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Efficiency of Biochar in Combination with Compost or Sugar Lime Mud for Improving Growth Performance and Nutritional Status of Wheat Plant

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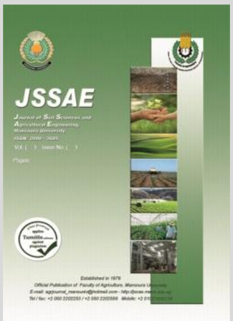

ABSTRACT

Agriculture in sandy soils, one of the most degraded soils in Egypt, faces numerous challenges. So, a field trial was implemented during two consecutive seasons (2022/2023 and 2023/2024) on sandy soil using wheat as experimental plant. A split-plot design was used, as biochar represented the main factor (B_0: Without biochar, B_1: Biochar at rate of 0.4%, B_2: Biochar at rate of 0.8%), while compost and sugar lime mud treatments represented the sub main factor (C_0: Without soil conditioners, C_1: Compost at rate of 1.0%, C_2: Compost at rate of 2.0%, C_3: Sugar lime mud at rate of 1.0%, C_4: sugar lime mud at rate of 2.0%). All amendments were applied only once before the first season to evaluate the direct effect in the 1st season and residual effect in the 2nd season. Measurements included straw fresh and dry weights as well as NPK contents and uptake in straw. The results indicate that the addition of biochar at a concentration of 0.8%, had a positive and effective impact on improving plant growth and the absorption of major nutrients in wheat, both in the first season (as a direct effect) and the second season (as a residual effect). C_2 treatment showed superiority in improving straw fresh and dry weights, NPK contents and uptake, followed by the C_3 treatment. Overall, the sustainability of agricultural production can be enhanced by using biochar, compost, and sugar lime mud to improve sandy soil fertility and increase the efficiency of nutrient absorption.

Keywords: Sandy soils, biochar, compost, sugar lime mud, wheat, sustainability

INTRODUCTION

Agriculture under sandy soil conditions, which considered one of the most degraded soils in Egypt, faces many challenges, most notably its poor water and nutrient retention capacity (Ghazi *et al.* 2022), leading to low crop productivity and long-term instability (Elwan, 2023). These challenges are exacerbated when irrigation is relied upon, given its high salt content, which can cause physiological stress to higher plants and negatively affect the absorption of macro and micronutrients. Consequently, there is an urgent need to find a sustainable approach to enhance the properties of sandy soils, thus improving their agricultural efficiency. Biochar is one of the most promising substances in this regard, given its ability to improve soil physical and chemical traits, increase water and nutrient use efficiency, and potentially stabilize some soil pollutants and reduce nutrient loss through both leaching and volatilization (Abdel-Motaleb *et al.* 2025). Biochar is the residue of pyrolysis under wide range of heating temperatures which ranging from 400 and 500°C (giving the process the name “low-temperature pyrolysis”), so we need to know more about this by-product and whether it would be valuable when be added to soil. Two aspects of biochar make it valuable for this purpose: (1) its high stability against decay and (2) its superior ability to retain nutrients compared to other forms of soil organic matter. Three environmental benefits arise from these properties: (1) mitigation of climate change, (2) enhancement of soils characteristics, and (3) reduction of environmental pollution. (Pessenda *et al.* 2001, Bridgwater 2003, Czernik and Bridgwater, 2004). The mineralization of biochar in soil occurred much more slowly than other sources of soil organic matter. This confirms that biochar is very stable in soil and can resist microbial degradation by its inherent chemical stability (Bruun and El- Zehery, 2012).Biochar has a positive impact on wheat plants, stimulating vegetative growth by improving nutrient absorption. It also plays an effective role in increasing chlorophyll in leaves, thereby enhancing photosynthesis efficiency. It also enhances plant resistance to water stress, thereby improving adaptation to drought. It also improves root growth and increases root mass, thereby enhancing water and nutrient absorption. All of this positively impacts grain yield (Bista *et al.* 2019). In addition, organic additives such as compost and sugar lime mud are common methods for improving soil fertility, as they contribute to increasing organic matter, stimulating microbial activity, and improving plant nutritional balance. They also have the ability to counteract some of the harmful effects of salts by improving soil structure and increasing soil exchange capacity (Ghazi *et al.* 2021; Oueriemmi *et al.* 2021). Compost has a positive effect on wheat plants, as it increases branching and shoot development, contributing to improved plant growth. Due to the continuous and balanced supply of nutrients, compost also plays an effective role in improving plant health. It enhances the efficiency and suitability of macro and microelements, resulting in increased stem length, leaf number, biomass, and improved spike productivity (Ghazi *et al.* 2022). Sugar lime mud as soil conditioner also has a vital impact on wheat plants, as it improves stem firmness, reduces lodging and increases vegetative growth due to its calcium and magnesium content. Also sugar lime mud plays an important role in combating fungal diseases, thus improving the overall status of the whole plant (Ghazi *et al.* 2021). On the other hand, wheat (*Triticum aestivum* L) is the most important strategic crop in Egypt, as most Egyptians

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rely on it to meet their food needs. Therefore, the Egyptian government has always paid great attention to increasing its cultivated area, especially in degraded soils such as sandy soils (Asseng *et al.* 2018). Thus, the major objective of this research work was to evaluate the efficiency of biochar amendment when used at different levels in combination with another organic additives (compost and sugar lime mud), in improving the growth performance of wheat plant and its nutritional status under sandy soils conditions. The aim of implementing the experiment during two consecutive seasons was to evaluate the direct impact of the treatments in the first season and the residual impact in the second season, making this research point of great importance in the integrated and sustainable management of sandy soils.

