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Rice straw biochar and NPK minerals for sustainable crop production in arid soils: a case study on maize-wheat cropping system

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Abstract

Maize and wheat are the main cereals grown in Egypt. However, the country relies on grain imports to meet its local demands. In order to improve their production, appropriate fertilization programs are needed. The present study investigates the effects of amending a clayey soil of an arid region with rice straw biochar and NPK mineral fertilizers, individually or in combination, for increasing growth and productivity of maize and wheat crops. Additionally, impacts of these additives on soil biological activities and carbon (C) transformations in soil were a matter of concern herein. To achieve this objective, a field research of a randomized block design was conducted during the summer (maize) and winter (wheat) seasons of 2020/2021. The following treatments were considered: unmodified control (CK), 100% N inputs in the form of biochar (reference organic treatment, RSB) (T_1), 100% mineral treatment (reference inorganic treatment, T_2), 75% RSB + 25% NPK minerals (T_3), 50% RSB + 50% NPK minerals (T_4) and 25% RSB + 75% NPK minerals (T_5). Additional doses of mineral fertilizers were added to treatments from T_3 to T_5 to maintain NPK inputs within the recommended doses. Key results showed that all additives significantly enhanced plant growth parameters and productivity. They also increased soil organic carbon level by the end of the growing season hence reduced soil bulk density, even for the treatment that received only mineral NPK applications (T_2). All additives also upraised soil cation exchange capacity (CEC), soil available nitrogen (N), and soil salinity. However, sole application of biochar recorded the least increase in soil salinity. Combined mineral-organic treatments not only recorded the highest increases in soluble and microbial fractions of organic carbon and nitrogen in soil; but also noted the greatest improvements in growth and grain productivity of maize and wheat versus sole applications of mineral fertilizers or biochar. The alkaline nature of biochar was buffered by soil while no significant differences were observed in harvest index among treatments. In conclusion, combined use of biochar and mineral fertilizers, especially T_5 is recommended for increasing soil fertility and wheat and maize grain productvity.

Keywords Wheat, Maize, Biochar, Arid soils, Microbial biomass carbon, Microbial biomass nitrogen

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Introduction

Maize (Zea mays L.) and wheat (Triticum aestivum L.) are the main staple crops globally. Wheat (Triticum aestivum L.) plays a crucial role in the Egyptian cuisine (Khalil et al. 2020; Hussein et al. 2022; Saad et al. 2023). Neverthless, there is a significant disparity between its production and consumption (Saad et al. 2023). Approximately 38% of domestic needs for wheat in Egypt were satisfied via imports (Ouda and Zohry 2016), making Egypt the largest wheat importer in the world (Khalil et al. 2020; Abdalla et al. 2023).

Maize (Zea mays L.) is another essential grain crop in Egypt (Farid et al. 2014a, 2014b; Abd El-Aziz et al. 2020; Abbas et al. 2021). It contributes to the rural economy in this country and also supports its livelihoods (Salama et al. 2021). Additionally, maize serves as a source of maize oil, starch, and fructose (Elbeltagi et al. 2020). Despite that, Egypt relies on maize imports to meet its local demands (Farid et al. 2014a). It is therefore imperative to follow up sustainable strategies to increase wheat and maize production in this region to ensure long-term food security (Abdelaal and Thilmany 2019). Implementing effective fertilization practices, such as using balanced organic and mineral inputs of NPK fertilizers (Ferreira et al. 2023), can potentially help to achieve this goal (Adnan et al. 2014).

Biochar is an environmentally friendly organic substance, which is commonly produced by pyrolysis of organic matter in absence of oxygen or under limited oxygen conditions (Abdelhafez et al. 2014; Mohamed et al. 2018; Calcan et al. 2022; Khalil et al. 2023). When being applied as an amendment to agricultural lands, soil physical and chemical properties are considerably improved (Bassouny and Abbas 2019). This carbonaceous material resist oxidation by soil biota versus other organic additives (Tolba et al. 2021) and this may help in minimizing greenhouse gases emissions; hence mitigating climate change (Farid et al. 2022). Moreover, biochar chelates insoluble nutrients in soil (Elshony et al. 2019) thereby prolonging their availability in soil (Alburquerque et al. 2013). Besides, biochar plays a crucial role in reducing soil nitrogen losses, such as NH_3 volatilization (Clough et al. 2013), N_2O emissions (Wei et al. 2020), and NO_3 leaching (Liu et al. 2019). As a result, nitrogen use efficiency is increased (Chen et al. 2021). Additionally, biochar application promotes the activities of beneficial soil microbes (Jia et al. 2022), while simultaneously suppress soil pathogens (Diatta et al. 2020; Murtaza et al. 2021). Overall, biochar application is a sustainable approach (El-Naggar et al. 2019a, 2019b; Rawat et al. 2019; Abdelhafez et al. 2021) for improving crop performance and soil productivity (Ali 2018; Khan et al. 2021),

Prices of mineral fertilizers are increasing continiously (Bonilla-Cedrez et al. 2021). Also, extensive use of these chemicals has adverse effects on the environment (Abdelhafez et al. 2012). Alternatively, amending soils with biochar can partially substitiute mineral inputs in crop production (Mavi et al. 2018; Alkharabsheh et al. 2021; Murtaza et al. 2021). This combination could have superior effect on plant growth and productivity than relying solely on mineral fertilizers (Jose et al. 2013). It is therefore crucial to determine the appropriate ratio for mixing biochar with inorganic fertilizers to achieve the sustainable goals of development, especially in countries that mainly rely on imports to meet their local demands.

The main objective of this study was to investigate the implications of using rice straw biochar (RSB), in combination with NPK mineral fertilizers, for stimulating soil biota, and their consequencies on plant growth and productivity in a maize-wheat cropping system under field conditions. Transformations of organic carbon (C) and nitrogen (N) fractions in soil as well as changes in activities of soil enzymes owing to these additives were also a matter of concern herein.

Application of biochar alone to supply 100% N requirement is thought to be technically not feasible or economic, because large quantities of straw would come from to generate this application rate. In this study, this treatment was used as a reference organic one to evaluate the outcomes of amending organic additives alone on plant growth and soil biological activities. Generally, three hypotheses were formulated for this research: (1) RSB would significantly stimulate the activities of soil biota, leading to concurrent increases in microbial C and N fractions in the soil. This in turn promotes plant growth and productivity. Neverthless, readily available forms of soil nutrients could be much lower when using RSB alone versus mineral fertilizers (hypothesis 1). On contrary N may be partially subjected to loss from soils when being added in inorganic forms, while inorganic PO_4^{2-} and K^+ ions may undergo rapid fixation in soil. Therefore, combination of biochar and mineral fertilizers could potentially be more beneficial for soil biota and plant growth than applying each component individually, because biochar may form soluble organic complexes with soil nutrients thus prolong their bioavailability in soil (hypothesis 2).

