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Improvement in nitrogen use efficiency and associated parameters by integration of biochar and nitrogenous fertilizers for optimum wheat production

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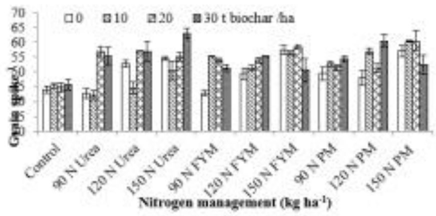
Abstract

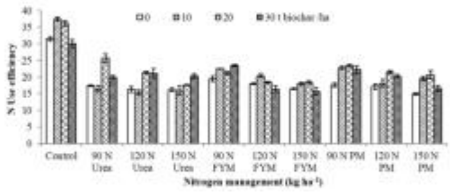
Nitrogen (N) losses are predominant in alkaline soils due to the excessive use of N fertilizers, and the resulting low nitrogen use efficiency (NUE). The objective of this study was to evaluate the effects of Acacia prunings biochar (BC) applied at the rate of 0, 10, 20 and 30 t ha^{-1}, in combination with 0, 90, 120 and 150 kg N ha^{-1} applied from urea, farm yard manure (FYN), poultry manure (PM) on Wheat yield components, NUE, and its associated parameters over 2 years of field experiment (2015-2017). Results indicated that the sole application of BC significantly improved thousand grains weight (TGW), grains $spike^{-1}$, NUE and nitrogen uptake efficiency (NUpE) by 10.81, 9.02, 21.35 and 16.43% respectively, over the absolute control when averaged across both years. Similarly, the application of only N management significantly improved TGW, grains $spike^{-1}$, nitrogen utilization efficiency (NUtE) and nitrogen harvest index (NHI) by 32.14, 27.98, 4.47 and 16.66% respectively, over the absolute control when averaged across the years. Moreover, the combined application of BC + N fertilizers significantly affected all of the above parameters. Hence, it was summarized from our study that combined application of 20 t BC and 150 kg N ha^{-1} lonely from poultry manure significantly improved yield components of wheat as well as NUE of fertilizers under semi-arid conditions.

Keywords: Biochar, Acacia, wheat, FYM, PM, NUE.

Graphical abstract



Improvement in nitrogen use efficiency and associated parameters can accomplish by combined application of biochar and nitrogenous fertilizers



1. Introduction

The global population is increasing rapidly and by 2050 it is expected to reach 9 billion (Haider *et al.*, 2017). Consequently, the demand for food, freshwater, energy, feed, and fiber is also expected to rise gradually (Haider *et al.*, 2017; Zabel *et al.*, 2014). The green revolution of the 1970s significantly boosted cereal crop production in Pakistan. Howeer, many issues such as soil erosion, perpetual decline in soil organic matter, conventional tillage operations and the ever-escalating prices of synthetic fertilizers have overshadowed these gains (Farhad *et al.*, 2009). By encouraging technological innovation and enforcing environmental protection measures, the new urbanization policy supports sustainable agricultural production and accelerates the process of agricultural modernization (Li and Lei; 2025). Meeting the need to increase crop yield and reduce production cost while maintaining soil health at the same time has become a challenge for agricultural scientists to ensure sustainable agriculture. To overcome these challenges, several strategies are under consideration such as incorporation of organic material (FYM and Biochar) as well as integrated nutrient management and organic farming all over the world (Angle *et al.*, 1993).

Given the growing demand for food, there is a dire need to intensify efforts on judicious use of the available land through integrated application of proper fertilizers particularly nitrogenous fertilizer as well as to maintain soil fertility for optimum crop production. Synthetic fertilizers are widely used but their prices are too exorbitant for the low resource farmers of Pakistan. Moreover, their prolonged and excessive use by the progressive and resourceful farmers has increased soil acidity which in turn deteriorates the efforts aimed at crops yield improvement.