MATERIALS AND METHODS

A field trial was implemented during two consecutive agricultural seasons (2022/2023 and 2023/2024) on sandy soil located within the New Lands (Qalabsho area near the Coastal Gamasa City, Egypt 31°28’54.63” N, 31°19’29.68” E). Wheat Sakha 95 cultivar its recommended dose is 120 N:30 P_2O_5:25 K_2O) was used in the study. Seeds were sown using the dry sowing method at a rate of 60 kg fed^{-1} in both seasons on November 11, 2022, for the first season, and November 25, 2023, for the second season. Harvest process was done on March 19, 2023, and March 23, 2024, respectively. A split-plot design with three replicates was used in this experiment, with biochar as the main plot factor, while compost and sugar lime mud treatments as the subplot factor. The area of the experimental unit was 19.76 m² (7.6 m x 2.6 m).

Biochar (as the main factor) was added only once before planting in the first season, at the following rates;

B_0: Without biochar (equivalent rate was 0.0 kg m^2)

B_1: Biochar at rate of 0.4% (equivalent rate was 30.875 kg/plot =6562.5 kg/fed)

B_2: Biochar at rate of 0.8% (equivalent rate was 61.75 kg/plot=13125 kg/fed)

Organic amendments (as the sub main factor) were added only once before planting in the first season, as follows;

C_0: Without organic amendments

C_1: Compost at rate of 1.0% (equivalent rate was 78.125kg/plot≈16 tons/fed)

C_2: Compost at rate of 2.0% (equivalent rate was 156.25kg/fed≈32 tons/fed)

C_3: Sugar lime mud at rate of 1.0% (equivalent rate was 78.125kg/plot≈16 tons/fed)

C_4: Sugar lime mud at rate of 2.0% (equivalent rate 156.25kg/fed≈32 tons/fed)

The soil was analyzed before the beginning of each season to determine some chemical and physical properties, depending on the standard methods described by Tandon (2005), as shown in Table 1. Additionally, the analysis of biochar, compost, and sugar lime mud was done according to the same reference, as their traits are also shown in Table 2.

SAR, RSC and SSP was calculated in irrigation water according to Richards, (1954) and Ayres and Westcot, (1994) shown in Table 3.

Table 1. Some physical and chemical characteristics of the studied soil.

Soil Property	Unit	Value: Soil, first season, winter 2022	Value: Soil, second season, winter 2023
Particle size distribution:			
Coarse sand	(%)	75.95	76.50
Fine sand	(%)	15.05	15.20
Silt	(%)	5.32	5.45
Clay	(%)	3.87	3.92
Texture class		Sand	Sand
Bulk density (BD)	(Mg m^{-3})	1.56	1.51
Particle density (Pd)	(Mg m^{-3})	2.607	2.454
Total porosity (TP)	(%)	40.16	38.46
pH (1 soil :2.5 water suspension)		8.74	9.1
EC (1:5 soil: water extract)	dSm^{-1}	1.967	2.735
Organic matter (OM)	(g kg^{-1})	2.18	3.08
Soluble cations			
Ca^{2+}	(meq L^{-1})	0.50	0.70
Mg^{2+}	(meq L^{-1})	0.2	0.30
Na^{+}	(meq L^{-1})	0.9	1.29
K^{+}	(meq L^{-1})	0.28	0.382
Soluble anions			
CO_3^{2-}	(meq L^{-1})	0.00	0.00
HCO_3^{-}	(meq L^{-1})	0.6	0.9
Cl^{-}	(meq L^{-1})	1.10	1.50
SO_4^{2-}	(meq L^{-1})	0.18	0.274
Available nutrients			
N	(mg kg^{-1})	33.82	91.52
P	(mg kg^{-1})	1.03	2.70
K	(mg kg^{-1})	165.00	340.00

Table 2. Some Characteristics of biochar, compost and sugar lime mud before the experimental trail:

Organic Amendments	*EC dSm^{-1} (1:10)	**pH 1:2.5	***OC %	Total N%	Total P%	Total K%
Biochar	2.02	8.81	71.88	1.50	0.37	0.72
Compost	4.92	7.97	28.5	1.75	0.46	2.66
Sugar lime mud	0.583	9.21	33.2	1.54	2.5	0.18

***EC was determined in organic amendments: water (1:10) suspension.**
**** Soil pH was determined in organic amendments: water (1:2.5) suspension.**
*****Organic carbon**

Table 3. Chemical composition of Irrigation water in the experimental site of Qalabsho farm:

pH	EC ($dS.m^{-1}$)	Cations meq/L: Ca^{2+}	Cations meq/L: Mg^{2+}	Cations meq/L: Na^{+}	Cations meq/L: K^{+}	Anions meq/L: CO_3^{-}	Anions meq/L: HCO_3^{-}	Anions meq/L: Cl^{-}	Anions meq/L: SO_4^{-}	(SSP) (%)	SAR	RSC
8.42	9.28	6.59	4.49	74.31	2.44	ND	30.17	42.02	15.64	84.60	31.57	19.09

Sodium adsorption ratio (SAR) is a measure of the sodicity of the water.

$$SAR = Na+ / (Ca^{2+} + Mg^{2+}]/2)1/2$$

Soluble Sodium Percentage (SSP)

$$SSP= Na \% =(Na^{1+} + K^{1+}) / (Na^{1+} +Ca^{2+} +Mg^{2+} +K^{1+}) \times 100 .$$

Residual sodium carbonate (RSC)

$$RSC = (CO3^{2-} + HCO3^{1-}) - (Ca^{2+} + Mg^{2+}).$$

Phosphate fertilizer was added at a rate of 200 kg fed^{-1} (15.5% P_2O_5) by spreading it before the last plowing to mix it well with the soil. Potassium fertilizer was added at a rate of 50 kg fed^{-1} as potassium sulphate after 45 of germination (just at the beginning of spike emergence). Nitrogen fertilizer was added at a rate of 120 kg. fed^{-1} in three doses during the different growth stages (20% (as Ammonium nitrate 33% N) at the cultivation-40% (as Urea 46%N) with the first irrigation (30 days of cultivation)-40% (as Urea 46%N) after 60 days of cultivation). Five irrigations were done during the season, with care taken to avoid excessive water use.

