OPEN ACCESS

ISSN: 2835-7868

Fentie D, et al. (2024): 364
DOI: 10.47991/2835-7868/JEES-124

Research Article

Journal of Earth & Environment Science

Locally Produced Biochar Derived from Water Hyacinth Impacts on Soil Nutrients and Bread Wheat Production in Ethiopia

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Citation: Fentie D, Mihretie FA, Kohira Y, Legesse SA, Abune BB, Sato S (2024) Locally Produced Biochar Derived from Water Hyacinth Impacts on Soil Nutrients and Bread Wheat Production in Ethiopia. J Earth Envi Sci: JEES-124.

Received Date: 17 January, 2024; **Accepted Date:** 07 March, 2024; **Published Date:** 03 April, 2024

Abstract

Crop production is affected by poor soil conditions such as acidification, nutrient deficiency, and compaction. The use of biochar, made from various biomass, is one of the options to improve those problems. However, few studies have been conducted under field conditions, especially using biochar derived from water hyacinth in a highland of Ethiopia. This study investigated the effects of combining different amounts of water hyacinth biochar (WHB) and NPS (19-38-7) chemical fertilizer on soil nutrients and wheat production conducted in a randomized block design with four replications (a total of 24 experimental plots). Four application rates of WHB (0, 5, 10, and 20 t ha^{-1}) and three rates of chemical fertilizer (0, 100, and 200 kg ha^{-1}) were evaluated during the 2021 and 2022 cropping seasons. The biochar was applied only in the 2021 season and chemical fertilizer was applied in each year. Combined application of 20 t ha^{-1} WHB and 100 kg ha^{-1} fertilizer significantly increased soil pH by 1% to 13% and 2.9% to 7.1% in the 2021 and 2022 seasons, respectively. NH_4^+-N and NO_3^--N concentrations increased significantly for the plots amended with 20WHB compared to those without biochar in both seasons. Wheat crop dry biomass and grain yield were improved by 13% and 6.4% under treatments of 20 t ha^{-1} WHB and 200 kg ha^{-1} fertilizer and 10 t ha^{-1} WHB and 200 kg ha^{-1} fertilizer, respectively, in the 2021 season. Similarly, as residual effects in the 2022 season, treatments of 10 t ha^{-1} WHB and 200 kg ha^{-1} fertilizer and 20 t ha^{-1} WHB and 100 kg ha^{-1} fertilizer improved dry biomass and grain yield by 14% and 11%, respectively, compared to control. Therefore, the amendment of the soil with WHB can be recommended to increase crop production in sustainable conditions in the highlands of Ethiopia.

Keywords: *Nitisol, Lake Tana, Residual effect, Bread wheat.*

1. Introduction

Healthy soil is the foundation of agricultural productivity; it produces healthy crops, and provides healthy food and livelihoods that improve human well-being [1]. Poor soil conditions such as acidification, nutrient deficiency, compaction, and salinization inhibit and/or prevent plant growth and development [2]. Soil nutrient deficiency is the main problem of African agriculture in general and in Ethiopia in particular. In Ethiopia, a large part of the population is hardly satisfied with reliable crop production, instead, the crop yield decreases due to low soil fertility [3]. Wheat crop, one of Ethiopia's most important food security crops, suffers from soil acidity, declining soil fertility, terminal moisture stress, diseases, and climate change. It was cultivated on a total area of 2.1 million hectares annually with a total production of 6.7 million tons in the 2021/2022 cropping season in Ethiopia. However, there is a huge gap between wheat production and supply due to the increasing demand of the population and low productivity due to low soil fertility and other related factors. [4].

Soil pH is often used as an indicator for soil fertility status [5] which regulates the entire chemistry of plant nutrient colloidal solutions. Plant growth often occurs under a range of soil acidity conditions. Beyond a certain level of pH, multiple stresses such as ion toxicity and nutrient imbalance are induced in plants [6]. It also hinders the uptake of essential nutrients by plants and increases the possibility of toxic metals being absorbed from the soil [7]. In the humid tropics including Ethiopian highlands, soils become naturally acidic because alkaline cations which are important for plant growth are washed out during heavy rainfall [8]. Soil acidity associated with soil fertility problems is the main constraint hindering crop production in most highlands of Ethiopia. About 40.9 % of the Ethiopian highlands with an altitude of > 1500 m arable lands are affected by soil acidity. About 27.7% is moderate to weakly acidic (pH 5.5–6.7) and 13.2% is strong to moderately acidic (pH < 5.5). Strong acidic soils with pH < 5.5 considerably influence crop growth and require intervention [9]. This acidic and infertile soil requires a large amount of fertilizer for growing crops, which is not affordable for poor farmers in Ethiopia. Moreover, frequent application of chemical fertilizers can adversely affect the soil environment and reduce nutrient uptake efficiency by crops [8]. Liming is an important and currently implemented method of managing acidic soils in Ethiopia. However, large quantities may be needed for severely affected areas, which can cause costly and difficult transportation [10]. Therefore, soil amendment using locally available resources such as biochar produced from various biomass can be one solution for poor farmers of Ethiopia.

Biochar is widely used as a soil conditioner to improve the physical, chemical, and biological properties of soil [11, 12]. Due to its liming potential, it is increasingly considered as an effective soil amendment to reduce soil acidity, thereby improving soil fertility and productivity in acidic soils [7]. For effective plant growth, biochar generally contains some macronutrients (nitrogen, phosphorus, and potassium), micronutrients (sulfur, calcium, and magnesium), and trace elements (iron, copper, boron, zinc, manganese, etc.) [13]. Crop responses to biochar application show average yield increases by 10% to 42%, with the greatest responses on acidic and sandy soils where biochar was applied along with organic and/or mineral fertilizers [14]. Biochar`s effect depends on the feedstocks, which affect the nutrient content, pH, and structure of biochar [15]. Water hyacinth, which is one of the most invasive aquatic weeds globally including Ethiopia, affecting socioeconomic activities and watershed ecosystems, can be as a good feedstock source for biochar production. Since 2011, water hyacinth (*Eichhornia crassipes*) has invaded Lake Tana, Ethiopia, causing significant damage to the lake's biodiversity and livelihoods [16]. Currently, the Ethiopian government uses various control mechanisms, including mechanical and manual removal, biological control, and a combination of these measures to remove the weeds from the lake. Transportation and management of the removed biomass is labor-intensive and not economical. However, it could be a good feedstock source of biochar for soil amendment.

According to [17] review, although large numbers of biochar-related research have been conducted across the world, there is still insufficient field-based evidence for biochar's applicability in developing countries where significant soil constraints have been identified. Since the characteristics of biochar and its effect on soil dynamics depend on the feedstock, pyrolysis temperature, biochar application rate, and type of soil [18], it is necessary to evaluate the effect of different rates of biochar produced from water hyacinth. The behavior of the biochar made of water hyacinth for the soil qualities and crop yield has not been well studied. Moreover, studies on long-term biochar effects on soil environment and crop production have rarely conducted, thus recommended to evaluate on the nutrient cycle in the soil [19].

Therefore, this study was conducted with the objective of evaluating the effects of locally produced biochar derived from water hyacinth on soil nutrients and yield for bread wheat crop production in Ethiopia.

2. Materials and Methods

2.1. Biochar production

Water hyacinth was collected from Lake Tana (12°03'98" N and 37°59'83" E), Amhara Region, Ethiopia. The stem part of the water hyacinth was collected from the biomass removed by different machineries from the lake. The collected biomass was sun-dried and pyrolyzed in limited oxygen to produce biochar by gathering dried water hyacinth on the ground and covering biomass with teff straw (*Eragrostis tef*) and soil to limit the entrance of oxygen. The produced water hyacinth biochar (WHB) was sun-dried, mixed well, and sieved with a 2 mm sieve before applied on the soil.