Materials and methods

Soil preparations

Prior to the experimental trial, a surface layer soil sample (0–30 cm) was collected from the experimental farm of the Faculty of Agriculture, Benha University. This sample underwent a series of procedures including air drying, grinding and sieving through a 2 mm sieve. Subsequently,

Table 1 Chemical and physical characteristics of the farm (0–30 cm) prior to the experimental study

Properties	Values	Properties	Values
pH	7.51	Particle size distribution	
EC, dS m^{-1}	1.10	Sand, %	4.9
CEC, cmolc kg^{-1}	24.80	Silt, %	21.4
Organic carbon, g kg^{-1}	8.50	Clay, %	73.7
Available N, mg kg^{-1}	20.80	Texture	Clay
Available P, mg kg^{-1}	8.90	Bulk density, Mg m^{-3}	1.40
Available K, mg kg^{-1}	116.50		

pH was determined in 1:2.5 (soil: water) suspension, EC was measured in the saturation paste extract

Table 2 Main properties of the rice straw biochar (RSB) under study

Properties	Values
pH	7.92
EC, dS m^{-1}	2.29
Organic carbon, g kg^{-1}	238
Organic matter, g kg^{-1}	455
Total N, g kg^{-1}	10.70
Total P, g kg^{-1}	7.28
Total K, g kg^{-1}	21.63
Bulk density, Mg m^{-3}	0.418

pH and EC were regulated in biochar: H_2O suspension (1:10)

the physical and chemical characteristics of the sample were analyzed separately, according to the methods described by Klute (1986) and Sparks et al. (1996). The results obtained from these analyzes are presented in Table 1.

The seeds used in the experiment were yellow maize (hybrid cv T.W.C. 368) and wheat (Sakha 95), which were obtained from the Field Crops Research Institute, ARC, located in Giza, Egypt.

Rice straw biochar creation

Rice straw was collected from nearby farms in Moshtohor village (31° 22"26" E and 30° 36"02" N), Qalubia Governorate, Egypt for use in the preparation of biochar, then cut into small fragments of approximately 10 cm and subjected to thermal pyrolysis at 400–500 °C for half a year. hour, as reported by Lu et al. (2014). Biochar characteristics are presented in Table 2.

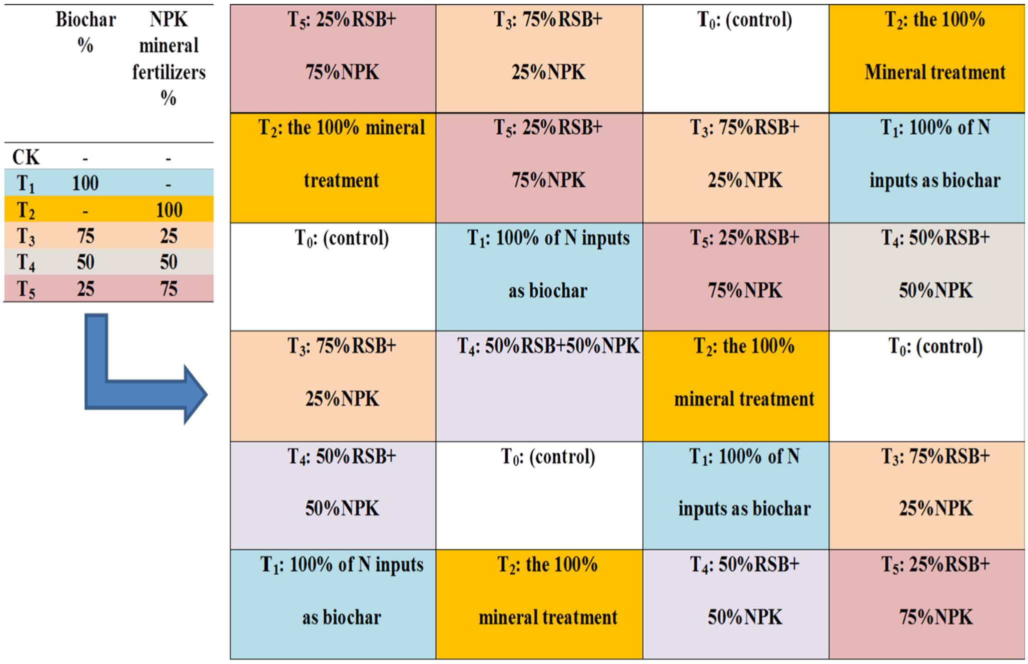
Field study

A field experiment was carried out for two consecutive seasons: a summer season for maize cultivation, which began on May 1st, 2020, and a winter season for wheat sowing, which began on December 3rd 2020/2021. The experiment consisted of different treatments, including no organic additive as a control (CK), biochar application to satisfy 100% of the nitrogen needs for crops (RSB, T_1). Although, this dose (24 and 22 tonnes/hectare for maize and wheat crops, respectively) may not be economic for farmers, yet its consequences on soil sustainability is thought to be positive. Generally biochar was applied 15 days before seed sowing and this treatment was used herein as an organic reference one for evaluating the feasability of the investigated combined treatments on improving soil chemical and biological properties, and finally on enhancing crop productivity.

Mineral and combined organic-mineral treatments were also considered in this experiment as follows: mineral NPK fertilizers added to meet 100% of the crop requirements (T_2), 75% of NPK was added in form of RSB + 25% mineral fertilizers (T_3), 50% of NPK in the form of RSB + 50% mineral fertilizers (T_4) and 25% of N as RSB + 75% mineral fertilizers (T_5). In this concern, mineral fertilizers were added in full or with biochar (from T_2 to T_5) to meet the rates recommended by the Egyptian Ministry of Agriculture. The estimated NPK doses for wheat were as follows: 180 kg N ha^{-1} (urea, 460 g N kg^{-1}), 75 kg P ha^{-1} (calcium superphosphate, 67.7 g P kg^{-1}), and 120 kg K ha^{-1} (potassium sulfate, 400 gKkg^{-1}). For maize, the corresponding rates were 286 kg N ha^{-1}, 31 kg P ha^{-1} and 47 kg K ha^{-1}. A point to note is that the full dose of P mineral fertilizer and approximately 50% mineral N and K fertilizers were added after plant thinning (two weeks after sowing), while the remaining half of N and K fertilizers was applied one month later.These treatments were applied in the field, following a randomized complete block design (Fig. 1), where each plot was 20 m^2 (4 m × 5 m). All treatments were repeated four times.