Wheat performance under the studied conditions was evaluated using the following measurements, conducted in both seasons;

- Straw fresh weight (kg fed^{-1})
- Straw dry weight (kg fed^{-1}) after drying at 70°C to constant weight.
- Nutrient concentrations in straw: nitrogen (N), phosphorus (P), and potassium (K) were determined using Kjeldahl method, Spectrophotometer (Olsen method) and Flame photometer method, respectively as described by Tandon (2005).
- Total uptake of elements (N, P, and K) in straw (kg fed^{-1}), calculated based on dry weight and element concentrations.

Data were statistically analyzed using CoStat software. Comparison of means was performed using the least significant difference (LSD) test at the 0.05 probability level (Gómez and Gómez, 1984), and Duncan's letters were also used.

RESULTS AND DISCUSSION

1.Straw fresh and dry weights:

Tables 4a and 4b present the direct impact of biochar with compost or sugar lime mud on the growth parameters of wheat straw during the first season (2022/23). Table 4a shows the individual impacts of the main factor (biochar) and the sub main factor (compost and sugar lime mud), while Table 4b shows the interaction effect of these two factors on both fresh and dry weight of straw (kg fed^{-1}). F-test results indicate highly significant differences (**) for all treatments and their interactions, indicating a clear response of the wheat plant to the various applications. The B_1 treatment (0.4%) significantly outperformed the other treatments, recording the highest fresh and dry weights of straw, followed by the B_2 treatment (0.8%), which showed a significant improvement compared to the control treatment (B_0), indicating that the medium dose of biochar was most suitable for growth.

Table 4a. Direct effect of biochar, compost and sugar lime mud on the growth criteria of the wheat straw during the first season (individual effects)

Parameters / Treatments	Straw fresh weight, kg fed^{-1}	Straw dry weight, kg fed^{-1}
Individual effect of biochar treatments		
B_0: Without biochar	4620.24 c	3671.73c
B_1: Biochar at rate of 0.4%	5896.61 a	4937.41a
B_2: Biochar at rate of 0.8%	5147.23 b	4566.99 b
F-test	**	**
LSD at 5%	114.9276	80.9507
Individual effect of compost or sugar lime mud treatments		
C_0: Without soil conditioners	4179.49 d	3400.87d
C_1: Compost at rate of 1.0%	5281.13 b	4496.78b
C_2: Compost at rate of 2.0%	6340.99 a	5167.73a
C_3: Sugar lime mud at rate of 1.0%	5342.05 b	4598.64b
C_4: Sugar lime mud at rate of 2.0%	4963.14 c	4296.19 c
F-test	**	**
LSD at 5%	151.2574	131.3589
Interaction		
F-test	**	**
LSD at 5%	254.26769025	227.5203

Table 4b. Direct effect of biochar combined with compost or sugar lime mud on the growth criteria of the wheat straw during the first season (interaction effects)

Treatments	C_0	C_1	C_2	C_3	C_4	Mean
Straw fresh weight, kg fed^{-1}						
B_0	3204.27 h	4545.13 f	5798.75 bc	4994.26 e	4558.77 f	4620.24 c
B_1	5133.37 e	5840.93 bc	6721.09 a	6100.26 b	5687.42 cd	5896.61 a
B_2	4200.84 g	5457.32 d	6503.14 a	4931.64 e	4643.23 f	5147.23 b
Mean	4179.49 d	5281.13 b	6340.99 a	5342.05 b	4963.14 c	
Straw dry weight, kg fed^{-1}						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	2455.76 i	3886.86g	4515.07 e	3934.60 g	3566.36 h	3671.73c
B_1	4215.95 f	4995.23 c b	5680.88 a	5081.45 b c	4713.54e	4937.41a
B_2	3530.91 h	4608.26 e	5307.25 b	4779.87 de	4608.65 e	4566.99 b
Mean	3400.87 d	4496.78b	5167.73a	4293.95 b	4296.19 c	

Biochar demonstrated a clear impact on improving straw growth parameters.

Regarding soil amendments (compost and sugar lime mud), the C_2 treatment (2.0% compost) showed the highest value for all aforementioned traits, followed by the C_3 treatment (1.0% sugar lime mud), and then the C_1 treatment (1.0% compost), demonstrating the overall effectiveness of compost, especially at the highest rate. The control treatment C_0 (without amendments) recorded the lowest values, highlighting the tangible positive role of organic amendments in improving growth characteristics.

On the other hand, the data in Table 4b confirms the presence of strong interactive impacts among biochar and organic amendments. The combined treatment $B_1 \times C_2$ (0.4% biochar + 2.0% compost) significantly outperformed both aforementioned traits, indicating a synergistic impact between biochar at the medium dose and compost at the highest dose.