The application of BC to soil is amazingly helpful for rehabilitating soil fertility, as well as to invigorate plant growth, and therefore, plays an important role in building up a sustainable approach in agriculture (Rawat *et al.*, 2019; El-Naggar *et al.*, 2019). To counter the conceivably inaccessible N, it has been discovered that application of BC alongside N fertilizer can have beneficial outcome, thus improving the effectiveness of mineral nitrogen N fertilizer, reducing the need for inorganic fertilizers, and minimizing the production cost (Sarfraz *et al.*, 2017).

Biochar (BC) contains some important plant nutrients that significantly influence crop growth. The use of wood BC, either alone or in integration with other manure mends crop yield compared to soils that receive no wood BC (Mensah and Frimpong, 2018). For instance, Solaiman *et al.* (2010) reported an 18% improvement in wheat yield components when wood BC (6 t ha^{-1}) was applied in combination with N (30 kg ha^{-1}). Similarly, nitrogen use efficiency (NUE) improved by 38% in the plots that received BC at 25 and 50 t ha^{-1} compared to plots have no BC (Ali *et al.*, 2015a). In another study Ali *et al.* (2015b) reported that BC applied to wheat at 25 t ha^{-1} had maximized spikes m^{-2}, grains in spike, 1000 grain weight, resulting in higher economic and biological yields by 6.64, 5.6 and 3.73% respectively relative to the control plots (Furthermore the application of BC at the rate of 30 tones ha^{-1} along with inorganic N fertilizer at the rate of 75 kg ha^{-1} increased number of rows per ear, 1000 grain weight, and both grain and biological yields of maize (Arif *et al.*, 2012). The presence of BC in soil also has encouraging effects on germination of seed, establishment of crop plants, and early crop growth (Genesio *et al.*, 2012). In this study, we investigated that incorporation of BC and N improved NUE and associated parameters in wheat grown for two consecutive years, with the goal of identifying optimal fertilization management strategies for sustainable wheat production.

The novelty of this study is that unlike previous studies, this research uniquely investigates the interactive effects of Acacia-derived biochar and multiple nitrogen sources under alkaline, semi arid field conditions. It provides new insights into how biochar nitrogen synergies can be optimized to enhance wheat productivity and nitrogen efficiency, offering a practical, low-cost soil management strategy for regions facing N losses and fertilizer inefficiency.

2. Materials and methods

2.1. Study area: geology

The study was undertaken at Agriculture Research Station Swabi, Khyber Pakhtunkhwa Pakistan, during Fall 2015 and 2016. The location lays on 34° 7', 48" N latitude and 72° 28', 11" E longitude, at an elevation of 350 m above sea level. Topographically, the site is relatively smaller slope gradient. Climatically, the study area has climate classified as warm and temperate, with an average annual rainfall of approximately 639 mm. Prior to sowing in 2015, composite soil samples were collected at the experimental site from a layer of 0-15 cm. The sample was analyzed for routine soil analysis and is already published (Khan *et al.*, 2020).

2.2. Biochar Preparation

Biochar was produced from Acacia prunings collected locally. The feedstock was air dried, cut into small pieces (2–5 cm), and pyrolyzed in a closed-drum kiln under limited oxygen conditions at 450 ± 10°C for 3 hours. The resulting biochar was cooled, crushed, and sieved through a 2 mm mesh to obtain a uniform particle size before field application. This temperature range ensured partial carbonization, retaining both aromatic carbon structures and nutrient availability suitable for agricultural use.