Soil and rice straw biochar analysis

Three samples were taken from each treatment and the average was calculated for them. Soil organic carbon (SOC) was quantified using the Walkely and Black method, while total nitrogen (TN) was determined using the Kjeldahl method. Soil samples collected from the rhizosphere were treated with a mixture of H_2SO_4 and HClO4, and the resulting digestate was analyzed for total phosphorus (total P) by molybdenum blue colorimetry with a Jenway 6705 UV/Vis. Spectrophotometer. The sodium (Na) content was determined using a flame photometer (Jenway PFP7). Available phosphorus (AP) was extracted using $NaHCO_3$ according to the Olsen method,



	Biochar %	NPK mineral fertilizers %
CK	-	-
T_1	100	-
T_2	-	100
T_3	75	25
T_4	50	50
T_5	25	75

T_5: 25%RSB+ 75%NPK	T_3: 75%RSB+ 25%NPK	T_0: (control)	T_2: the 100% Mineral treatment
T_2: the 100% mineral treatment	T_5: 25%RSB+ 75%NPK	T_3: 75%RSB+ 25%NPK	T_1: 100% of N inputs as biochar
T_0: (control)	T_1: 100% of N inputs as biochar	T_5: 25%RSB+ 75%NPK	T_4: 50%RSB+ 50%NPK
T_3: 75%RSB+ 25%NPK	T_4: 50%RSB+50%NPK	T_2: the 100% mineral treatment	T_0: (control)
T_4: 50%RSB+ 50%NPK	T_0: (control)	T_1: 100% of N inputs as biochar	T_3: 75%RSB+ 25%NPK
T_1: 100% of N inputs as biochar	T_2: the 100% mineral treatment	T_4: 50%RSB+ 50%NPK	T_5: 25%RSB+ 75%NPK

Fig. 1 The experimental design scheme. Biochar (RSB) was applied 15 days prior to sowing seeds. The full dose of P mineral fertilizer and approximately 50% mineral N and K fertilizers were added after plant thinning (two weeks after sowing), while the remaining half of N and K fertilizers was applied a month later

and available potassium (AK) was extracted using $NH_4CH_3CO_2$ (A.O.A.C., 1995). Soil bulk density was estimated using the soil ring procedure. Soil cation exchange capacity (CEC) was assessed using a modified NH_4 acetate replacement test at a soil pH of 7 (Gaskin et al. 2008). Dissolved organic carbon (DOC) was extracted from soil using dH_2O at a ratio of 1:5, shaken for one hour, and then separated by centrifugation (Klein et al. 1971). The concentration of DOC in the supernatant was determined using a TOC analyzer (Phoenix 8000). Total dissolved nitrogen was measured using the alkaline potassium persulfate digestion method followed by UV spectrophotometry, while inorganic nitrogen forms (NH_4-N and NO_3-N) were analyzed at using a continuous flow analyzer (AA3). Dissolved organic nitrogen (DON) was calculated as the difference between total nitrogen and dissolved inorganic nitrogen (Yang et al. 2019).

Soil microbial biomass and enzymes activity

Composite soil samples from the first 15 cm depth were collected by taking 8 random cores per plot and then carefully combined. These samples were passed through a 2 mm sieve, mixed and stored at a temperature of 4°C. Organic carbon content was determined in soil extracts using fumigated and non-fumigated K_2SO_4 solutions (Vance et al. 1987). Subsequently, microbial biomass carbon (C) was assessed by comparing the difference in organic carbon content between fumigated and non-fumigated soil samples, using an efficiency constant of 0.45 (Wu and Joergensen 1990). Microbial biomass nitrogen (N) was measured using the fumigation isolation protocol developed by Vance et al. (1987), with a correction factor of 0.54 (Shentu et al. 2008). Dehydrogenase activity in soil was determined by monitoring the production of tri-phenyl formazon (TPF) from tri-phenyl tetrazolium chloride (TTC), following the method described by Kaurin et al. (2018) and Mohamed et al. (2018). The effects of alkaline phosphatase enzymes were measured using the p-nitrophenol (PNP) assay developed by Turan et al. (2019). Urease activity was quantified in a phosphate buffer solution (0.1 M, pH 7) then determined by colorimetry (Kandeler and Gerber 1988).

Plant measures analysis

Evaluation of aboveground biomasses and grain yields of maize and wheat were carried out after harvesting the plants. The main outcomes of this study is to figure out the appropriate combination of biochar and inorganic NPK fertilizers to achieve the highest possible straw and garin yields. Evaluating the effectiveness of these treatments at different stages of crop growth will be considered in further studies. To determine the Harvest Index (HI), the grain yield was divided by the biological yield (grain + straw) and multiplied by 100, according to the methodology proposed by Buresh et al. (1988).

$$HI = Grain\ yield/Biological\ \left(grain\ +\ straw\right)\ yield\ \times\ 100$$

Determination of maize and wheat grains involved wet digestion using sulfuric and perchloric acids. The percentage of nitrogen (N%) in the grains was determined using the micro Keldahl method. Grain protein content (%) was calculated by multiplying grain N ratios by 5.83 for wheat and by 6.25 for maize, as suggested by FAO (2003).

Statistical analysis

Data analyzes were performed via one-way ANOVA at 0.05 and Tukey's honestly significant variance (HSD) test using SPSS 18. Figures were plotted with Sigma-Plot 10 software.

Results

Effect of biochar and mineral NPK applications (either solely or in combinations) on Soil organic carbon (SOC) and bulk density (BD) after crop harvesting

All additives had significant impacts on increasing soil organic carbon within the two seasons of study (Table 3, Fig. 2A). This, in turn, led to a concurrent decrease in the bulk density of the soil (Fig. 2B). Even in the treatment that received only mineral applications of NPK, soil organic carbon levels were increased significantly by the end of growing seasons. The highest increases in soil organic matter were attained for application of biochar solely, while achieving the least soil bulk density. Following this, the treatment combining 75% biochar and mineral supplements gave similar results. No significant variations was observed owing to the application of the other treatments on the studied parameters. These results suggest that biochar plays an effective role in increasing soil organic carbon content, thereby improving soil structure and reducing its bulk density.

Effect of biochar and mineral NPK applications (either merely or in mixtures) on soil chemical characteristics after crop harvesting

Application of biochar as a substitute for NPK mineral fertilizers resulted in some significant changes in soil chemical properties (Table 4). For example, notable increases occurred in soil cation exchange capacity (CEC) (Fig. 3C) and nitrogen (N) availabile content in soil within both seasons of the study (Fig. 3D), especially with the application of higher dose of biochar. In contrast, biochar lessened soil salinity (Fig. 3A) versus 100% NPK as mineral fertilizers, in spite of that, the EC in biochar amended soil was higher than the unamended control. On the other hand, no significant differences were observed among treatments in terms of soil pH (Fig. 3B), or the available contents of phosphorus (P) and potassium (K) in soil (Fig. 3E and F).