In contrast, the control treatment $B_0 \times C_0$ (without additives) realized the lowest values, reflecting the negative impact of not using any additives under sandy conditions. Furthermore, some treatments combining biochar with sugar lime mud, such as ($B_2 \times C_3$) and ($B_1 \times C_3$) improved the growth of straw but did not reach the level of treatments using compost. This indicates the relative superiority of compost as an organic material rich in active elements and compounds.

The positive effect of biochar is due to its physical and chemical properties. It improves the structure of sandy soils by increasing porosity and water-holding capacity. It also contributes to reducing nutrient loss under irrigation conditions with wastewater, enhancing absorption efficiency, and reducing salt stress.

Compost, especially at the high rate (2.0%), provided a rich and balanced source of macro- and microelements, as well as improving microbial activity and increasing organic matter, which led to enhanced vegetative growth and dry weight. While lime-sugar clay showed a moderate positive effect, likely due to its calcium and other nutrient content, its less balanced chemical composition compared to compost may have limited its full effectiveness.

The effectiveness of the interaction between B_1 and C_2 is attributed to the ideal balance between improving soil physical properties (*via* biochar) and providing nutrients (*via* compost), which contributed to the overall growth enhancement. The results are consistent with the findings of Oueriemmi *et al.* (2021); Ghazi *et al.* (2021&2022); Abdel-Motaleb *et al.* (2025).

Table 5a presents the individual impacts of biochar and soil amendments (compost and sugar lime mud) as residual effects on fresh and dry weight of wheat straw (kg fed^{-1}) during the second season (2023/24), while Table 5b presents the interactive impacts among biochar levels and organic soil amendment types/rates as residual effects during the second season (2023/24), showing the combined response to straw growth in both fresh and dry weight.

Table 5a. Residual effect of biochar, compost and sugar lime mud on the growth criteria of the wheat straw during the first season (individual effects)

Parameters / Treatments	Straw fresh weight, kg fed^{-1}	Straw dry weight, kg fed^{-1}
Individual effect of biochar treatments		
B_0: Without biochar	5188.42 c	3883.86b
B_1: Biochar at rate of 0.4%	7362.18 a	4962.80a
B_2: Biochar at rate of 0.8%	6557.02 b	5089.84a
F-test	**	**
LSD at 5%	210.1411	135.7511
Individual effect of compost or sugar lime mud treatments		
C_0: Without soil conditioners	4170.61 e	3429.43 e
C_1: Compost at rate of 1.0%	6731.64 c	4790.01 c
C_2: Compost at rate of 2.0%	8469.85 a	5556.19a
C_3: Sugar lime mud at rate of 1.0%	6946.62 b	5075.91b
C_4: Sugar lime mud at rate of 2.0%	5527.32 d	4375.98 d
F-test	**	**
LSD at 5%	149.8399	124.0293
Interaction		
F-test	**	**
LSD at 5%	259.53040	214.8251

Table 5b. Direct effect of biochar combined with compost or sugar lime mud on the growth criteria of the wheat straw during the second season (interaction effects)

Treatments	C_0	C_1	C_2	C_3	C_4	Mean
Straw fresh weight, kg fed^{-1}						
B_0	3239.12 j	4967.297 h	6814.177 d	6093.417 e	4828.087 h	5188.42 c
B_1	5454.92 g	8494.567 b	9269.033 a	7846.753 c	5745.61 f	7362.18 a
B_2	3817.777 i	6733.047 d	9326.35 a	6899.677 d	6008.25 e	6557.02 b
Mean	4170.61 e	6731.64 c	8469.85 a	6946.62 b	5527.32 d	
Straw dry weight, kg fed^{-1}						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	2513.27 i	3854.178 g	5014.62 c	4484.21 e	3553.04 h	3883.86b
B_1	4246.85 f	5056.25 c	5659.19 b	5148.78 c	4702.98 d	4962.80a
B_2	3528.18 h	5459.62 b	5994.76 a	5594.73 b	4871.90 cd	5089.84a
Mean	3429.43 e	4790.01c	5556.19a	5075.91b	4375.98 d	

As shown in Table 5a, the biochar treatments showed a significant and statistically superior residual effect in the second season, with both straw fresh and dry weights significantly increased compared to the treatment without biochar. The best results were achieved at the B_1 rate (0.4%) in terms of fresh weight, while B_2 (0.8%) achieved the highest dry weight, with no significant differences between B_1 and B_2 in dry weight.

Concerning organic amendments, the 2.0% compost (C_2 treatment) showed the highest values, both in fresh straw and dry straw weights. The 2.0% sugar-lime mud (C_3 treatment) also achieved good results but ranked second only to compost in terms of efficiency.

Table 3b illustrates that the combined treatment of $B_1 \times C_2$ (0.4% biochar with 2.0% compost) resulted in the highest value of the straw fresh weight, indicating a strong synergistic effect between biochar and compost. While the combined treatment of $B_2 \times C_2$ was the best in terms of dry weight of straw, indicating that increasing the biochar level to 0.8% can improve dry weight accumulation, even if it is not the highest in fresh weight. It can also be noted that the lowest values of both above traits were found with the $B_0 \times C_0$ combination (without any additives), confirming that the residual effect of organic and soil amendments is still effective in improving growth in the second season.

This can be explained by biochar's high ability to improve soil physical and chemical properties, such as increasing aeration, water retention, and reducing nutrient loss. Since it is a stable, slow-decomposing material, its effect persists into subsequent seasons, explaining the increased growth in the second season. Furthermore, it can be argued that compost was a rich source of organic matter and medium- and long-term nutrients. It may also have stimulated the activity of microorganisms in the second season, which decompose organic matter and gradually release nutrients. This explains the high effectiveness, especially at a rate of 2.0%. While sugar lime mud contains a good percentage of calcium and organic matter, and contributes to improving soil structure and adjusting pH, its effect was relatively less than compost, perhaps due to differences in decomposition rates or bioavailability of elements.