2.3. Experimental layout and design

A total of 120 subplots, each with a size of 3 × 4 m, were laid out at experimental stations. The plots were prepared using traditional implements. Each subplot was raised and bunded, while a spacing of 1 m^2 was maintained between adjacent plots. Acacia pruning's biochar (BC) was tilled into the 15 cm soil in each plot according to the planned treatment doses with the help of rotavator. An improved variety of Wheat (Pirsabak 2013) commonly cultivated in the region, was manually sown at a rate of 120 kg ha^{-1} using hand hoe. Experimental treatment was arranged in a 2-factorial randomized complete block design arranged in a split plot layout with three replications. The treatments consisting of: Four BC rates: 0, 10, 20 and 30 t ha^{-1}, and N management (control 0, 90, 120, 150 kg from urea, 90, 120, 150 kg from FYM, 90, 120 and 150 kg from PM). The appropriate rates of N were calculated from urea, FYM and PM based on the percent N present in each source. Urea was applied in split doses (half at sowing and half at tillering stage). While FYM and PM were applied a week before sowing and BC were applied at the time of seedbed preparation. A basal dose of P and K at 90 & 60 kg ha^{-1} was calculated from both single super phosphate and potassium sulphate, respectively and were applied uniformly to all sub-plots. BC was applied once, while urea, FYM and PM were applied during both seasons. Sowing was done on November 8th, 2015, and November 5th, 2016. Weeds were controlled manually using a hoe to avoid competition with the wheat plants. Crops were irrigated with canal water as required to avoid water stress. The same field and layout of the experiments were maintained for the experiment in 2016-17 to ensure consistency across years.

2.4. Procedure for recorded observations

Spikes of the five randomly selected plants in each subplot were threshed individually with the help of single spike thrasher; grains were counted and converted into average grains $spike^{-1}$. From the grains of four harvested rows of each subplot, 1000 grain weight was determined using a sensitive weight balance. Nitrogen use efficiency (NUE), Nitrogen Uptake Efficiency (NUpE) and nitrogen utilization efficiency (NUtE) were determined according to (Rahimizadeh *et al.*, 2010).

$$\text{NUE}\left(\text{kg kh}^{-1}\right) = \frac{\text{Grain Yield}}{\text{N Supply}}$$

Where GY is grain yield, N supply is sum of soil N content at sowing and N fertilizer applied. According to Limon-Ortega *et al.* (2000), N supply was defined as the sum of (i) N applied as fertilizer and (ii) total N uptake in control (0 N applied).

$$\text{NUpE}\left(\text{kg kh}^{-1}\right) = \frac{\text{NT}}{\text{N Supply}}$$

Where NT is the total plant N uptake and N supply is sum of soil N content at sowing and N fertilizer applied.

$$\text{NUtE}\left(\text{kg kh}^{-1}\right) = \frac{\text{GY}}{\text{NT}}$$

Where GY is grain yield and NT is the total plant N uptake.

$$\text{NHI}(\%) = \frac{\text{NG}}{\text{NT}} \times 100$$

Where NG is total grain N uptake. NG was determined by multiplying dry weight of grain by N concentration and NT is the total plant N uptake.

2.5. Statistical analysis

Analysis of variance (ANOVA) was used to analyze the data following a 2 factorial RCBD with split plot arrangement. All analysis was done using SPSS 20th edition (SPSS, Inc., Chicago, IL, USA). In case of significant F test, the various treatments were compared at 5% probability value using LSD test (Steel and Torrie, 1980).

3. Results

Biochar and N management had a significant effect ($p \leq 0.05$) on number of grains $spike^{-1}$, 1000 grains weight and nitrogen use efficiency (NUE) of wheat (**Table 1**). Year as a source of variation was also significant for the above-mentioned parameters. Moreover, the interaction between BC and N was found significant while all other interactions were found non-significant for the above parameters. The application of BC significantly increased grain $spike^{-1}$ of wheat. The application of BC in the amount of 30 t·ha^{-1} resulted in an increase (9.42%) in the grain $spike^{-1}$ in relation to the control treatment, followed by (9.02 and 3.38%) increase in grain $spike^{-1}$ for 20 and 10 t ha^{-1} respectively. However, both 20 and 30 t BC ha^{-1} was statistically non-significant when compared to each other. As regards the N management, all the treatments produced significantly higher grains spike^{-1} than control. The maximum increase in numbers of grains spike^{-1} (27.98%) was obtained in treatments where 150 kg N ha^{-1} applied as PM followed by 150 kg N ha^{-1} applied as urea (24.01%) and 150 kg N ha^{-1} applied as FYM (23.81%). Combined application of BC and N on grains spike^{-1} of wheat indicated that grains spike^{-1} increased significantly among various treatments (**Figure 1**). Highest grains spike^{-1} was observed in plots where 30 t BC ha^{-1} was applied and 150 kg N ha^{-1} applied from urea. However, these results were statistically similar with those obtained in plots where 20 and 30 t BC ha^{-1} along with 150 kg N ha^{-1} was applied from PM and 30 t BC ha^{-1} with 120 kg N ha^{-1} applied as PM.