Impact of biochar and mineral NPK applications on dissolved and microbial fractions of C and N after crop harvesting

Soil additives affected significantly dissolved and microbial fractions of C and N after cultivation of maize and wheat (Table 5). The highest increases in dissolved

Table 3 Effect of single and combined applications of RSB and NPK mineral fertilizers on soil organic matter and bulk density

	Summer season (maize)					**Winter season (wheat)**			
	Sum of squares	**df**	**Mean square**	**F**	**Sig**	**Sum of squares**	**Mean square**	**F**	**Sig**
Soil organic matter									
Between groups	213.008	5	42.602	93.693	< 0.001	305.163	61.033	109.670	< 0.001
Within groups	5.456	12	0.455			6.678	0.557		
Total	218.464	17				311.841			
Soil bulk density									
Between groups	0.084	5	0.017	6.275	0.004	0.107	0.021	8.228	0.001
Within groups	0.032	12	0.003			0.031	0.003		
Total	0.116	17				0.139			

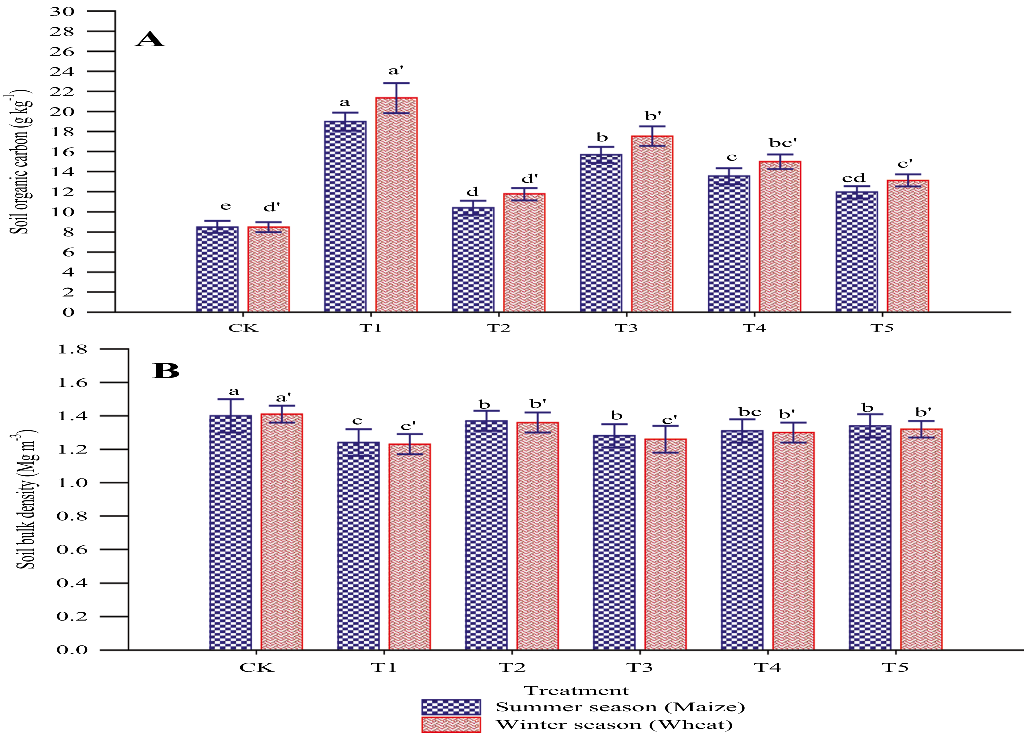


Fig. 2 SOC (**A**) and BD (**B**) as affected by the single and combined applications of RSB and NPK after maize and wheat harvesting (2020 and 2021). CK: the non-amended control, T_1: 100% of N inputs as biochar, T_2: the 100% mineral treatment, T_3: 75%RSB + 25%NPK, T_4: 50%RSB + 50%NPK, T_5: 25%RSB + 75%NPK. Different letters specify significant variations among treatments

organic carbon (Fig. 4A) and nitrogen (Fig. 4B), as well as their microbial fractions (Fig. 4C, D) were detected when the soil received 100% NPK mineral fertilizers or the combined applications of NPK mineral fertilizers and biochar (Fig. 4). Probably, such increases occurred due to the concurrent increases in root growth and its exudates owing to these applications.

Impact of biochar and mineral NPK uses on the activities of Urease, phosphatase and Dehydrogenase (DHA) enzymes after crop harvesting

Urease, phosphatase and dehydrogenase enzymes are used in our study as indicators of soil microbial activities (Fig. 5). In this concern, organic and minerals additives (applied solely or in combinations) recorded insignificant impacts on alkaline phosphatase activity (Fig. 5B); nevertheless these additives (organic ± mineral fertilizers) affected significantly urease (Fig. 5A) and dehydrogenase (Fig. 5C) within the winter and summer seasons of the study. Urease activity raised significantly in T_1 to T_5 versus CK; yet variations among these treatments seemed to be comparable; except for T_4 in the second season. Regarding the activity of dehydrogenase enzyme, all additives also upraised its activity versus Ck, with superiority for T_2 (the 100% mineral treatment) and T_3 (75%RSB + 25% mineral NPK fertilizers) (Table 6).

Impact of biochar and mineral NPK applications on growth parameters and productivity of wheat and maize crops

Application of organic and inorganic fertilizers improved significantly straw and grain yields of both maize and wheat compared to the control (Table 7). The most notable improvements were observed in the soil that received a combination of “25% biochar + 75% mineral fertilizer” (T_5) as well as the one recieved “50% biochar + 50% mineral fertilizer” (T_4), exceeding even 100% mineral NPK treatment (Fig. 6A, D). However, biochar alone was not effective enough for promoting plant growth and productivity (especially in wheat).

There were no significant differences in harvest index among treatments in the two studied crops (Fig. 6B and E). Concerning protien content in wheat and maize grains (Fig. 6C and F), all combined applications recorded higher protien percentage than single ones.

Table 4 Effect of single and combined applications of RSB and NPK mineral fertilizers on soil chemical chracteristics

		Summer season				Winter season			
	df	Sum of squares	Mean Square	F	Sig	Sum of squares	Mean Square	F	Sig
Soil salinity (EC, dS m-1)									
Between groups	5	0.137	0.027	6.924	0.003	0.137	0.027	6.750	0.003
Within groups	12	0.048	0.004			0.049	0.004		
Total	17	0.185				0.186			
pH									
Between groups	5	0.015	0.003	0.020	1.000	0.022	0.004	0.030	0.999
Within groups	12	1.765	0.147			1.765	0.147		
Total	17	1.780				1.787			
CEC ($cmol_c\ kg^{-1}$)									
Between groups	5	29.171	5.834	3.246	0.044	31.054	6.211	3.410	0.038
Within groups	12	21.571	1.798			21.857	1.821		
Total	17	50.743				52.911			
Available N ($mg\ kg^{-1}$)									
Between groups	5	643.310	128.662	46.043	< 0..001	718.563	143.713	49.645	< 0..001
Within groups	12	33.533	2.794			34.738	2.895		
Total	17	676.843				753.300			
Available P ($mg\ kg^{-1}$)									
Between groups	5	0.784	0.157	0.706	0.630	0.893	0.179	0.800	0.571
Within groups	12	2.667	0.222			2.680	0.223		
Total	17	3.451				3.573			
Available K ($mg\ kg^{-1}$)									
Between groups	5	7.688	1.538	0.043	0.999	8.187	1.637	0.046	0.998
Within groups	12	429.166	35.764			429.561	35.797		
Total	17	436.854				437.748			

In this regard, the effects of these combined treatments were similar on maize, while T_5 showed superiority on increasing this percentage in wheat.