Overall, it can be said that the synergistic impact between biochar and organic amendments creates a synergistic effect between improving soil structure (from biochar) and increasing nutrient content (from compost/sugar lime mud), which enhances overall plant growth. The obtained results are in harmony with those of Oueriemmi *et al.* (2021); Ghazi *et al.* (2021&2022); Abdel-Motaleb *et al.* (2025).

2.Chemical constituents in straw and nutrients uptake (NPK)

Table 6a shows the direct individual effect of biochar, compost, sugar lime mud on the chemical constituents (N, P,K,%) of the wheat straw during the first season (2022/23), while Table 6b illustrate the interaction effects.

Table 6a. Direct effect of biochar, compost and sugar lime mud on the chemical constituents of the wheat straw during the first season (individual effects)

Parameters Treatments	Nitrogen, %	Phosphorus, %	Potassium, %
Individual effect of biochar treatments			
B_0: Without biochar	0.848b	0.0068c	2.380 b
B_1: Biochar at rate of 0.4%	0.866b	0.0078b	2.430 b
B_2: Biochar at rate of 0.8%	0.999a	0.0085a	2.510 a
F-test	**	**	*
LSD at 5%	0.03072411	3.77744186e-4	0.0624591
Individual effect of compost or sugar lime mud treatments			
C_0: Without soil conditioners	0.8587 ab	0.0065b	2.265c
C_1: Compost at rate of 1.0%	0.8300 b	0.0078a	2.463b
C_2: Compost at rate of 2.0%	0.8916 ab	0.0084a	2.525a
C_3: Sugar lime mud at rate of 1.0%	0.92214 a	0.0080a	2.544a
C_4: Sugar lime mud at rate of 2.0%	0.8924 ab	0.0079a	2.413b
F-test	**	**	**
LSD at 5%	0.03017058	6.06507787e-4	0.0591190
Interaction			
F-test	**	*	**
LSD at 5%	0.0523	0.0011	0.1024

Table 6b. Direct effect of biochar combined with compost or sugar lime mud on the chemical constituents of the wheat straw during the first season (interaction effects)

Nitrogen,%						
Treatments	**C_0**	**C_1**	**C_2**	**C_3**	**C_4**	**Mean**
B_0	0.602e	0.849cd	1.148a	0.793d	0.8493cd	0.848b
B_1	0.806d	0.944b	0.959b	0.817d	0.805d	0.866b
B_2	0.889c	0.979b	1.173a	0.978b	0.977b	0.999a
Mean	0.766d	0.924b	1.09a	0.862c	0.877c	
Phosphorus,%						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	0.005d	0.007abc	0.008a	0.007bc	0.007bc	0.0068c
B_1	0.006cd	0.007abc	0.009a	0.009a	0.008a a	0.0078b
B_2	0.0079ab	0.0086a	0.0087a	0.0087a	0.0086a	0.0085a
Mean	0.0065b	0.0078a	0.0084a	0.0080a	0.0079a	
Potassium,%						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	2.045d	2.459abc	2.505ab	2.540a	2.369bc	2.38b
B_1	2.326c	2.453abc	2.519ab	2.525ab	2.327c	2.43b
B_2	2.424abc	2.478abc	2.551a	2.567a	2.567a	2.51a
Mean	2.265c	2.463b	2.525a	2.544a	2.413b	

As shown in Table 4a, the percentage of nitrogen, phosphorus and potassium (%) gradually increased as the level of added biochar increased, with B_2 treatment recording the highest percentage, compared to the control treatment (without biochar). As for organic matter, the 2.0% compost treatment (C_2) and sugar-lime clay (C_3) outperformed the control (C_0).

Table 6b indicates that the combined treatment of B_2C_2 recorded the highest nitrogen percentage, followed by B_0C_2 treatment, indicating a positive interaction among biochar and compost. The highest phosphorus values were achieved with the B_1C_2, B_1C_3, B_2C_2, and B_2C_3 treatments, respectively, with clear superiority for treatments containing biochar and compost or sugar lime mud. For potassium (%), the highest values were recorded with the combined treatments of B_2C_3 and B_2C_4, indicating the effectiveness of the interaction among 0.8% biochar and sugar lime mud or compost.

The results in both Tables above indicate that adding biochar, especially at a rate of 0.8% (B_2 treatment), had a clear positive impact on improving the nutritional content of wheat straw (NPK). Compost and sugar lime mud (C_2 and C_3) also played a pivotal role in increasing the concentration of these elements. Interactions demonstrate that combining biochar with organic matter sources leads to the highest nutrient uptake. These results can be explained by the fact that biochar acts as a porous medium that improves nitrogen absorption in the soil and reduces its loss through leaching or volatilization. Biochar can also reduce the fixation of phosphorus with calcium or iron, improving its availability to plants. Furthermore, it contains significant amounts of absorbable potassium. Meanwhile, compost and sugar lime mud add significant amounts of organic nitrogen and minerals and may enhance microbial activity that releases nitrogen. Organic materials such as compost stimulate the secretion of organic acids by microorganisms, which helps release phosphorus from its insoluble form. Compost contains significant amounts of absorbable potassium. Improving the soil's physical properties (such as aeration and water retention) also facilitates plant uptake of potassium. The obtained results are in harmony with those of Oueriemmi *et al.* (2021); Ghazi *et al.* (2021&2022); Abdel-Motaleb *et al.* (2025).