Table 1. Effect of BC N management on grains spike^{-1}, thousand grain weight (TGW)and NUE of wheat

Biochar (t ha^{-1})	**Grains spike^{-1}**	**TGW(g)**	**NUE (kg kg^{-1})**
0	49.82c	40.2 b	18.49 c
10	51.50b	41.2 b	20.66 b
20	54.31 a	44.5 a	22.44 a
30	54.51 a	43.2 a	20.59 b
LSD $_{(0.05)}$	1.42	1.36	0.57
Nitrogen Management (kg ha^{-1})			
Control	44.96 f	35.4 e	33.78 a
90 N Urea	49.21 e	38.9 d	19.88 c
120 N Urea	52.82 cd	42.7 bc	18.52 de
150 N Urea	55.75 ab	45.5 a	17.51 fg
90 N FYM	50.80 de	41.4 bc	21.66 b
120 N FYM	52.48 cd	42.8 bc	18.27 ef
150 N FYM	55.67 ab	45.7 a	17.16 g
90 N PM	51.96 cd	40.7 cd	21.00 b
120 N PM	54.17 bc	43.0 b	19.23 cd
150 N PM	57.54 a	46.8 a	17.93 efg
LSD $_{(0.05)}$	2.25	2.17	0.90
2015-16	49.53 b	40.0b	19.85 b
2016-17	55.54 a	44.5 a	21.24 a
Interactions	$P_{0.05}$	$P_{0.05}$	$P_{0.05}$
BC x N	Figure 1	Figure 2	Figure 3

Table 2. Nitrogen use efficiency (kg kg^{-1}), nitrogen uptake efficiency (kg kg^{-1}), nitrogen utilization efficiency (kg kg^{-1}) and harvest index (%) of wheat as affected by BC and N management

Biochar (t ha^{-1})	**NUpE (kg kg^{-1})**	**NUtE (kg kg^{-1})**	**NHI(%)**
0	0.45 d	38.17 a	62.84 a
10	0.48 c	35.92 b	59.94 c
20	0.51 b	36.33 b	61.16 b
30	0.52 a	33.59 c	58.73 d
LSD (0.05)	0.01	0.56	0.95
Nitrogen Management (kg ha-1)			
Control	0.76 a	34.92 e	54.30 f
90 N Urea	0.48 c	35.41 cde	58.54 e
120 N Urea	0.45 ef	36.62 ab	61.65 bc
150 N Urea	0.42 h	37.41 a	63.53 a
90 N FYM	0.52 b	36.21 bc	61.28bcd
120 N FYM	0.46 de	35.27 de	60.24 cd
150 N FYM	0.42 gh	36.32 b	62.19 ab
90 N PM	0.53 b	35.25 de	59.81 de
120 N PM	0.47 d	36.12 bcd	61.77 b
150 N PM	0.43 fg	36.48 b	63.35 a
LSD (0.05)	0.02	0.84	1.50
2015-16	0.48 b	36.77 a	62.41 a
2016-17	0.50 a	35.24 b	58.93 b
Interactions	P0.05	P0.05	P0.05
BC x N	Figure 4	Figure 5	Figure 6

Abbreviations: N, FYM, PM, BC, NUpE, NUtE, NHI stands for nitrogen, farmyard manure, poultry manure, biochar, nitrogen uptake efficiency, nitrogen utilization efficiency and nitrogen harvest index respectively.

Abbreviations: N, FYM, PM, BC, TGW, NUE stands for nitrogen, farmyard manure, poultry manure, biochar, thousand grains weight and nitrogen use efficiency respectively.