Discussion

Effect of organic and mineral fertilizers on soil bio-chemical characteristics

Soil microbial activities were significantly enhanced owing to the usage of organic and inorganic additives, either individually or in combinations. In case of adding mineral fertilizers, they enrich soil with soluble nutrients, thereby promoted plant growth. This, in turn, stimulate the release of root exudates (Zhu et al. 2016), which contribute to about 11 to 40% of total fixed carbon through the process of photosynthesis (Sun et al. 2021). These exudates enhance the activities of soil biota. On the other hand, biochar, although is considered a less readily available source of nutrients (Elshony et al. 2019), it contains additional microorganisms which cope to biotic and abiotic stressors. This makes biochar an effective additive for improving soil microbial activities (Pathy et al. 2020).

Soil enzymes are considered indicators of the overall activity of soil biota (Curyło and Telesiński 2020; Mohamed et al. 2021). Results obtained herein indicate that all treatments significantly improved activities of urease and dehydrogenase enzymes compared to the control group. However, no significant variations were observed among the investigated treatments in terms of alkaline phosphatase enzyme activity. This probably occur because biochar is a relatively stable organic compound against microbial degradation (Farid et al. 2022). Thus soil biota secret excessive amounts of urease which is extracellular enzymes (Pokharel et al. 2020) as well as dehydrogenase which is an intracellular enzyme (Pokharel et al. 2020). These enzymes are thought to play crucial roles in degradation of organic matter (Li et al. 2019); neverthless because of the complexity of organic carbon in biochar, these additive did not significantly enhance some activities of soil biota (McCormack et al. 2019) i.e. activity of alkaline phosphatase enzyme.

The highest fractions of dissolved organic carbon (C) and nitrogen (N) were found in the soil that received combined applications of organic and mineral

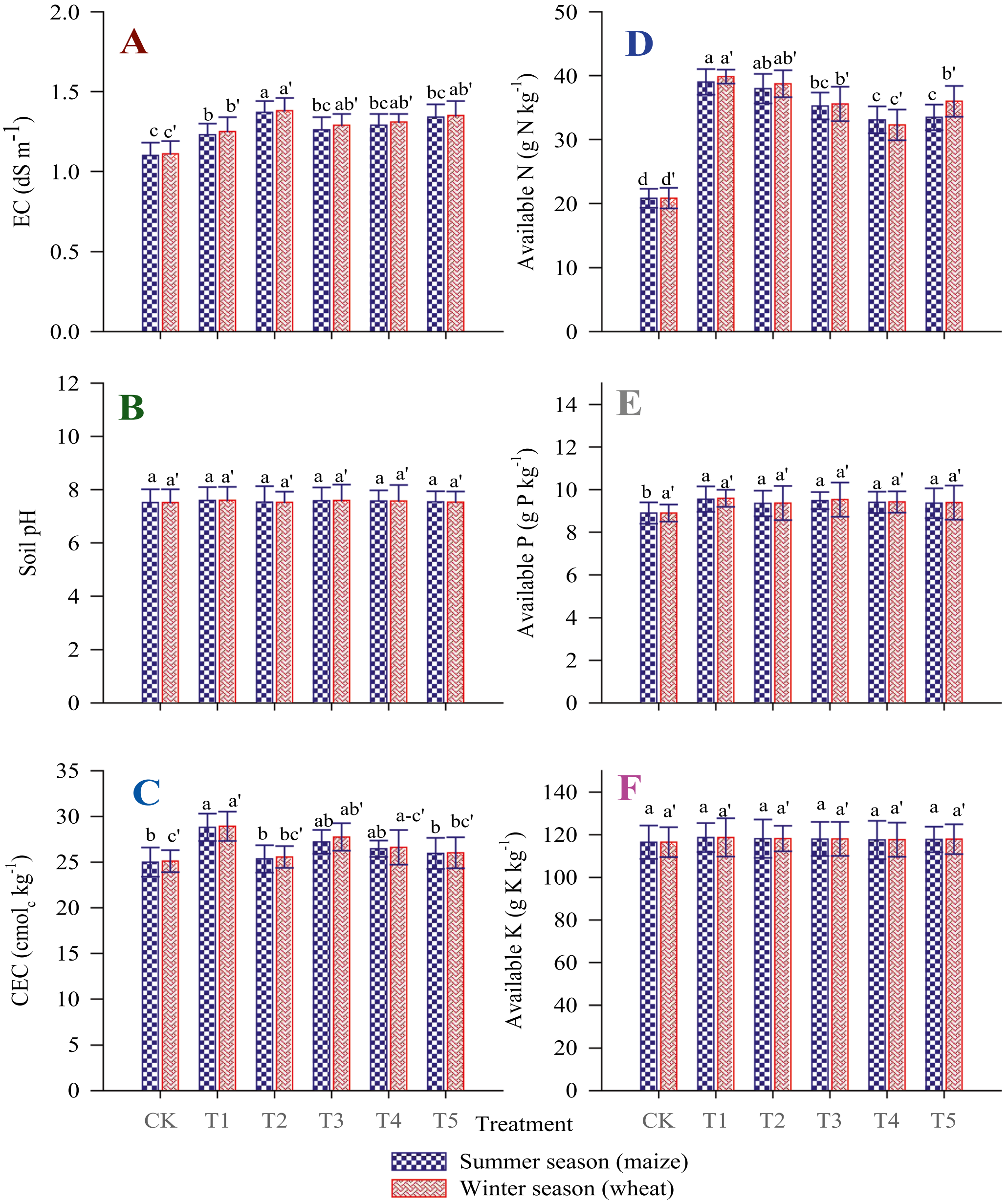


Fig. 3 Soil chemical properties (EC (**A**), pH (**B**), CEC (**C**), available N (**D**), available P (**E**) and available K (**F**),means ± SD) as affected by single and combined applications of RSB and NPK after maize and wheat harvesting (2020 and 2021). See footnote Fig. 2. Different letters specify significant variations among treatments

treatments (T_3, T_4 and T_5). Such increases exceeded even the corresponding ones of the treatment biochar to satisfy 100% of N requirements (T_1). Mostly mineral fertilizers raised the levels of available nutrients in soil for optimal plant growth (Gram et al. 2020), while biochar retain the availability of these nutrients in soil for longer time periods (El-Naggar et al. 2019b). Therefore, this combination (inorganic and organic inputs) enhanced plant growth and subsequently stimulated the activities of soil organisms through increasing root secretions (Wolny-Kołladka et al. 2022). Some of these secretions were used by microorganisms, while others