Table 7a shows the residual individual effect of biochar, compost and sugar lime mud on the chemical constituents of the wheat straw during the second season, while Table 7b illustrates the interaction effects.

Tables 7a and 7b indicate that the residual impacts of adding biochar, compost and sugar lime mud remained clear and significant on the concentration of nutrients (NPK, %) in wheat straw during the second growing season (2023/24), even without reapplication.

Table 7a. Residual effect of biochar, compost and sugar lime mud on the chemical constituents of the wheat straw during the second season (individual effects)

Parameters Treatments	Nitrogen, %	Phosphorus, %	Potassium, %
Individual effect of biochar treatments			
B_0: Without biochar	0.883b	0.0079b	2.585b
B_1: Biochar at rate of 0.4%	0.898b	0.0087b	2.621b
B_2: Biochar at rate of 0.8%	1.04a	0.0098a	2.750a
F-test	**	*	**
LSD at 5%	0.02832057	8.9154448e-4	0.04683384
Individual effect of compost or sugar lime mud treatments			
C_0: Without soil conditioners	0.791d	0.0073b	2.374c
C_1: Compost at rate of 1.0%	1.01b	0.0093a	2.655b
C_2: Compost at rate of 2.0%	1.09a	0.0091a	2.773a
C_3: Sugar lime mud at rate of 1.0%	0.90c	0.0097a	2.796a
C_4: Sugar lime mud at rate of 2.0%	0.91c	0.0089a	2.663b
F-test	**	**	**
LSD at 5%	0.02744894	6.30728767e-4	0.06608774
Interaction			
F-test	**	*	**
LSD at 5%	0.0475	0.0011	0.1145

Table 7b. Residual effect of biochar combined with compost or sugar lime mud on the chemical constituents of the wheat straw during the second season (interaction effects)

			Nitrogen, %			
Treatments	**C_0**	**C_1**	**C_2**	**C_3**	**C_4**	**Mean**
B_0	0.642g	0.928e	1.107b	0.844f	0.895e	0.883b
B_1	0.818f	1.047cd	0.984d	0.832f	0.809f	0.898b
B_2	0.914e	1.053c	1.175a	1.031cd	1.038cd	1.04a
Mean	0.791d	1.01b	1.09a	0.90c	0.91c	
			Phosphorus, %			
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	0.0060d	0.0091abc	0.0083bc	0.0085bc	0.0079c	0.0079b
B_1	0.0065d	0.0089abc	0.0091abc	0.0102ab	0.0091abc	0.0087b
B_2	0.0095abc	0.0099ab	0.0097abc	0.01048a	0.0096abc	0.0098a
Mean	0.0073b	0.0093a	0.0091a	0.0097a	0.0089a	
			Potassium, %			
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	2.166e	2.483d	2.650bc	2.851a	2.776ab	2.585b
B_1	2.353d	2.810ab	2.831a	2.736abc	2.376d	2.621b
B_2	2.603c	2.673abc	2.839a	2.801ab	2.836a	2.750a
Mean	2.374c	2.655b	2.773a	2.796a	2.663b	

A significant increase in the content of N, P and K (%) in straw was observed with increasing biochar application rates, with treatment B_2 (0.8%) recording the highest values.

This indicates that biochar contributes to improving soil fertility, retaining nitrogen, and reducing its loss through leaching or volatilization over the long term. Biochar also improves phosphorus fixation and reduces its loss through chemical fixation. In addition to its role in improving potassium retention and reducing leaching loss,

The organic treatments (C_2, 2.0% compost) and (C_1, 1.0% compost) also showed a significant impact in increasing the values of N, P and K (%) in straw. This is attributed to the decomposition of organic matter and the gradual release of these elements. Sugar lime mud treatments also showed superiority over the treatment without additives (C_0 treatment), indicating that these materials contribute to increasing nutrient availability to wheat plants.

The combined treatment of B_2C_2 exchange treatment achieved the highest nitrogen content, reflecting the positive interaction between biochar and compost in improving wheat plant nutrition. The highest phosphorus value was recorded with the combined treatment of B_2C_3, demonstrating the effectiveness of the interaction among biochar and sugar lime mud in enhancing P-uptake. The combined treatments of B_2C_2 showed the highest K value, confirming the positive interaction between organic fertilizer and biochar in improving nutrient availability.

The results demonstrate that the residual effects of biochar, compost, and sugar lime mud continue to improve the chemical properties of wheat straw throughout the following season without the need for re-fertilization, reflecting the importance of these materials in improving soil fertility and sustaining production. The combination of 0.8% biochar and 2.0% compost (B_2C_2) was the best in terms of residual effects on nutrient content. The findings are in accordance with those of Oueriemmi *et al.* (2021); Ghazi *et al.* (2021&2022); Abdel-Motaleb *et al.* (2025).

Tables 8 (a &b) and 9 (a &b) examine the impact of biochar, compost, and sugar lime mud, either individually or in combination, on the uptake of macronutrients (NPK, kg fed^{-1}) by wheat straw over two seasons, as Table 8 (a &b) shows the direct effect of these treatments in the first season (when applied), while Table 9 (a & b) shows the residual effect of the same treatments in the second season (without reapplication). The individual effects of treatments in the first season (Table 8a) show that biochar, especially at the highest rate (B_2 = 0.8%), contributed to increased uptake of the three nutrients (NPK) compared to the control treatment (without biochar = B_0). The improvement was most pronounced in nutrients uptake, reflecting biochar's ability to improve soil properties and increase nutrient availability for growing wheat. Compost and sugar lime mud (C_1 to C_4) all significantly improved nutrient uptake compared to the treatment without additives (C_0). The 2.0% compost (C_2 treatment) outperformed in all elements, indicating its richness in nutrients and rapid decomposition compared to lime sugar, which showed relatively good results, especially in treatment (C_3), but its effect was less than that of compost.