The addition of BC notably increased 1000 grain weight of wheat. Compared to BC control, the corresponding increase in 1000 grain weight for 10, 20 and 30 t BC ha^{-1} were 2.47, 10.81 and 7.43%, respectively. No significant differences in 1000 grain weight were found between 20 and 30 t BC ha^{-1}. Similar trend was also observed for 0 and 10 t BC ha^{-1}. Application of N from organic and inorganic sources resulted in higher 1000 grains weight compared to N control treatment. The application of N at 150 kg N ha^{-1} as PM, FYM and urea had higher (32.14, 29.00 and 28.42%) 1000 grains weight over control followed by 120 kg N ha^{-1} applied as PM. The corresponding increase for 120 kg N ha^{-1} applied as PM was (21.54%) over control. Combined application of BC and N on 1000 grains weight of wheat indicated that 1000 grains weight increased significantly among various treatments (**Figure 2**). However, highest 1000 grains weight was measured in plots where BC applied at the rate of 30 t ha^{-1} and N applied at the rate of 150 kg ha^{-1} d from urea. However, these results were statistically similar to results obtained by applying 20 t BC ha^{-1} along with 150 kg N ha^{-1} lonely from PM.

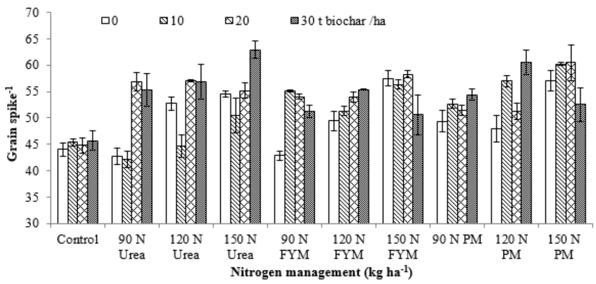


Figure 1. Interactive effect of BC and N on grain $spike^{-1}$ of wheat

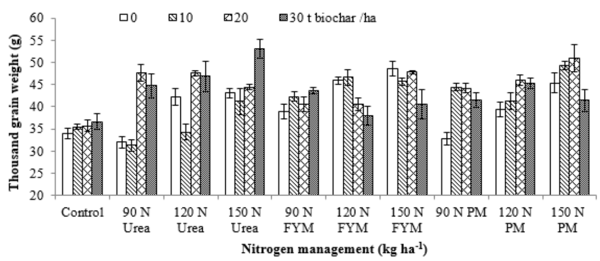


Figure 2. Interactive effect of BC and N on thousand grain weight of wheat

Increasing trend was observed for NUE with the application of BC from 10 and 20 t BC ha^{-1} . Specifically, incorporations of 10, 20 and 30 t BC ha^{-1} enhanced NUE by (11.70, 21.35 and 11.34%), respectively over BC control treatment. Generally, NUE in wheat decreased as the level of N increases from both organic and inorganic sources. Highest NUE in wheat were recorded in unfertilized plots as compared to N added plots. Figure 3 shows that application of BC alone improved NUE of wheat. Thus, higher NUE was observed by the application of 10 and 20 t BC ha^{-1} respectively.

Biochar and N management had significantly ($p \leq 0.05$) affected nitrogen uptake efficiency (NUpE), nitrogen utilization efficiency (NUtE) and nitrogen harvest index (NHI) of wheat (**Table 2**). Year as a source of variation was also significant for the said parameters. Moreover, the interaction between BC and N was found significant for all the above parameters.

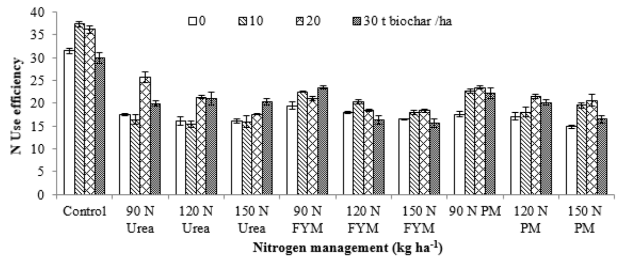


Figure 3. Interactive effect of BC and N on nitrogen use efficiency of wheat.