Table 5 Effect of single and combined applications of RSB and NPK mineral fertilizers on the dissolved and microbial fractions of C and N

	Summer season (maize)					Winter season (Wheat)			
	df	**Sum of Squares**	**Mean Square**	**F**	**Sig**	**Sum of squares**	**Mean Square**	**F**	**Sig**
Dissolved organic carbon									
Between groups	5	48,760.5	9752.1	18.985	< 0.001	49,996	9999.2	18.91	< 0.001
Within groups	12	6164.04	513.67			6345.32	528.777		
Total	17	54,924.54				56,341.32			
Dissolved organic nitrogen									
Between groups	5	446.336	89.267	15.355	< 0.001	509.625	101.925	15.907	< 0.001
Within groups	12	69.764	5.814			76.89	6.407		
Total	17	516.1				586.515			
Microbial biomass carbon									
Between groups	5	5572	1114.4	18.089	< 0.001	5740	1148	17.803	< 0.001
Within groups	12	739.289	61.607			773.793	64.483		
Total	17	6311.289				6513.793			
Microbial biomass carbon									
Between groups	5	758.792	151.758	14.657	< 0.001	1330.679	266.136	21.911	< 0.001
Within groups	12	124.246	10.354			145.754	12.146		
Total	17	883.038				1476.433			

were stored in aggregates for later use, thereby increasing the organic matter content of the soil (Abdelhafez et al. 2018). As mentioned above, biochar acts as a slow-release nitrogen source and its application alone can reduce nitrogen uptake by soil organisms. Additionally, the slow rate of biochar degradation (Farid et al. 2022) ensured significant improvements in soil organic carbon retention, leading to increasing soil aggregation (Bassouny and Abbas 2019) and soil cation exchange capacity (CEC).

Effect of the investigated treatments on available contents of soil nutrients (N, P and K)

Mineral additives exhibited higher impacts on increasing soil N- available contents versus biochar. Specifically, the two treatments T_2 and T_3 recorded the highest increases. Maybe the degradation of biochar is slow (Hasnat et al. 2022); yet, its functional groups retained most of the avaialble nitrogen in the topsoil soil for longer time periods consequently preventing its loss (Li et al. 2021). In addition, biochar could have increase secretions of root exudates, which take part in the N-cycle in soil (Sun et al. 2021).

In case of soil available phosphorus (P) and potassium (K), variations among all treatments were almost insignificant. Maybe. the release of phosphorus and potassium from biochar is low during its degradation (Elshony et al. 2019). On the other hand, inorganic forms of these two nutrients are more prone to be fixed rapid in soil (Billah et al. 2019; Portela et al. 2019). Therefore, no significant variation was observed in the availability of these two nutrients according to the different treatments, whether organic or inorganic.

Effect of the investigated treatments on growth and productivity of maize and wheat

Over two consecutive summer and winter seasons, use of biochar resulted in significant improvements in growth and productivity of maize and wheat plants. However, these improvements were significantly lower than those achieved due to the usagee of mineral NP fertilizers. This observation confirms the first hypothesis. Notably, the combined treatments (T_4 and T_5) showed the greatest increases in grain and straw yields for both maize and wheat, even surpassing the results of the mineral treatment (100% NPK mineral fertilizers, T_2).

Increases in proportion of grain and straw yields of both crops remained almost constant, resulting in no significant differences in crop harvest index. Nevertheless, it was observed that the combined treatments (T_3, T_4 and T_5) demonstrated the greatest improvements in protein

