDGs) associated with biochar application for soil amendment

Using wastewater sludge-derived biochar for soil enrichment directly/indirectly contributes to achieving sustainable development goals for Agenda 2030 of the United Nations [11]. The increase in crop productivity owing to biochar application is helpful for farmers in becoming self-sufficient and having monetary gain, achieving no poverty (SDG 1). Moreover, higher agricultural yields in degraded soils and agroecosystem resilience boost food security, achieving zero hunger (SDG 2). Through increased crop yield, the nutritional health of people can be accomplished, which meets SDG 3 (good health and well-being). The recalcitrant nature of organic biochar C and reducing emissions of CH_4 and CO_2 from amended soils abate the possibility of climate change [9]. Increasing agroecosystem resilience helps adapt and mitigate future anticipated climate change effects (SDG 13). Biochar addition, through the improvement of soil fertility and decrease in soil-water pollutants, can provide habitats for beneficial soil microorganisms, ensuring better soil health and supporting life on land (SDG 15).

4. Conclusions

Wastewater sludge-derived biochar application (2.5% - 10%) significantly improved the plant height and shoot and root weight of grown lettuce crops by pot experimentation. Amending soil with biochar at a rate of 5% supported lettuce farming with related agronomic benefits for vegetable production. The economic benefits associated with farming practice included improved lettuce productivity (1795 €/ha) and carbon fixation (371 €/ha), achieving a payback period of 0.89 years. The study benefits were interlinked with multiple SDGs regarding agricultural soil amendment, climate change mitigation, sustainable sludge handling and management, human health protection, and improved food production. Moreover, upgrading the proposed scheme to a commercialized field scale is suggested for future consideration.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: Computation of the crop benefit for each biochar application rate.

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Conflicts of Interest: The authors declare no conflict of interest.

Supplementary material

Table S1. Computation of the crop benefit for each biochar application rate.

Application rate (%)	Mean productivity (t/ha)	Improvement (%)	Price received by farmers (€/t)	Crop income (€/ha)
2.5	6.24	41.0	269.9	690.51
5	8.96	58.9	269.9	1424.38
10	9.44	61.0	269.9	1554.19

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