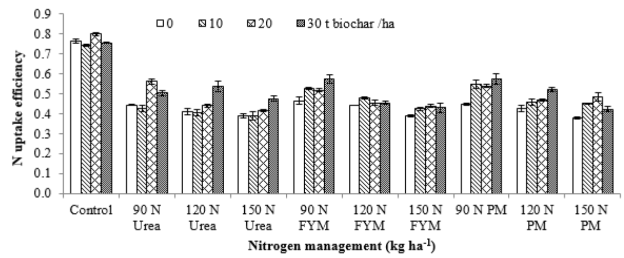


Figure 4. Interactive effect of BC and N on nitrogen uptake efficiency of wheat.

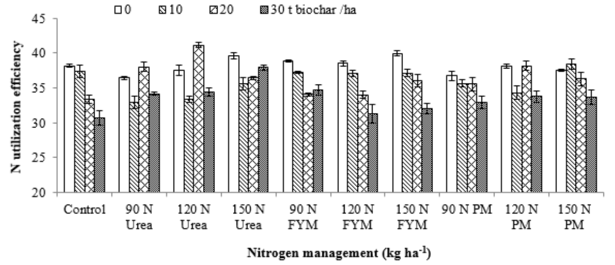


Figure 5. Interactive effect of BC and N on nitrogen utilization efficiency of wheat.

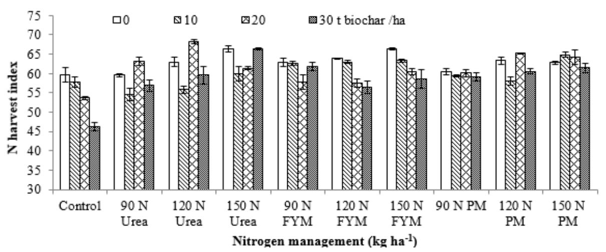


Figure 6. Interactive effect of BC and N on nitrogen harvest index of wheat.

Generally, increasing BC rates (0 to 30 t ha^{-1}) increased NUpE of wheat. Compared to BC control, the corresponding increase in NUpE of wheat for 10, 20 and 30 t BC ha^{-1} were 7.61, 13.57 and 16.43%, respectively. Similarly, NUpE of wheat also decreased as the level of N increased from both organic and inorganic sources. Highest NUpE of wheat was observed in unfertilized plots as compared to N added plots. Figure 3 and figure 4 show that application of BC alone improved NUpE of wheat. Thus, higher NUpE was observed by the application of 20 t BC ha^{-1}.

Compared to BC control, the wheat NUtE for 10, 20 and 30 t BC ha^{-1} were significantly reduced by 6.26, 5.06 and 13.64%, respectively. The corresponding decrease in wheat NHI was 4.84, 2.75 and 7.00%, respectively for 10, 20 and 30 t BC ha^{-1}. In addition, the application of N increased NUtE of wheat as compared to the control. The highest increased in wheat NUtE (7.14%) were recorded for treatment where 150 kg N ha^{-1} as FYM was applied, followed by 150 kg N ha^{-1} as FYM and PM. The corresponding increase in wheat NUtE for 150 kg N ha^{-1} as FYM and PM was (4.02 and 4.47%) over control. However, no significant differences in wheat NUtE were found between 150 kg N ha^{-1} as FYM and PM. Similarly, the application of N increased NHI in wheat as compared to the control. The highest increased in wheat NHI of (17.00 and 16.66%) were recorded for treatment where 150 kg N ha^{-1} as urea and PM was applied, followed by 150 kg N ha^{-1} as FYM. The corresponding increase of NHI in wheat for 150 kg N ha^{-1} as FYM was (14.54%) over control. However, no significant differences in NHI of wheat were found between 150 kg N ha^{-1} applied each from urea and PM. Figure 5 and 6 shows that application of BC alone decreases NUtE and NHI of wheat. However, the combined application of BC and N significantly improved both of the above parameters. Thus, higher NUpE and NHI were observed by the application of 20 t BC ha^{-1} and 120 kg N lonely applied from urea.