2.2. Experimental land/plot preparation and treatment

The experiment was conducted at the Injibara University campus (10°94'40") N and 36°91'86" E) in the Amhara Region, Ethiopia. According to [20] weather data collected from the National Meteorological Agency of Ethiopia from 1984 to 2017, the average minimum and maximum temperatures of the study area were 10.3 and 22.5°C, respectively. The mean annual rainfall was 1344 mm, with the main wet season lasting from June to September, followed by a less pronounced wet period until November. The experimental area was plowed five times by oxen and the plots were laid out with a width of 1.6 m and length of 2.4 m. The same land (fixed plot) was used for a consecutive two-year open-field experiment in rainy season; the first season experiment was done from July to December 2021 and the second from July to December 2022. The experimental design was a randomized block design with four replications with a total of 24 experimental plots. The study consists of four biochar application rates of WHB (0, 5, 10, and 20 t ha^{-1}) and three NPS (38-19-7) fertilizer application rates (NPS; 0, 100, and 200 kg ha^{-1}). For each treatment, the biochar was applied on 22 July 2021 and mixed with the soil within a depth of 20 cm. Biochar was not applied in the 2022 season for those plots receiving biochar treatments. Chemical fertilizers of all NPS and one-third of recommended urea (200 kg ha^{-1}) were applied at planting (22 July 2021 and 20 July 2022, respectively) (0 day after planting; DAP) and the remaining two-thirds of urea was applied in the split at the tillering growth stage of the crop for both years (45 and 60 DAP for 2021 and 2022 seasons) [21]. The experimental treatments are summarized in Table 1.

Table1: Treatment abbreviation and description.

Biochar (t ha^{-1})	Fertilizer (kg ha^{-1})	Treatment abbreviation	Treatment description
0	200	0WHB200F	No biochar, only 200 kg ha^{-1} NPS fertilizer
5	200	5WHB200F	5 t ha^{-1} water hyacinth biochar with 200 kg ha^{-1} NPS fertilizer
10	200	10WHB200F	10 t ha^{-1} water hyacinth biochar with 200 kg ha^{-1} NPS fertilizer
20	0	20WHB0F	20 t ha^{-1} water hyacinth biochar only
20	100	20WHB100F	20 t ha^{-1} water hyacinth biochar with 100 kg ha^{-1} NPS fertilizer
20	200	20WHB200F	20 t ha^{-1} water hyacinth biochar with 200 kg ha^{-1} NPS fertilizer

2.3. Soil sampling and analyses

A composite of 5 sub-samples was taken from the experimental land before the preparation of experimental plots for the characterization of the experimental soil. Soil samples were taken on 0 DAP after mixing biochar and chemical fertilizer from each plot, then samples were taken from each plot on 15, 30, 60, 90, and 150 DAP at a depth of 0–20 cm. The samples were stored in a refrigerator until being analyzed.

Soil and biochar pH were measured from 10 g of air-dried samples (45℃). 25 ml of pure water was added in a 50 ml centrifuge tube, shaken with a horizontal shaker at 160 strokes min^{-1} for 1 hr, allowed to stand for 30 min, and then measured the pH using a pH meter (LAQUA F-71). Total carbon (C) and nitrogen (N) of soil and biochar samples were measured using a CHN analyzer (Perkin Elmer, 2400 series II) from two milligrams of sample into tin capsules and analyzed as described by [22]. To analyze ammonium and nitrate-nitrogen (NH_4^+-N and NO_3^--N) concentration of the soil and biochar samples, the samples were extracted from 2.0 g of dry-weight equivalent soil with 20 mL of 2 mol L^{-1} potassium chloride solution in a centrifuge tube [23]. The tube was shaken for 1 hour (hr) on a horizontal shaker at 160 strokes min^{-1}. After filtrating through a 0.45 µm filter membrane, the concentration of NH_4^+-N and NO_3^--N in the extractant was determined at 670 and 540 nm, respectively, by using an auto-analyzer 2000 (FIAlyzer-1000, FIAlab Instruments). Available phosphorus (P) was extracted from 2.0 g of dry-weight equivalent soil and 0.5 g of 45°C dried biochar with 20 mL of Mehlich 3 extraction solution in a 50 mL centrifuge tube. The tube was shaken on a horizontal shaker at 200 strokes min^{-1} for 5 min, filtered through a 0.45 µm pore size membrane filter, and the concentration of P was determined at 870 nm by using the auto analyzer. Cation exchange capacity (CEC) of soil and biochar was determined using 1 mol L^{-1} ammonium acetate adjusted pH to 7 from 10 g of dry soil and 1 g of biochar [24]. The mixture was shaken at 160 strokes min^1 for 5 min and filtered with Whatman filter paper of 42, and measured NH_4^+ by using the auto analyzer to calculate CEC. The water content of the soil sample was measured from 4 g of wet soil. The samples were weighed into an aluminum dish and then dried in an oven at 105°C for 24 hr. The weight of the aluminum dish and soil was then taken out and weighed together. The water content was determined by the wet soil mass minus the dry soil mass divided by the dry soil mass. Biochar specific surface area, pore volume, and pore size were determined by using N_2 adsorption-desorption performed at 77K using Micromeritics ASAP 2020. The specific surface area was calculated by Brunauer Emmette Teller (BET) method. Fixed carbon, volatile matter, and ash content of the biochar were determined by Thermogravimetric Analyzers (TGA).

To measure soil bulk density, the soil samples were taken two times before experimental land preparation for 2021 season and beginning of 2022 season one year after WHB application from each experimental plot. It was measured after drying the core sampler soil in an oven at 105ºC until constant mass was achieved. Bulk density was calculated as mass of the core sample dried at 105°C minus mass of the core sample holder (g) divided by the volume of the core sample holder (cm^3).

2.4. Plant height, dry biomass, and grain yield of wheat plant

Ten plant samples were randomly selected at the maturity stage of the crop from each plot from six central rows to avoid border effects in both seasons, and plant height was measured from the ground until the tip of the plant excluding awn. After the full maturity of the crop, the whole above-ground of all plants from six central rows were harvested and weighed to measure dry biomass by sun-drying before threshing. Grain yield was weighed after separating wheat straw from the grain from all plants from six central rows.

2.5. Statistical analysis

Analysis of variance was conducted using the R-software program, version R-4.3.0 packages [25]. Data normality was checked by the Shapiro-Wilk procedure [26]. The difference among means of treatments was determined using Tukey's Highly Significant Difference (HSD) at the probability of 5% ($p < 0.05$).

3. Results

3.1. Characteristics of soil and biochar

The soil on which the field experiments were conducted was classified as Nitisol [27] of the silt loam texture class with 30.0%, 51.9%, and 18.1% sand, silt, and clay contents, respectively (Table 2). Soil total C and N were 9.3% and 0.677%, respectively. The soil was strongly acidic with pH of 5.23. The amount of NH_4^+-N, NO_3^--N, and available P were 1.67, 11.6, and 4.19 mg kg^{-1}, respectively. Soil CEC was 19.2 $cmol_c$ kg^{-1}. The soil bulk density of the experimental field before plowing was 1.14 g cm^{-3}.

The WHB total C and N contents were 33.9% and 0.783%, respectively (Table 2). The concentrations of NH_4^+-N, NO_3^--N, and available P were 2.13, 3.21, and 613 mg kg^{-1}, respectively. Biochar CEC was 32.2 $cmol_c$ kg^{-1}. The biochar was at alkaline pH of 9.33. The biochar fixed C, volatile matter, and ash contents were 17.7%, 40.2%, and 42.0%, respectively. The biochar showed 12.4 m^2 g^{-1}, 0.023 cm^3 g^{-1}, and 7.58 nm specific surface area, pore volume, and average pore size, respectively.