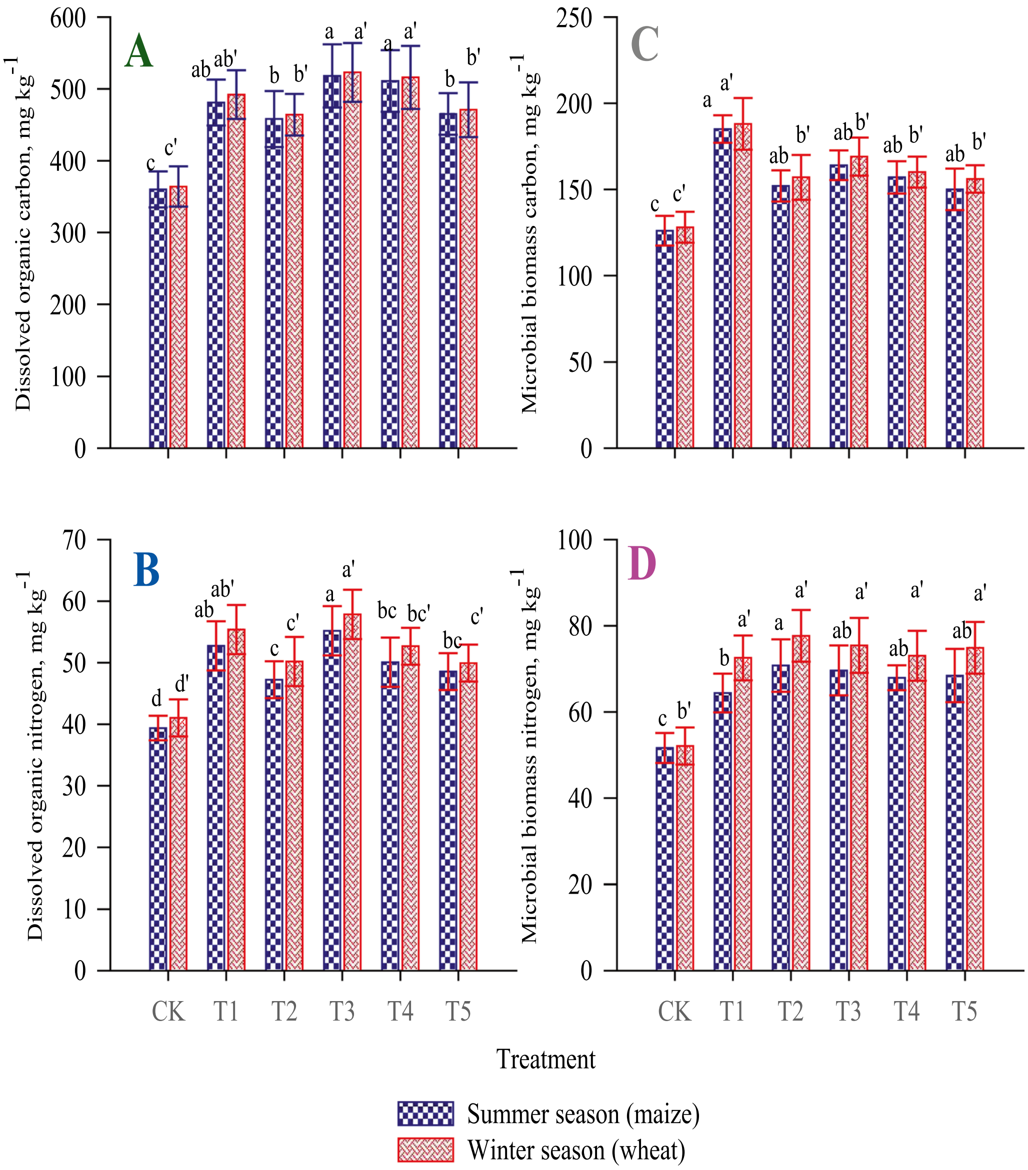


Fig. 4 Dissolved organic C (**A**) and N (**B**) as well as their microbial fractions (**C**, **D**) (means ± SD) as impacted by the single and combined uses of RSB and NPK after maize and wheat harvesting (2020 and 2021). See footnote Fig. 2. Different letters specify significant variations among treatments

content of maize and wheat grains, outperforming the reference treatment (T_2). The highest protein content in crop cereals were estimated in the combined application of organic and mineral fertilizers, exceeding even the effect of fertilization with NPK mineral fertilizers to satisfy 100% of plant needs (Farid et al. 2018, 2021a, 2021b). Additionally, the combined use of biochar and mineral fertilizers has been shown to improve soil nitrogen retention and reduce N_2O emissions (Li et al. 2021). Based on these results, the second hypothesis gains credibility.

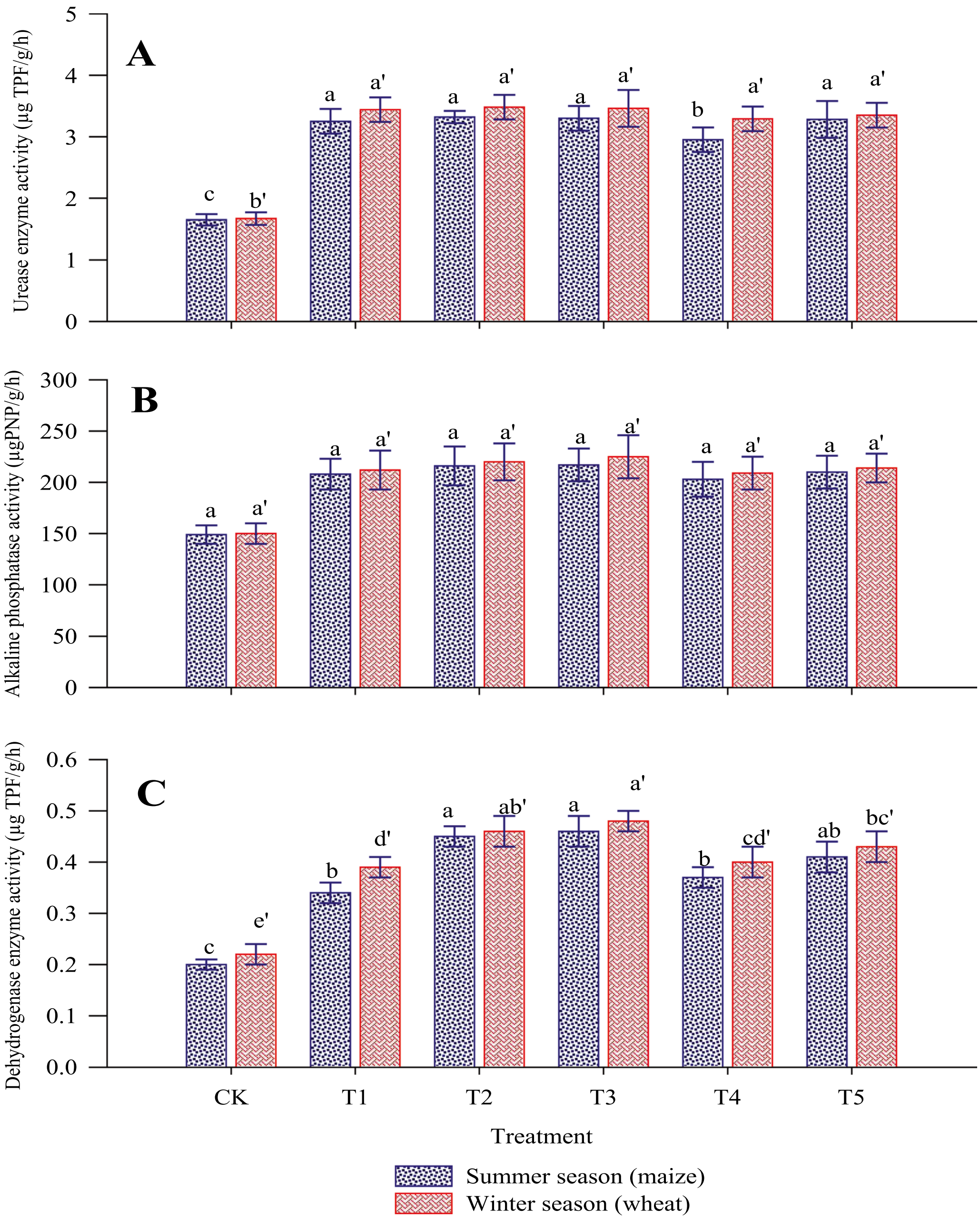


Fig. 5 Soil enzyme activities (urease **A**, alkaline phosphatase **B** and dehydrogenase **C**) (means ± SD) as impacted by the single and combined uses of RSB and NPK after maize and wheat harvesting (2020 and 2021). See footnote Fig. 2. Different letters specify significant variations among treatments

Conclusion

Biochar stimulated activities of soil biota, i.e. increased urease and dehydrogenase enzymes. These microorganisms compete partially with cultivated plants for available nutrients in soil and therefore no notable increases were detected in availability of some nutrients in soil such as phosphorus (P) and potassium (K). Neverthless, biochar solely improved soil fertility and enhanced maize and wheat growth and productivity compared to the control.