4. Discussion

The valuable effects of biochar (BC) incorporation on crop production can largely be attributed to its influence on soil physicochemical properties and/or nutrients availability. In our experiment, BC as a soil amendment applied at 20 and 30 t ha^{-1} had significantly increased wheat grains $spike^{-1}$. This improvement is likely due to the organic and porous nature of BC, which puts a positive impact on soil physico-chemical attributes, which considerably enhances soil structure, aeration, and water-holding capacity, and improves the retention and slow release of nutrients particularly N. These changes create a more favorable rhizosphere environment for root growth and nutrient uptake, ultimately supporting better spike development and grain filling that ultimately improved crop growth, yield and its components. Similar findings were reported by Cornellisen *et al.* (2013) who observed that an enhanced application of BC improved the yield and other yield attributes of cereals. Our results are also supported by Liang *et al.* (2006) who stated that BC is a porous material thus considerably increases moisture and nutrient content in the soil thereby enhancing yield components such as the number of grains per ear. Increase in grains $spike^{-1}$ was observed due to N management from various organic and inorganic sources. Statistically more grains $spike^{-1}$ was counted for 150 kg N ha^{-1} lonely from PM, urea and FYM. This might be attributed to the improved nitrogen supply which enhances the photosynthetic activity and improves the re-translocation of photosynthates and biomass accumulation thus producing more seeds per spike and enhanced seeds filling after flowering, which further maximized grain yield, Nitrogen plays a vital role in chlorophyll synthesis, enzyme activation, and leaf area expansion, leading to greater assimilate production. The above statement is also supported by Li *et al.* (2018). Similarly, various studies reported that enhanced N utilization improves the number of spikes per unit area (Duan *et al.*, 2018), which in turn enhanced vegetative growth and tillering (Tian *et al.*, 2017), subsequently increases the number of fertile tillers (Xiong *et al.*, 2018), the number of spikes (Kubar *et al.*, 2021) and thus ultimately increased grains per spike. Yildirim *et al.* (2016) further explained that incorporation of organic manures in the soil is supposed to decrease the depletion or evaporation rate, therefore, ensures enough water availability in the soil for proper roots growth, or possibly due to the continues nutrients supply throughout the growth period of crops.

In our study we found that application of BC increased wheat TGW. Heaver grains weight was noted in 20 and 30 t BC ha^{-1} amended plots. This might be attributed to the greater availability of essential nutrients, particularly nitrogen in the BC incorporated plots, which further improved accumulation of food materials in the seed. It was supported by the findings of Ali *et al.* (2013) who observed maximum 1000 grain weight due to BC application at 25 t ha^{-1}. Moreover, BC as a soil amendment improves soil physio-chemical and biological properties, improves use efficiency of fertilizer, which further improves yield and its components and ultimately crop productivity (Deenik *et al.*, 2011; Van Zwieten *et al.*, 2010). Increase in grains weight is greatly associated with the accumulation of photosynthates. The improved grains weight in fertilized plots with higher dose of N may be due to availability of N during the critical stages. It was supported by the findings by Yildirim *et al.* (2016) who observed that increased N application enhanced grains weight of wheat. Also, heavier grains were produced when the inorganic N were applied in split doses (especially at sowing and/or boot stages) compared to single dose applied at the time of sowing. The heavier thousand grain weight in organic amendment like (PM and FYM) plots might be due the nature of organic amendments which decomposed slowly, improve water and nutrients holding capacity of the soil and supply nutrients to crop plants throughout the growth period, hence results in heavier grains weight (Mukhtiar *et al.*, 2018).