Table 8a. Direct effect of biochar, compost and sugar lime mud on the chemical constituents of the wheat straw during the first season (individual effects)

Parameters Treatments	**Nitrogen-uptake, kg fed^{-1}**	**Phosphorus-uptake, kg fed^{-1}**	**Potassium-uptake, kg fed^{-1}**
Individual effect of biochar treatments			
B_0: Without biochar	32.2103c	0.255120b	88.6775c
B_1: Biochar at rate of 0.4%	43.0084b	0. 39116a	120.3487a
B_2: Biochar at rate of 0.8%	46.1086a	0. 39117a	115.0173b
F-test	**	**	*
LSD at 5%	1.99685530	0.01730862787	2.295653891
Individual effect of compost or sugar lime mud treatments			
C_0: Without soil conditioners	26.7224e	0.22397c	77.9623e
C_1: Compost at rate of 1.0%	41.7712b	0.35179b	110.7925c
C_2: Compost at rate of 2.0%	56.1859a	0.43723a	130.522a
C_3: Sugar lime mud at rate of 1.0%	39.7866c	0.37355b	116.9847b
C_4: Sugar lime mud at rate of 2.0%	37.7456d	0.34254b	103.811d
F-test	**	**	**
LSD at 5%	1.65514005	0.02745181206	4.295291846
Interaction			
F-test	**	NS	**
LSD at 5%	2.866786	0.04754793332	7.43966374

Table 8b. Direct effect of biochar combined with compost or sugar lime mud on the chemical constituents of the wheat straw during the first season (interaction effects)

Treatments	C_0	C_1	C_2	C_3	C_4	Mean
Nitrogen-uptake, kg fed⁻¹						
B_0	14.7781g	33.0129f	51.8509b	31.1195f	30.2895f	32.2103c
B_1	33.9818f	47.1560c	54.4604b	41.5149d	37.9288e	43.0084b
B_2	31.4074f	45.1445c	62.2465a	46.7252c	45.0193c	46.1086a
Mean	26.7224e	41.7712b	5.61859a	39.7866c	37.7456d	
Phosphorus-uptake, kg fed⁻¹						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	0.12819f	0.28496e	0.36249d	0.26208e	0.23786e	0.25512b
B_1	0.26187e	0.37139cd	0.48734a	0.44223abc	0.39298bcd	0.39116a
B_2	0.28184e	0.39902bcd	0.46188ab	0.41634bcd	0.39679bcd	0.39117a
Mean	0.22.397c	0.35179b	0.43723a	0.37355b	0.34254b	
Potassium-uptake, kg fed⁻¹						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	50.23818h	95.58522f	113.1034de	99.93918f	84.52171g	88.6775c
B_1	98.05906f	122.5494cd	143.1045a	128.3421bc	109.6884e	120.3487a
B_2	85.58968g	114.2428de	135.3581b	122.673cd	117.2229de	115.0173b
Mean	77.9623e	110.7925c	130.522a	116.9847b	103.811d	

The interaction effect in the first season (Table 8b) shows a significant interaction between biochar and organic additives on nitrogen, phosphorus, and potassium uptake, indicating a synergistic effect between these treatments. The highest uptake of nitrogen, phosphorus and potassium was recorded at the B_1 or $B_2 \times C_2$ interaction, indicating that the combination of biochar and compost significantly enhanced plant nutrition.

The residual effect (individual and combined) in the second season can be illustrated by the data in Table (9a & b). It can be noted that the positive impact of biochar persisted in the second season, as nitrogen, phosphorus, and potassium uptake values increased significantly with increasing biochar application rates, with the best results achieved with B_2, proving the continued effectiveness of biochar as a soil conditioner.

Compost also excelled, especially C_2 (2.0% compost), recording the highest uptake of the three elements, followed by the sugar lime mud treatment (C_3), demonstrating the continued effectiveness of organic matter in improving plant nutrition even one season after application. A significant interaction remained between the treatments, with the combined treatment of $B_2 \times C_2$ treatment showing the highest uptake values for the three elements. This reinforces the hypothesis that the residual effect of the interaction between biochar and compost is no less significant than the direct effect, and may even extend beyond one season, contributing to lower fertilization costs and achieving sustainable soil fertility. The obtained results are in agreement with those of Oueriemmi *et al.* (2021); Ghazi *et al.* (2021&2022); Abdel-Motaleb *et al.* (2025).