Table 2: Basic characterization of soil and biochar samples.

	Sand	Silt	Clay	Bulk density	pH	T-C	T-N	NH_4^+-N	NO_3^--N
	%			$g\ cm^{-3}$		%		$mg\ kg^{-1}$	
Soil†	30.0	51.9	18.1	1.14	5.23	9.3	0.677	1.67	11.6
Biochar‡	–	–	–	–	9.33	33.9	0.783	2.13	3.21
	Available P§	CEC#	Fixed carbon	Volatile matter	Ash	Specific surface area	Pore volume	Average pore size	
	$mg\ kg^{-1}$	$cmol_c\ kg^{-1}$	%			$m^2\ g^{-1}$	$cm^3\ g^{-1}$	nm	
Soil†	4.19	19.2	–	–	–	–	–	–	
Biochar‡	613	32.2	17.7	40.2	42.0	12.4	0.023	7.58	

† Silty loam Nitosol collected at Injibara University, Ethiopia
‡ Locally produced from water hyacinth
§ Mehlich 3-extraction
# Cation exchange capacity

3.2. Effects of water hyacinth biochar on soil parameters

Soil pH significantly increased ($p < 0.05$) with WHB application for both cropping seasons (Fig. 1), but relatively higher in 2021 than 2022 cropping season (Fig. 6a). Biochar addition significantly ($p < 0.001$) increased soil pH from 5.24 (0WHB200F) up to 5.93 (20WHB100F) on 0 DAP, and continued higher pH on 15, 30, 60, 90, and 150 DAP over no biochar addition during 2021 season (Fig. 1). The residual effect of WHB application was evident in the beginning of 2022 season (0 DAP) significantly ($p < 0.001$) increasing from 5.05 (0WHB200F) up to 5.40 (20WHB100F; Fig. 1). This residual liming effect of WHB continued to be significantly different on 30 DAP during the 2022 season.

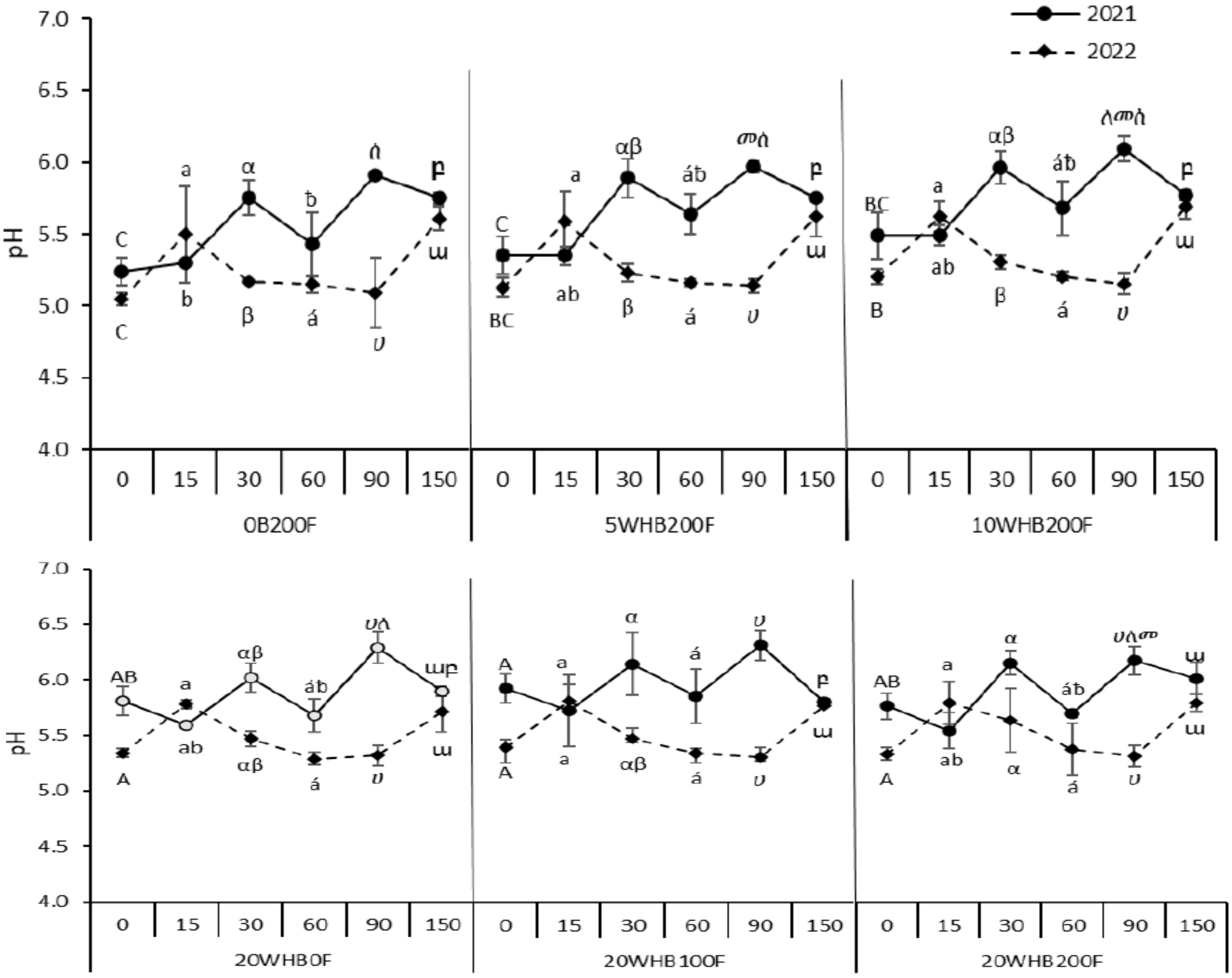


Figure 1: Effects of biochar and fertilizer application on soil pH during 2021 and 2022 cropping seasons for bread wheat production Mean separation was done separately for each day after planting (DAP) among different treatments. Means that do not share the same letter in each treatment were significantly different at 5% level of significance.

The mean NH_4^+-N concentration was higher in 2021 than 2022 cropping season (Fig. 6b). The NH_4^+-N concentration was generally increased on 30 DAP and decreased afterward regardless of treatments for the 2021 season (Fig. 2). Particularly on 0–30 DAP, higher fertilizer application rate (200F) caused higher NH_4^+-N, and among 200F treatments higher WHB application rates resulted in higher NH_4^+-N. On 15 DAP, NH_4^+-N in 20WHB200F (5.20 mg kg^{-1}) was significantly ($p < 0.05$) higher than that in 10WHB200F (2.69 mg kg^{-1}). NH_4^+-N in 20WHB200F (3.79 mg kg^{-1}) was significantly ($p < 0.01$) higher than that in 20WHB0F (1.54 mg kg^{-1}) on 60 DAP. On 90 DAP, NH_4^+-N in 20WHB0F (6.55 mg kg^{-1}) was significantly ($p < 0.05$) higher than that in 5WHB200F (3.58 mg kg^{-1}), and NH_4^+-N in 20WHB100F (2.24 mg kg^{-1}) higher ($p < 0.001$) than that in 0WHB200F (0.360 mg kg^{-1}) on 150 DAP in 2021 season. The residual effect of WHB application was seen in the 2022 season where the NH_4^+-N concentration was significantly ($p < 0.001$) higher in 20WHB200F (4.42 mg kg^{-1}) than in 0WHB200F (1.79 mg kg^{-1}) at the beginning of the season and continued higher NH_4^+-N on 15, 30, 60 and 150 DAP (Fig. 2).