Application of BC largely improved NUE through positive and additive effects. The enhanced NUE of wheat in BC amended pots may possibly be accredited to the improved available nutrients within the BC (Bu *et al.*, 2017), increased cation exchange capacity (CEC) (Pereira *et al.*, 2017), nutrient retention and availability to the plants (Pereira *et al.*, 2015). Ali *et al.* (2015a) find out that BC treated plots improved NUE by

38% compared to plots without BC. This increase in NUE might be due to improved soil organic matter (Yamato *et al.*, 2006), CEC and decrease in pH (Zavalloni *et al.*, 2011). NUE significantly decreased with increase in nitrogen levels. However, higher NUE was observed for un-fertilized plots when compared with fertilized treated plots. The higher need of N and dry matter by grain at grain filling or maturity stage of crop was fulfill by reserved N and dry matter in the unfertilized plots and therefore, had improved the re-translocation of N into the grain of the crop compared to fertilized plots. The required and effective translocation of N from plant vegetative to reproductive parts looks to be the physiological basis of greater grain protein in wheat (Peng *et al.*, 2014) and is greatly affected by nitrogen fertilization. This translocation of N was observed in barely either from the recent uptake or from reserved of the vegetative parts and was thoroughly associated to the leaf activity (Woodruff and Tonks, 1983). Transformation of plant N from vegetative parts to grains through source sink competition (Aulakh *et al.*, 2000) might have encouraged the NUE in control plants. Our results are in line with those of Sowers *et al.* (1994); Lopez Bellido and Lopez-Bellido (2001) who recorded higher N use efficiency in control plots. Our results are also supported by Qahar *et al.* (2010) who observed higher NUE at optimum availability of N. He further indicated that NUE increased as external nutrient concentration in soil decreased. In our experiment an encouraging influence of application of BC on wheat NUpE was observed. Increasing NUpE and utilization in plants might improve crop yields, while decreasing N fertilization and consequently, environmental pollution (Perchlik and Tegeder, 2017). Several studies have reported that BC has the potential to decrease N leaching (Wang *et al.*, 2017) and adsorb NH_4 in soils (Taghizadeh-Toosi *et al.*, 2012) indicating that the higher fertilizer N uptake under BC amended plots was linked with a decreased fertilizer N loss (Win *et al.*, 2019), Hence better N uptake is efficiently used for and returns maximum straw and grain yield production. NUpE significantly decreased with increase in N levels. However, higher NUpE was observed for un-fertilized plots when compared with fertilized treated plots. Which could be due to partitioning of the total nitrogen content more to the vegetative part of the crop than to the grain and increased the total aboveground biomass yield with the application of nitrogen Sowers *et al.* (1994) found that the application of high N rates may result in poor N uptake and low N use efficiency due to excessive N losses. Other researchers also reported similar results Staggenborg *et al.* (2003) and Camara *et al.* (2003). In our present study the addition of BC significantly reduces NUtE and NHI. However, the result was inverse when BC and N were applied in integration. Significantly high NUtE and NHI were observed by BC control plots. Similar to the conclusion of a higher NHI induced by a BC-fertilizer composite reported by Joseph *et al.* (2013). Win *et al.* (2019) observed similar improvement in NUtE of forage rice cultivar LTAT-29 due to the combine addition of BC and bio fertilizer.

Overall, the improvements in yield and NUE observed in this study can be attributed to the combined effects of enhanced soil fertility, better nutrient retention, improved plant physiological responses, and optimized N allocation. Biochar serves as both a nutrient reservoir and a soil conditioner, reducing nutrient losses while sustaining supply to plants. Therefore, integrating BC with appropriate N management strategies offers a sustainable approach for improving wheat productivity and nitrogen use efficiency in semi arid conditions.

5. Conclusion

The key takeaways from our research are that the application of BC produced from Accacia prunings either alone or in combination with N fertilizers, had a significant impact on wheat yield components, NUE and associated parameters such as NUpE, NUtE and NHI. The interaction between BC and N fertilizers was also found significant for all the above parameters. This study is the first to demonstrate that Acacia-based biochar, when integrated with organic N sources, can mitigate nitrogen losses and improve fertilizer efficiency in alkaline, semi-arid soils conditions where conventional biochar-N research has been limited. The findings provide a scientifically validated management approach for enhancing wheat productivity, soil fertility, and sustainable nitrogen utilization in dry land farming systems. Hence, it can be summarized that combined application of 20 t BC and 150 kg N meet from poultry manure significantly improved wheat yield components, NUE as well as most of the N associated parameters under alkaline calcareous soil conditions.

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Conflict of interest

The co-authors have no conflict of interest.

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