Combined applications of mineral and organic NPK inputs increased additionally the availability of nitrogen in soil and also enhances the activity of soil enzymes

Table 6 Effect of single and combined applications of RSB and NPK mineral fertilizers on soil enzyme activities (urease, alkaline phosphatase and dehydrogenase)

	Summer season (maize)					Winter season (wheat)			
	df	**Sum of squares**	**Mean square**	**F**	**Sig**	**Sum of squares**	**Mean square**	**F**	**Sig**
Urease enzyme activity									
Between groups	5	6.444	1.289	61.376	< 0.001	7.595	1.519	65.636	< 0.001
Within groups	12	0.252	0.021			0.278	0.023		
Total	17	6.696				7.873			
Alkaline phosphatase enzyme activity									
Between groups	5	1.419	0.284	1.476	0.268	1.934	0.387	1.677	0.215
Within groups	12	2.037	0.192			2.768	0.231		
Total	17	3.726				4.702			
Dehydrogenase enzyme activity									
Between groups	5	0.138	0.028	84.525	< 0.001	0.13	0.026	70.096	< 0.001
Within groups	12	0.004	0			0.004	0		
Total	17	0.142				0.134			

Table 7 Effect of single and combined applications of RSB and NPK mineral fertilizers on maize and wheat garin yields, protien content within garins and harvest index

	Maize					Wheat			
	df	**Sum of squares**	**Mean square**	**F**	**Sig**	**Sum of squares**	**Mean square**	**F**	**Sig**
Grain yield									
Between groups	5	39.232	7.846	50.289	< 0.001	21.194	4.239	18.822	< 0.001
Within groups	12	1.872	0.156			2.703	0.225		
Total	17	41.104				23.897			
Straw yield									
Between groups	5	29.3	5.86	41.49	< 0.001	12.492	2.498	9.531	0.001
Within groups	12	1.695	0.141			3.146	0.262		
Total	17	30.995				15.638			
Harvest index									
Between groups	5	44.469	8.894	1.051	0.433	68.225	13.645	1.424	0.284
Within groups	12	101.539	8.462			115.006	9.584		
Total	17	146.009				183.231			
Protein content in grains									
Between groups	5	29.137	5.827	11.371	< 0.001	10.375	2.075	6.89	0.003
Within groups	12	6.15	0.512			3.614	0.301		
Total	17	35.287				13.99			

which are responsible of building soil organic matter; thus take part in improving soil fertility and the formation of aggregates. This combination helps buffer the alkaline nature of biochar in the soil and reduces salinity stress on plants compared to using mineral fertilizers alone. As a result, the highest quantity and quality of maize and wheat crop yields were attained for these combined treatments, especially 25%RSB + 75% mineral NPK fertilizers.

Limititions of the study

This study did not consider evaluating NPK uptake within the different stages of plant growth. Thus, further studies are needed to satisfy this point of research. Also, extensive monitoring for the changes that occurred in soil enzymes owing to the investigated organic and mineral additives could be considered in such studies.

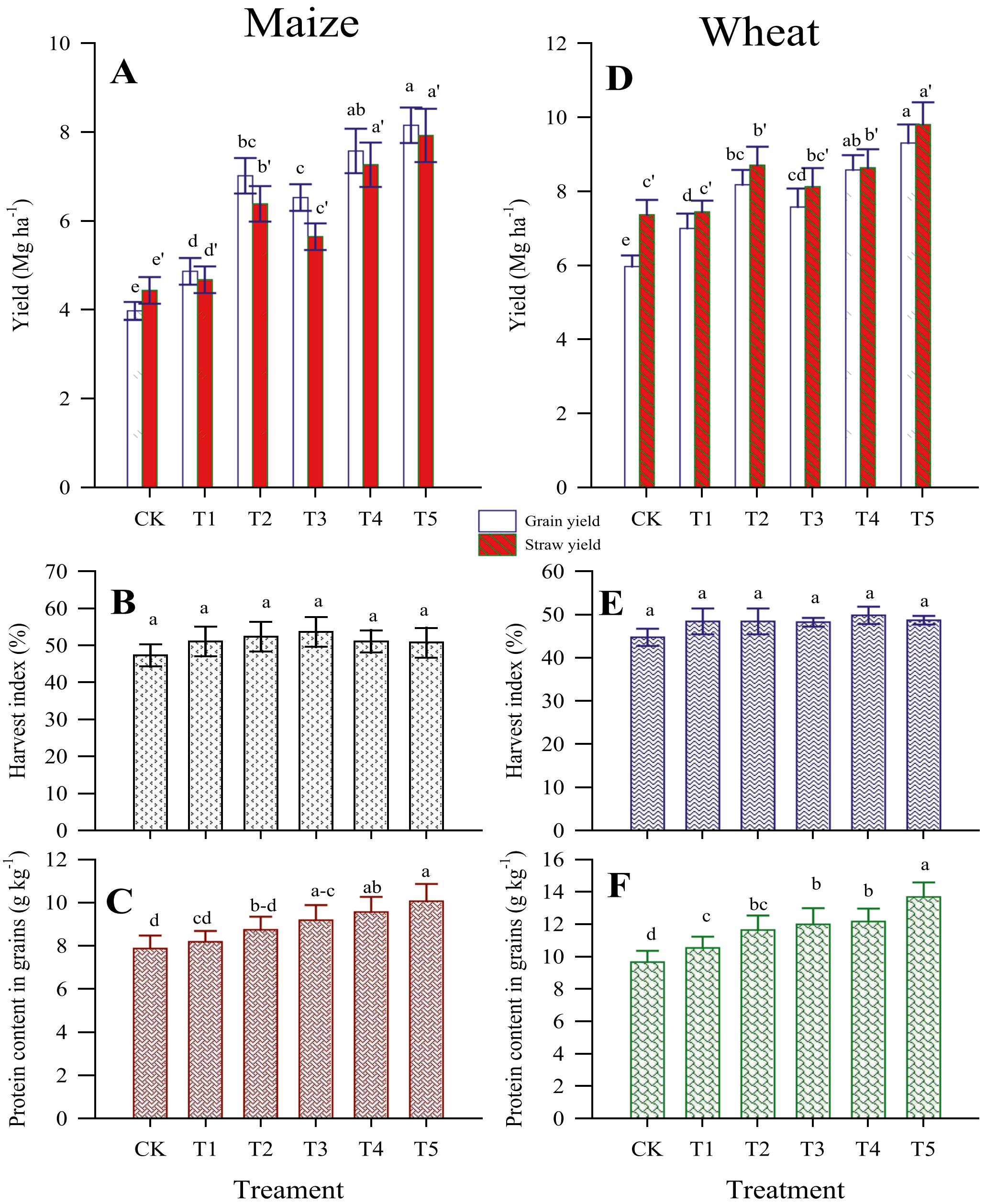


Fig. 6 Straw and gain yields of maize (**A**) and wheat (**B**) crops as well as their harvest indexes (**B**, **E**) and protien contents within grains (**C**, **F**) (means ± SD) as impacted by the single and combined uses of RSB and NPK after crop harvesting (2020 and 2021).See footnote Fig. 2. Different letters specify significant variations among treatments

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conceptualization, methodology, software, validation, formal analysis, investigation, resources, data curation, writing—original draft, writing—review & editing, supervision, project administration, funding acquisition.

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Competing interests
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