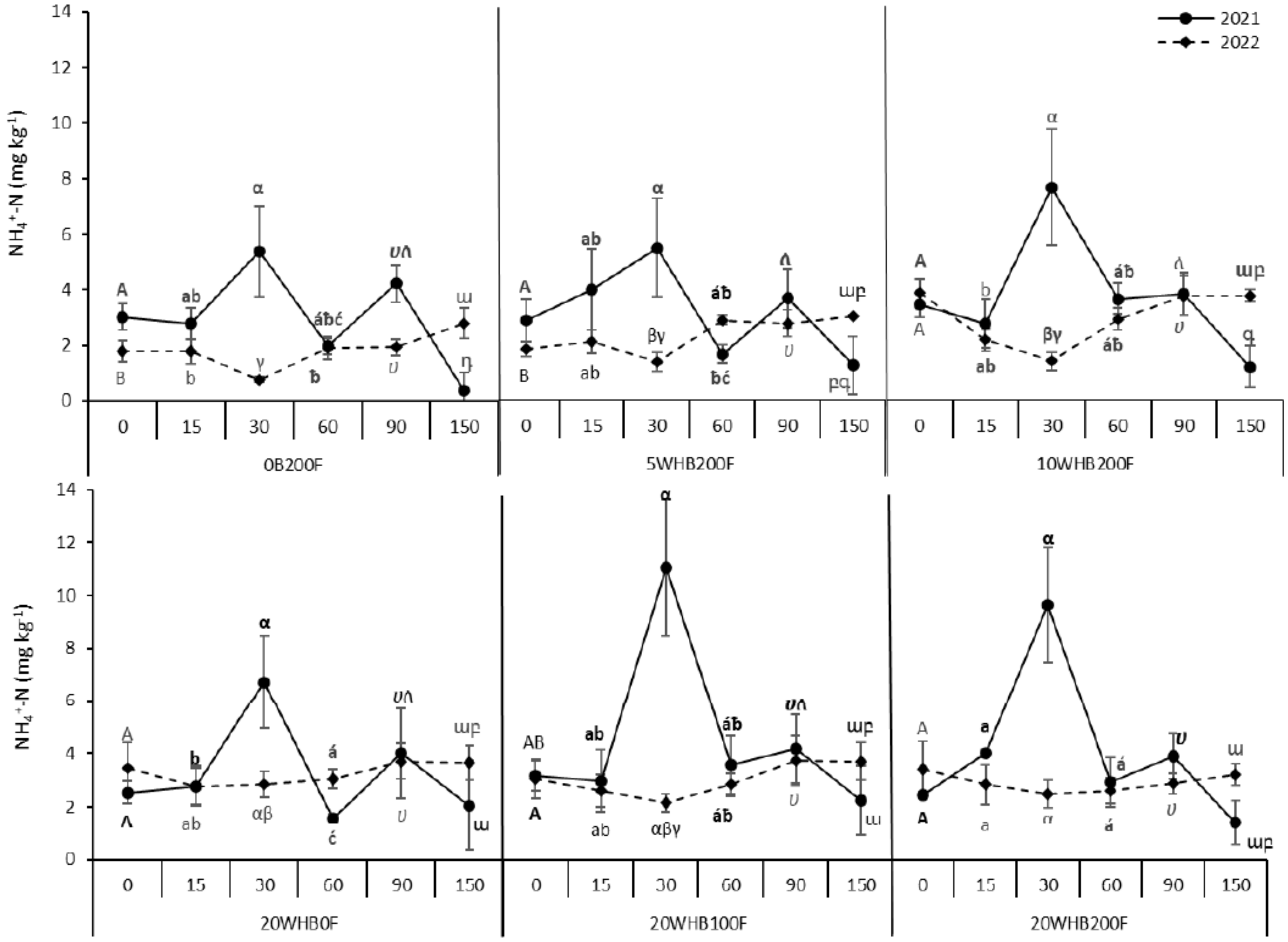


Figure 2: Effects of biochar and fertilizer application on soil NH_4^+-N during 2021 and 2022 cropping seasons for bread wheat production Mean separation was done separately for each day after planting (DAP) among different treatments. Means that do not share the same letter in each treatment were significantly different at 5% level of significance.

The NO_3^--N concentration was higher in 2021 than 2022 cropping season (Fig.6c). The NO_3^--N concentration generally decreased from 0 to 30 DAP and increased on 60 DAP regardless of treatments for the 2021 season (Fig. 3). Particularly on 60 DAP, NO_3^--N in 20WHB0F (23.0 mg kg^{-1}) was significantly ($p < 0.05$) higher than that in 5WHB200F (14.8 mg kg^{-1}). The NO_3^--N concentration remained low after 90 DAP in the 2021 season. The NO_3^--N concentrations were high in the beginning of 2022 season (0 DAP), decreased after 15 DAP, and remained relatively constant until 90 DAP (Fig. 3). For the residual effect of WHB application for 2022 season, NO_3^--N in 20WHB100F (6.28 mg kg^{-1}) was significantly higher ($p < 0.01$) than that in 5WHB200F (3.38 mg kg^{-1}) and control (3.81 mg kg^1) on 150 DAP. Although there was no significant difference among treatments on 0–90 DAP, NO_3^--N was generally higher for the plots amended with higher WHB (20WHB) than the control (0WHB200F).