Table 9a. Residual effect of biochar, compost and sugar lime mud on the nutrient's uptake of the wheat straw during the second season (individual effects)

Parameters Treatments	Nitrogen-uptake, kg fed⁻¹	Phosphorus-uptake, kg fed⁻¹	Potassium-uptake, kg fed⁻¹
Individual effect of biochar treatments			
B_0: Without biochar	35.4111c	0.31605c	101.8754c
B_1: Biochar at rate of 0.4%	44.8481b	0.43990b	130.9776b
B_2: Biochar at rate of 0.8%	53.6834a	0.50195a	140.5339a
F-test	**	*	**
LSD at 5%	230.550840	0.0436074427	4.021300093
Individual effect of compost or sugar lime mud treatments			
C_0: Without soil conditioners	27.6969e	0.25380d	82.04382e
C_1: Compost at rate of 1.0%	48.7146b	0.44761b	127.9055c
C_2: Compost at rate of 2.0%	60.5398a	0.50556a	154.412a
C_3: Sugar lime mud at rate of 1.0%	46.1154c	0.49703a	141.7882b
C_4: Sugar lime mud at rate of 2.0%	40.1708d	0.39251c	116.1621d
F-test	**	**	**
LSD at 5%	1.49685545	0.028891000638	3.82171779
Interaction			
F-test	**	*	**
LSD at 5%	2.5926296	0.08817815	6.61940930

Table 9b. Residual effect of biochar combined with compost or sugar lime mud on the nutrient's uptake of the wheat straw during the second season (interaction effects)

Treatments	C_0	C_1	C_2	C_3	C_4	Mean
Nitrogen-uptake, kg fed⁻¹						
B_0	16.1133h	35.7367f	55.5282bc	37.8266f	31.8504g	35.4111c
B_1	34.7221fg	52.9199cd	55.6624bc	42.8305e	38.1055f	44.8481b
B_2	32.2552g	57.4872b	70.4288a	57.6891b	50.5565d	53.6834a
Mean	27.6969e	48.7146b	60.5398a	46.1154c	40.1708d	
Phosphorus-uptake, kg fed⁻¹						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	0.15124g	0.35118e	0.41869cd	0.37929de	0.27986f	0.31605c
B_1	0.27647f	0.45148c	0.51647ab	0.52626ab	0.42884cd	0.43990b
B_2	0.33370ef	0.54018a	0.58152a	0.58553a	0.46881bc	0.50195a
Mean	0.25380d	0.44761b	0.50556a	0.49703a	0.39251c	
Potassium- uptake, kg fed⁻¹						
Treatments	C_0	C_1	C_2	C_3	C_4	Mean
B_0	54.45666h	95.59955g	132.8883de	127.8408e	98.59187g	101.8754c
B_1	99.91619g	142.1339c	160.2231b	140.888cd	111.727f	130.9776b
B_2	91.75862g	145.9829c	170.1247a	156.6358b	138.1675cd	140.5339a
Mean	82.04382e	127.9055c	154.412a	141.7882b	116.1621d	

CONCLUSION

The results of this research work indicate that the addition of biochar, especially at a concentration of 0.8%, had a positive and effective impact on improving plant growth and the absorption of major nutrients in wheat, both in the first season (as a direct effect) and the second season (as a residual effect). Compost treatments, especially at a rate of 2.0%, also demonstrated superiority in improving wheat plant nutrition, followed by the sugar lime mud. The interaction between biochar and compost showed the best performance, confirming the synergistic effect of the two organic materials in improving the chemical and biological properties of the soil and increasing the efficiency of plant nutrient absorption. Overall, in light of these results, the study recommends adopting the addition of biochar at a rate of 0.8% in conjunction with the use of compost at a rate of 2.0% as sustainable agricultural practices to improve wheat performance, increase nutrient use efficiency, and enhance the quality of plant residues such as straw, in agricultural lands suffering from poor fertility, such as sandy soils.

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كفاءة الفحم الحيوي مع سماد المكمورة أو طينة السكر الجيرية في تحسين أداء النمو والحالة الغذائية لنبات القمح

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الملخص

الزراعة في الأراضي الرملية، والتي تُعد من أكثر أنواع الأراضي تدهورًا في مصر، تواجه العديد من التحديات. وبناءً عليه، نُفِّذت تجربة حقلية خلال موسمين متعاقبين (٢٠٢٣/٢٠٢٢ و٢٠٢٤/٢٠٢٣) على تربة رملية ، باستخدام القمح كمحصول تجريبي. تم استخدام تصميم القطع المنشقة مرة واحدة ، حيث مثّل الفحم الحيوي العامل الرئيسي (B_0: بدون إضافة فحم حيوي ، B_1: فحم حيوي بمعدل ٠,٤%، B_2: فحم حيوي بمعدل ٠,٨ %)، في حين مثّلت معاملات سماد المكمورة وطينة السكر الجيريه العامل المنشق (C0: بدون محسنات تربة، C_1 : سماد مكمورة بمعدل ١,٠%، C_2: سماد مكمورة بمعدل ٢,٠%، C_3: طينة السكر الجيرية بمعدل ١,٠%، C_4: طينة السكر الجيرية بمعدل ٢,٠ %). تم تطبيق جميع الإضافات مرة واحدة فقط قبل الموسم الأول لتقييم الأثر المباشر خلال الموسم الأول والأثر المتبقي خلال الموسم الثاني. شملت القياسات الوزن الطازج والجاف للقش، بالإضافة إلى محتوى وامتصاص عناصر النيتروجين والفوسفور والبوتاسيوم في القش. أشارت النتائج إلى أن إضافة الفحم حيوي بتركيز ٠,٨٪ كان لها تأثير إيجابي وفعّال في تحسين نمو النبات وامتصاص العناصر الغذائية الكبرى في القمح، سواء في الموسم الأول (كتأثير مباشر) أو في الموسم الثاني (كتأثير متبقي). وقد أظهرت المعاملة C_2 تفوقًا ملحوظًا في تحسين الوزن الطازج والجاف للقش ومحتوى وامتصاص NPK ، تلتها المعاملة C_3 . وبشكل عام، يمكن تعزيز استدامة الإنتاج الزراعي من خلال استخدام الفحم حيوي و سماد المكمورة وطينة السكر الجيرية لتحسين خصوبة التربة الرملية وزيادة كفاءة امتصاص العناصر الغذائية