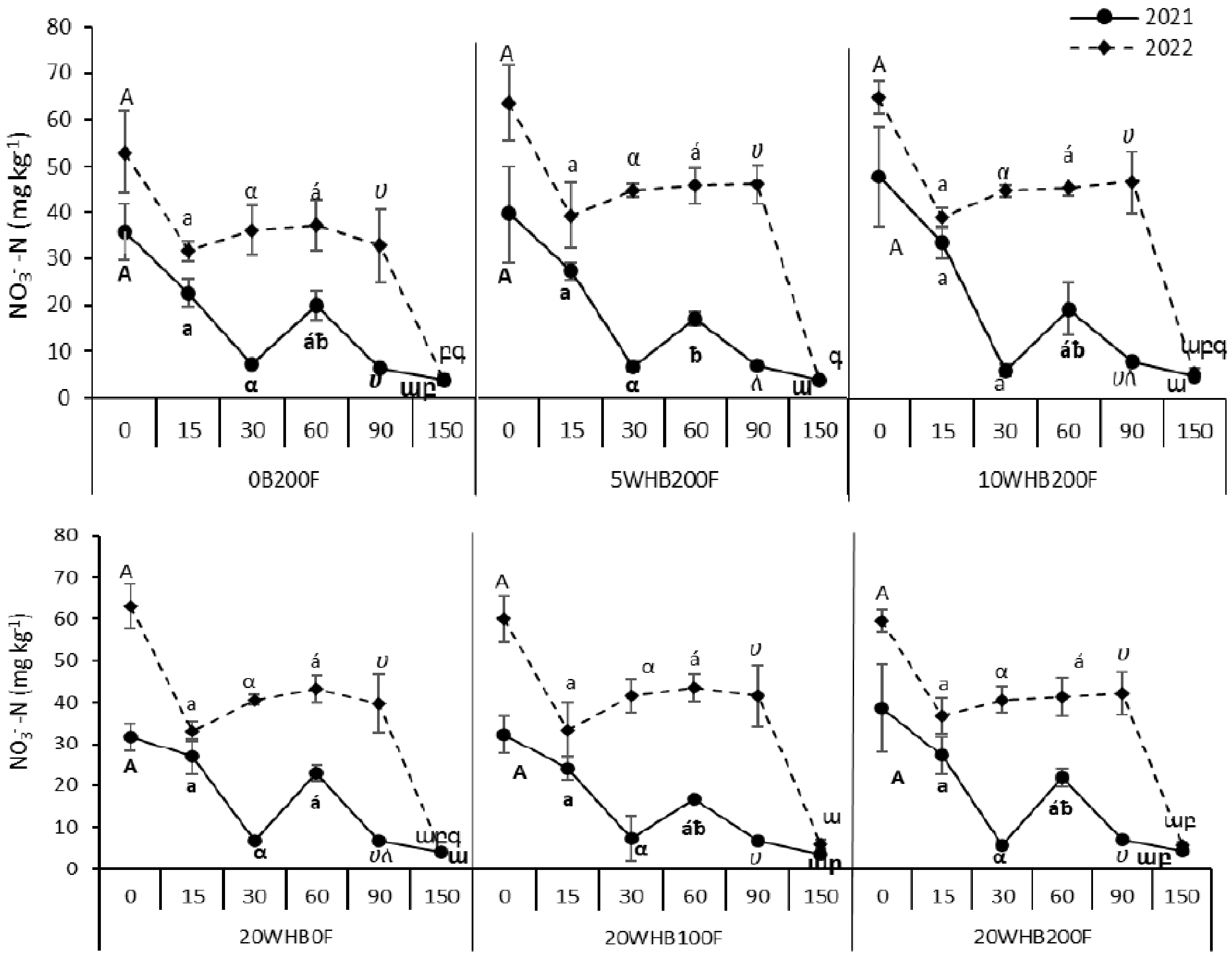


Figure 3: Effects of biochar and fertilizer application on soil NO_3^--N during 2021 and 2022 cropping seasons for bread wheat production Mean separation was done separately for each day after planting (DAP) among different treatments. Means that do not share the same letter in each treatment were significantly different at 5% level of significance.

Available P was generally higher in 2022 than 2021 cropping season (Fig. 6d). As shown in Fig. 4, both WHB and fertilizer applications did not cause much effect in the available P during in 2021 season remaining in low concentrations during 0–90 DAP except for increases on 150 DAP. Available P in 20WHB200F (7.33 mg kg^{-1}) was significantly ($p < 0.05$) higher than 20WHB0F (5.65 mg kg^{-1}) on 90 DAP. For the 2022 season, the available P concentration range was high already on 0 DAP and remained relatively constant during the season (Fig. 4).

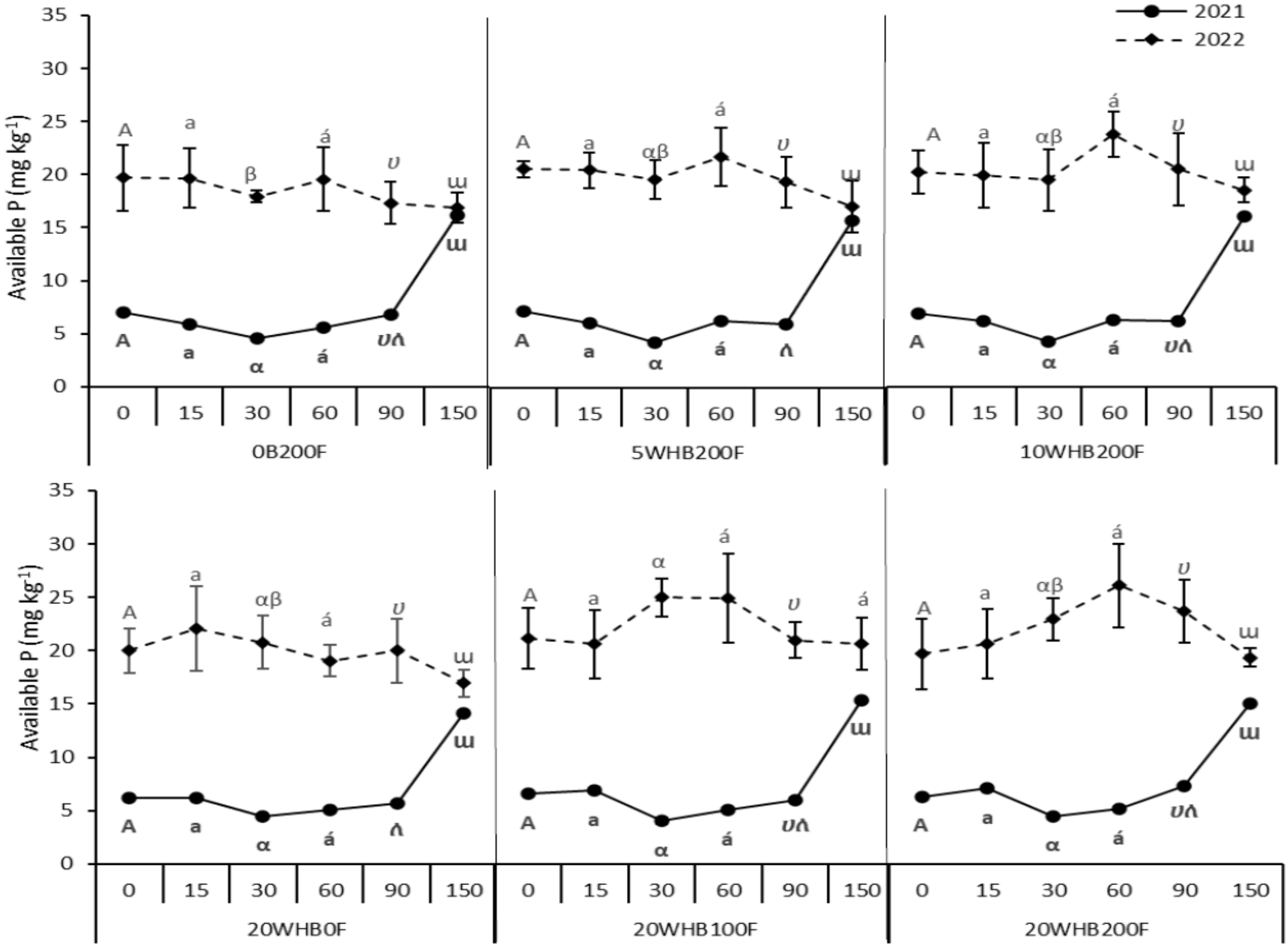


Figure 4: Effects of biochar and fertilizer application on soil available P during 2021 and 2022 cropping seasons for bread wheat production. Mean separation was done separately for each day after planting (DAP) among different treatments. Means that do not share the same letter in each treatment were significantly different at 5% level of significance.

Particularly on 30 DAP, available P was significantly ($p < 0.05$) higher in 20WHB100F (25.0 mg kg^{-1}) than that in 0WHB200F (17.9 mg kg^{-1}), and generally WHB application resulted in high available P until 60 DAP. Water content of the soil was relatively higher in 2022 than 2021 cropping season (Fig. 6e). Water content of the soil remained relatively constant ranging from 28% and 37% during 0–60 DAP and decreased afterwards in 2021 season (Fig. 5). The result of ANOVA showed that water content was significantly ($p < 0.01$) increased with the addition of WHB from 28% (0WHB200F) to 34% (20WHB100F) on 0 DAP. Although there was no significant difference among treatments, water content was high for the plots amended with WHB compared to those without WHB as the residual WHB effect in 2022 season (Fig. 5).

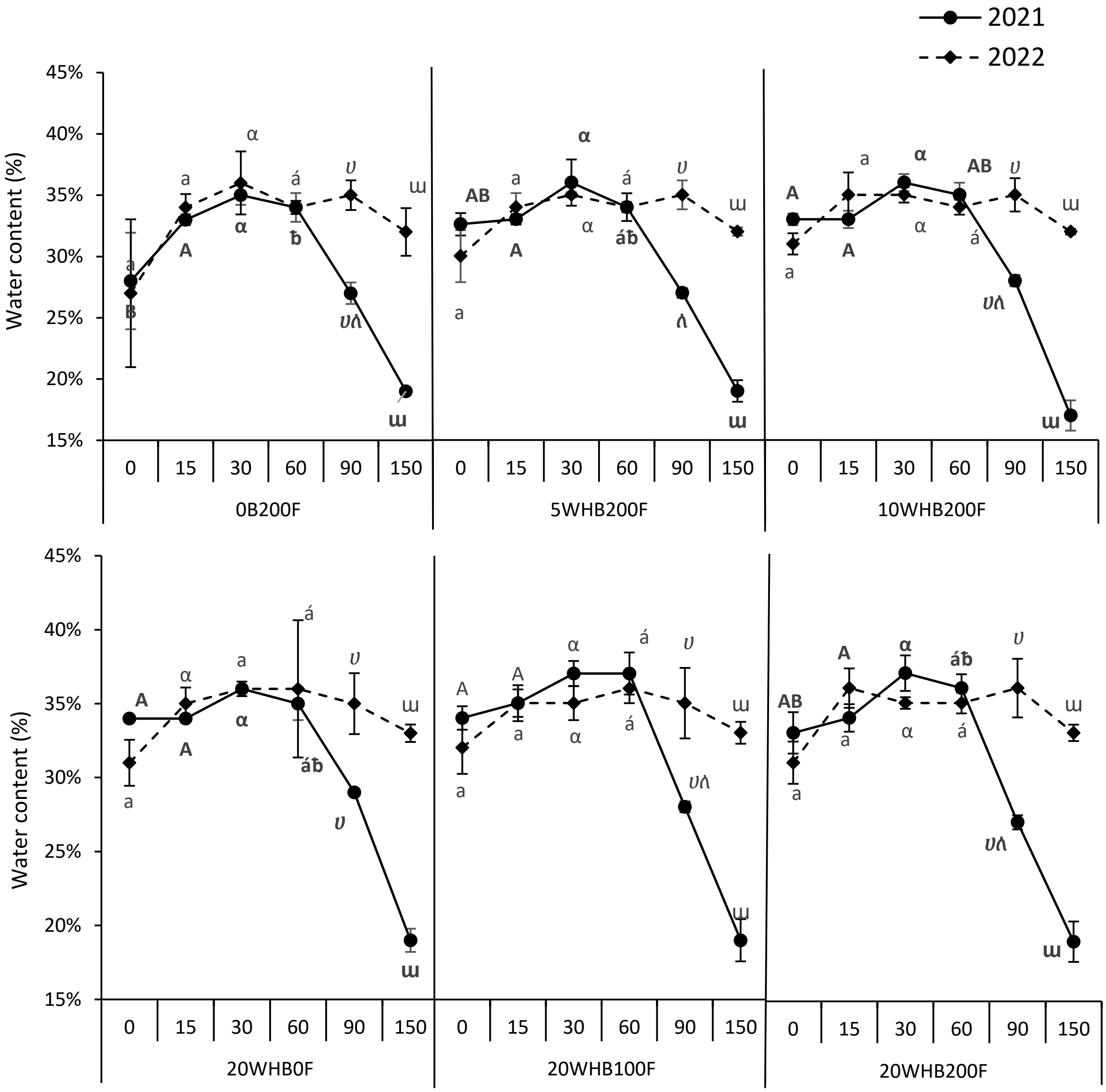


Figure 5: Effects of biochar and fertilizer application on soil water content during 2021 and 2022 cropping seasons for bread wheat production. Mean separation was done separately for each day after planting (DAP) among different treatments. Means that do not share the same letter in each treatment were significantly different at 5% level of significance.

The bulk density of the soil from the experimental plots was 0.978, 0.907, 0.815, 0.591, 0.785, and 0.662 g cm^{-3} for 0WHB200F, 5WHB200F, 10WHB200F, 20WHB0F, 20WHB100F, and 20WHB200, respectively at the beginning of 2022 season. Net changes of the soil bulk density due to WHB application was from 0.071 and 0.387 g cm^{-3}.

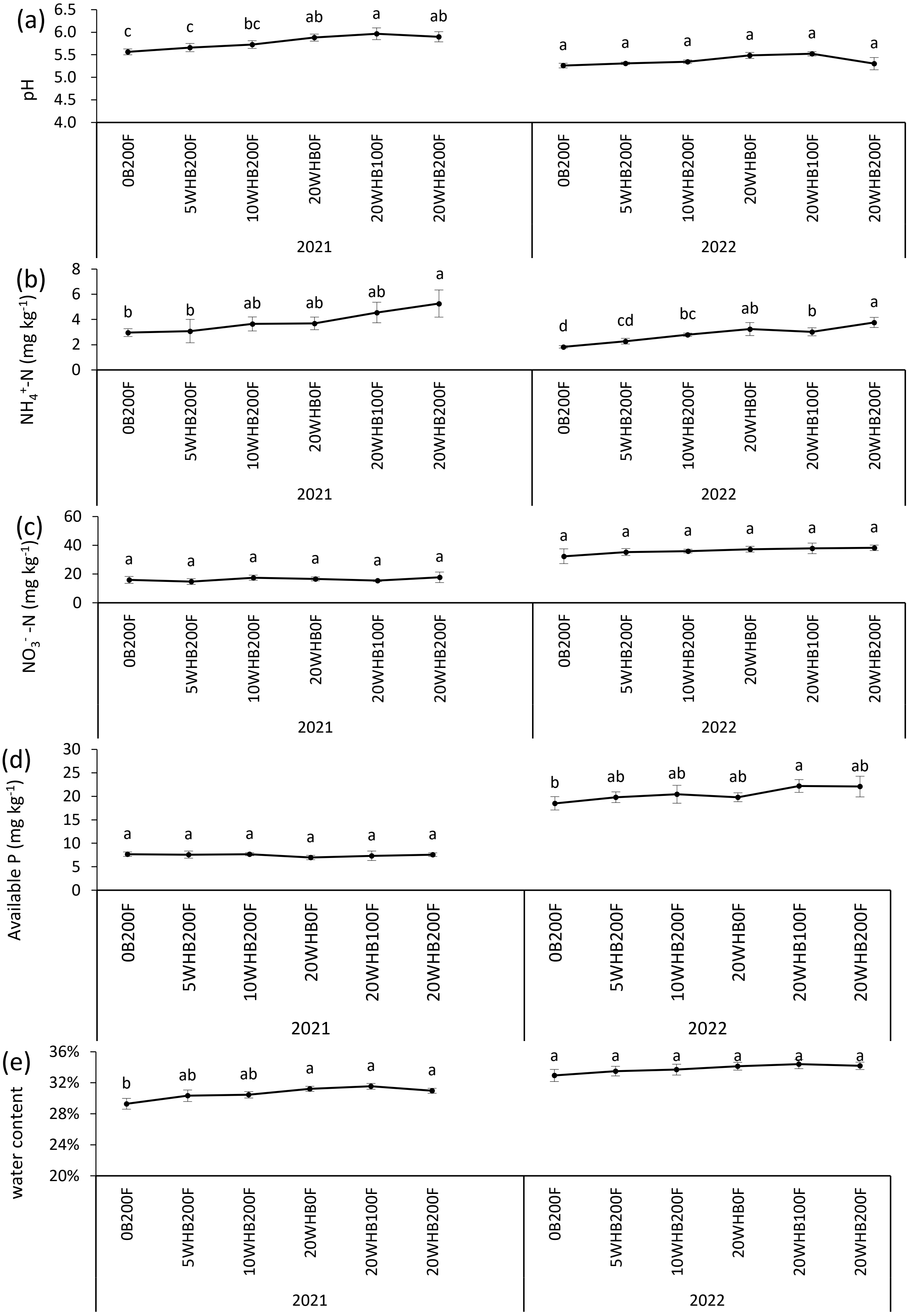
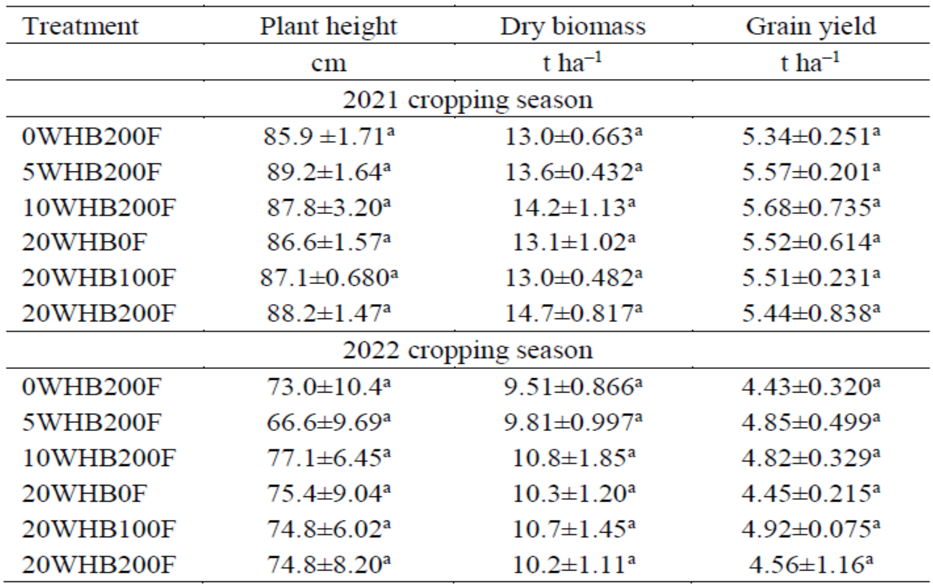


Figure 6: Effects of biochar and fertilizer application on soil pH (a), NH_4^+–N (b), NO_3^- –N (c), available P (d), and soil water (e) over 2021 and 2022 cropping seasons.

3.3. Effects of water hyacinth biochar on crop parameters

As general trend, the average aboveground biomass and grain yield of wheat regardless of the treatments were greater in 2021 season compared to those in 2022 season (Table 3). The result showed that the application of WHB had positive effects, although not significant, on plant height, dry biomass, and grain yield in both 2021 and 2022 seasons. For 2021 season, increasing WHB application rate (0WHB, 5WHB, 10WHB, and 20WHB) among 200F treatment caused increasing dry biomass and grain yield (except for 20WHB200F for grain yield). Dry biomass with 20WHB200F increased by 13.1% and grain yield with 10WHB200F increased by 6.4% compared to those with 0WHB200F, respectively, in 2021 season. Similarly, for 2022 season, dry biomass with 200F treatment increased with increasing WHB rate (except for 20WHB200F), however WHB application showed mixed effect on grain yield. Nevertheless, the highest dry biomass was with 10WHB200F being greater by 13.6%, and highest grain yield was with 20WHB100F being greater by 11.1% compared to those with 0WHB200F, respectively, in 2022 season.

Table 3: Effects of biochar and fertilizer application on plant parameters (plant height, dry biomass, and grain yield) during 2021 and 2022 cropping seasons for bread wheat production



Treatment	Plant height	Dry biomass	Grain yield
	cm	t ha^{-1}	t ha^{-1}
	2021 cropping season		
0WHB200F	85.9 ±1.71^a	13.0±0.663^a	5.34±0.251^a
5WHB200F	89.2±1.64^a	13.6±0.432^a	5.57±0.201^a
10WHB200F	87.8±3.20^a	14.2±1.13^a	5.68±0.735^a
20WHB0F	86.6±1.57^a	13.1±1.02^a	5.52±0.614^a
20WHB100F	87.1±0.680^a	13.0±0.482^a	5.51±0.231^a
20WHB200F	88.2±1.47^a	14.7±0.817^a	5.44±0.838^a
	2022 cropping season		
0WHB200F	73.0±10.4^a	9.51±0.866^a	4.43±0.320^a
5WHB200F	66.6±9.69^a	9.81±0.997^a	4.85±0.499^a
10WHB200F	77.1±6.45^a	10.8±1.85^a	4.82±0.329^a
20WHB0F	75.4±9.04^a	10.3±1.20^a	4.45±0.215^a
20WHB100F	74.8±6.02^a	10.7±1.45^a	4.92±0.075^a
20WHB200F	74.8±8.20^a	10.2±1.11^a	4.56±1.16^a

4. Discussion

4.1. Effects of water hyacinth biochar on soil parameters

Biochar soil amendment increases soil pH mainly because of its composition of alkaline substances, such as ash and carbonates of Ca^{2+}, K^+, and Mg^{2+} [28], as well as due to biochar surface properties and ability to reduce exchangeable acidic cations (Al^{3+} and H^+) [29]. Negatively-charged functional groups (phenolic, carboxylic, and hydroxyl) present at the surface of biochar could also contribute to the increment of soil pH by binding the surplus H^+ ions present in the soil solution [30]. The addition of WHB in this study increased significantly soil pH at the beginning of the 2021 season and then decreased on 15 DAP. This was probably because of urea applied to the soil reacting with water and the soil enzyme urease and rapidly converted to ammonium, namely urea hydrolysis. In this reaction, hydrogen ions (H^+) are consumed, causing the soil pH near the fertilizer to rise. There have been reports that pH increased after the application of urea in the first stage of incubation and then decreased due to urea hydrolysis after it was applied to the soil [31,32]. In our study, soil pH was increased with values of 0.27 (150 DAP) to 0.69 (0 DAP) and 0.20 (150 DAP) to 0.47 (30 DAP) units after the application of WHB compared to without biochar in the 2021 and 20212 seasons, respectively. In the 2022 season experiment, the pH was higher for the plots amended with 20WHB than 0WHB, 5WHB, and 10WHB at the beginning of the experiment and remained higher in the growing season. This was mainly because of the residual effect of WHB added to the plots in 2021 season. Similar finding was seen that chemical fertilizer and biochar (0.5%, 1%, 2%, and 4%) applications caused the soil pH increases by 0.23 to 0.88 units, compared to chemical fertilizer treatment alone [33].

Biochar can provide some source of N because it contains certain organic forms of nitrogen (hydrolysable and non-hydrolysable) as well as inorganic forms of nitrogen such as NH_4^+-N, NO_3^--N, and N_2O^--N [13]. In this study, the NH_4^+-N concentration in the soil at the beginning of the experiment (0 DAP) was increased from 3.03 mg kg^{-1} (0B200F) up to 3.33 mg kg^{-1} (10WHB200F). Then, it reached the peak on 30 DAP with values ranging from 5.37 mg kg^{-1} (0WHB200F) to 12.54 mg kg^{-1} (20WHB200F) in the 2021 season experiment probably due to ammonification of urea and mineralization of organic matter in the soil. This result was consistent with a past study whose NH_4^+-N concentration ranged from 5.21 mg L^{-1} to 6.22 mg L^{-1} on the first sampling date, then increased dramatically and peaked on day 20, thereafter, gradually decreased [33]. In our study, application of 20WHB200F improved the NH_4^+-N concentration by 4.95%, 85.9%, 133%, 92.1%, 20.5%, and 408% on 0, 15, 30, 60, 90, and 150 DAP, respectively in 2021 cropping season compared to the 0WHB200F. This trend was continued in the residual WHB effect ranging from 49.6% to 319% improvement of NH_4^+-N concentration all across the growing period in the 2022 season. This improvement was probably due to; (1) biochar could be some source of N since it contained some amount of NH_4^+-N, (2) biochar's broad surface area, higher porous structure, and CEC could facilitate biochar to decrease NH_4^+-N loss [13,34] (3) biochar increased microbial activity, accelerating nutrient cycling [35].

Combined application of biochar with chemical fertilizer is a promising strategy for increasing N availability and mitigating the leaching of soil inorganic nitrogen, particularly NO_3^- -N. [36] report showed combined application of 20 t ha^{-1} biochar with 120 kg ha^{-1} N fertilizer increased N availability in the soil and decreased NO_3^- -N leaching. Additionally, biochar may adsorb NO_3^- dissolved in soil water which may leave less NO_3^- in the soil solution for leaching and intern more NO_3^- in the soil solution [33]. Our combined application of 20WHB200F enhanced NO_3^--N significantly by 13.8% and 17.8% on 90 and 150 DAP, respectively, compared to 0WHB200F application in the 2021 season experiment. As shown in Fig. 3, the NO_3^--N concentration was high at the beginning of the experiment and then decreased until 30 DAP probably due to absorption by plants, denitrification, and leaching to a lesser extent. Then, NO_3^--N was raised on 60 DAP after the split application of urea which may have been caused by nitrification. In the 2022 experiment season, the residual effect of WHB improved the NO_3^--N concentration by 64.8% (20WHB100F) compared to the control (0WHB200F) on 150 DAP. The overall increase of soil nitrification in the soil amended by biochar was possibly due to: (1) biochar promoted the conversion of NH_4^+-N to NO_2^- which was a substrate for NO_3^--N [37] and (2) biochar raised the population of soil ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) which provided more basis for the biochemical reactions [38].

As a macronutrient, P is critical to plant growth; however, only 10% to 25% of the P applied in mineral fertilizers is absorbed by plants, with the remainder being retained in the soil and/or lost to aquatic environments [39]. Soil properties such as pH, mineral and organic matter composition, CEC, and texture control plant availability of P in soils [40]. Biochar application is known to affect soil P dynamics both directly and indirectly by adding additional P to the soil, changing soil pH, and altering microbial community composition [19]. In our first-season experiment, there was no significant improvement in available P except on 90 DAP from WHB application. Instead, the available P concentration from biochar amended plots was less than the control on 30 and 150 DAPs. Similar finding was seen that biochar had a negative effect on soil available P in sandy clay loam and loam silty soils when combined application of biochar with P fertilizer [40]. This was due to P sorbed by the surface area of the biochar and compounds formed during pyrolysis such as Ca, Mg, K, and others [40]. However, for the residual effects of the WHB in the 2022 season, the available P concentration in the soil was increased with the application of WHB. Combined application of biochar with fertilizer (20WHB100F) increased available P by 39.7% compared to the control on 30 DAP in the 2022 season. Because biochar could be a potential slow-release source that slowly and constantly supplied P to the soil over an extended period of time [41], the amount of available P released from WHB during our first growing season was low, but low absorption by plants and slow-release of P from WHB over time could have resulted in accumulation of residual P in the soil towards end of the 2021 growing seasons and in the beginning of the 2022 growing season. Therefore, the concentration of available P was higher in the 2022 growing season than in the 2021 growing season.

A biochar's combination of porosity (external and internal) and surface functionality which can improve soil compaction allows it to retain more soil water [42]. The application of 20WHB100F in this study improved the water-holding capacity of the soil by 2.91% to 21.4% at different growing stages of the crop when compared to the plots without biochar in the season of 2021. Similarly, it was found that the water-holding capacity of sandy loam soil was enhanced by 5.1% when biochar was applied at 1% (21.6 t ha^{-}[1] versus without biochar [43]. The bulk density of the soil was also improved with the residual effect of WHB application measured after one year (2022 cropping season). As a result of the amendment of the plots with 20WHB0F, the bulk density of the soil increased by 39.6% in comparison to the control plot. This was probably because of lower density of the biochar than soil particles lowering density of the whole soil, and formation of soil aggregates with biochar in the long-term interaction in soil rebuilding the soil structure [44].

4.2. Effects of water hyacinth biochar on crop parameters

For effective plant growth, biochar generally contains some macronutrients, micronutrients, and trace elements [13]. It is also used to increase microbial activity, accelerate nutrient cycling, and reduce the leaching and N volatilization, which are important for plant growth [35]. In our study, even though there was no significant difference between the treatments, the combined application of WHB with chemical fertilizers showed a positive effect on aboveground biomass and grain yield of wheat crop in both the 2021 and 2022 seasons. Previous studies showed that positive effects were probably due not only to the nutrients contained in the biochar but also to the stimulation of microorganisms that mineralized soil organic N, thus eliminating N depletion [36]. It was also reported that compared to the application of N fertilizer alone in an acidic Nitisol, the application of biochar at a rate of 10 t ha^{-1} in combination with N fertilizer resulted in a slight increase in plant biomass [45]. Application of 20WHB and 10WHB with chemical fertilizer increased crop biomass and grain yield by 13.1% and 6.4%, respectively, in the first season of this study. Similarly, biomass increased by 13.6%, and grain yield by 11.1% in the plots amended with 10WHB200F and 20WHB200F, respectively, in the residual effects of WHB in the 2022 season. A similar finding was showed in a review literature in that the simultaneous application of biochar with inorganic fertilizers resulted in an additional 10% increase in yield compared to inorganic fertilizers alone [46]. Another two-year biochar field trial done by [36] showed that the combined application of 20 t ha^{-1} biochar with 120 and 240 kg ha^{-1} N chemical fertilizer increased the aboveground biomass of winter wheat by 12.2%–13.8% compared to N fertilizer alone.

5. Conclusion

Our result showed that major parameters of physical and chemical properties of soil such as pH, NH_4^+-N, NO_3^--N, and soil water content improved for the plots amended with a high amount of WHB as compared to those without WHB. Application of 20WHB increased soil pH more than the lower rates of WHB and control. Combined application of WHB with NPS fertilizer showed a significant increment of NH_4^+-N and NO_3^--N compared to fertilizer alone. The residual effect of WHB also showed an improvement in soil pH, NH_4^+-N, NO_3^--N, and available P. Combined application of WHB with fertilizer application showed a positive effect on bread wheat plant dry biomass and grain yield for 2-year-long cropping seasons. Therefore, the amendment of the soil with WHB can be recommended to increase crop production in sustainable conditions.

Declarations

The authors declare that no competing interests.

Author roles

Desalew Fentie: conceptualization, investigation, methodology, formal analysis, validation, data curation, manuscript writing, reviewing, and editing. Fekremariam Asargew Mihretie: conceptualization, investigation, methodology, validation, supervision, reviewing and editing. Yudai Kohira: investigation, formal analysis, and reviewing and editing. Solomon Addisu Legesse: conceptualization, reviewing and editing, and project administration. Berhanu Belay Abune: investigation, formal analysis, and reviewing and editing. Shinjiro Sato: conceptualization, investigation, methodology, validation, supervision, fund acquisition, reviewing and editing, and project leader.

Acknowledgement

This research was supported by Science and Technology Research Partnership for Sustainable Development (SATREPS; Grant Number JPMJSA2005) funded by Japan Science and Technology Agency (JST)/Japan International Cooperation Agency (JICA).

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