WATER HYACINTH–DERIVED BIOCHAR FOR SUSTAINABLE WHEAT

PRODUCTION ON ETHIOPIAN SOIL

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Dissertation

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CONTENTS

ABSTRACT

Crop production faces various stresses that disrupt crop plants' usual growth, development, and productivity, falling outside the normal range of homeostatic control. Among these stresses, abiotic stress including nutrient imbalances (deficiency or toxicity), soil acidity, and moisture stress are major factors affecting crop production. Wheat, one of the most widely produced crops globally, is also susceptible to these stresses. Sustainable wheat crop production often involves rotating between rainfed and irrigated cultivation throughout the year or between different growing seasons. This strategy can help mitigate these stresses by optimizing water use, minimizing environmental impacts, and reducing risks associated with climate variability, thereby maintaining crop productivity. Biochar has recently emerged as a valuable tool for enhancing soil qualities and improving sustainable crop productivity by addressing both abiotic and biotic stresses in crop production particularly when combined with inorganic fertilizers. However, there is a paucity of information regarding the combined impacts of variable application rates and inorganic fertilizers on crop productivity across diverse biophysical contexts. Additionally, there is a dearth of research on utilizing water hyacinth weed biomass as biochar for soil amendment. Therefore, this study investigated the impact of different locally produced water hyacinth biochar rates and NPS (19-38-7) fertilizer amounts on wheat production in rainy (rainfed) and dry (irrigation) contrasting seasons. The experiment was conducted in 2021 and 2022 for the rainy season experiment and in 2023 for the dry season experiment. Four water hyacinth biochar rates (0, 5, 10, and 20 t ha^{-1}), three NPS fertilizer rates (0, 100, and 200 kg ha^{-1}), and two irrigation regimes (50% and 100%; only for the dry season) were evaluated for soil physicochemical properties, wheat yields, and profitability. Biochar was incorporated into the soil at a depth of 20 cm for

treatments that received biochar before sowing wheat crops. For treatments that received inorganic fertilizer, all NPS and half of the urea were applied at the time of planting, while the remaining half of the urea was applied at the tillering stage of the wheat crop. For the dry season experiment, plots were daily irrigated to meet 50% and 100% of the crop's water requirement, according to the treatment arrangement. Major soil physicochemical properties as well as wheat crop growth and yield components were measured to evaluate treatment effects on soil quality and crop yield. In the rainy season experiment (Study 1), the combined application of 20 t ha^{-1} biochar and 100 kg ha^{-1} fertilizer significantly increased soil pH by 0.40–0.69 units and 0.20–0.35 units in the 2021 and 2022 seasons, as fresh and residual effects, respectively. Soil NH_4^+-N concentration was improved by 4.95–408% and 49.6–319% in 2021 and 2022 as fresh and residual effects of biochar, respectively. Moreover, NO_3^--N concentrations also improved by 13.8–17.8% and 64% in the 2021 and 2022 seasons, respectively, for the plots amended with 20 biochar compared to those without biochar in both seasons. Wheat crop dry biomass and grain yield were also improved by 13% and 6.4% under treatments of 20 t ha^{-1} biochar and 200 kg ha^{-1} fertilizer and 10 t ha^{-1} biochar 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} biochar and 200 kg ha^{-1} fertilizer and 20 t ha^{-1} biochar and 100 kg ha^{-1} fertilizer improved dry biomass and grain yield by 14% and 11%, respectively, compared to the control. In the dry season experiment (Study 2), the results showed that biochar amendment significantly reduced soil bulk density by 15.1–16.7%, improved soil porosity by 6.8%–8.6%, and moisture content by 10.3%–20.2%. Additionally, soil pH (0.26–0.87 units), NH_4^+–N (73.7%–144%), NO^{3-}–N (131%–637%), and available phosphorus (85.8%–427%) improved with the combined application of biochar and fertilizer compared to the

application of fertilizer alone. Consequently, wheat dry biomass and grain yield increased by 260% and 173%, respectively. Furthermore, even with irrigation water reduced to 50% of the crop requirement, there was no significant adverse effect on crop performance. In conclusion, the study underscores the dual benefits of biochar derived from water hyacinth: remediation of invasive biomass and improvement of soil quality for enhanced crop productivity in both rainy and dry seasons. Such interventions hold significant promise for fostering resilience and sustainability in wheat crop production grappling with environmental and economic pressures.

CHAPTER ONE

1. GENERAL INTRODUCTION

1.1. Wheat crop production potential in Ethiopia

Wheat (*Triticum aestivum L.*), a prominent crop and a staple food, originated in the Central Asian region, which covered 225 million hectares and had a global production of 750 million tons (Singh *et al*., 2023). Wheat holds a vital role in ensuring food security in Ethiopia, where it is cultivated across a total area of 1.87 million hectares, with average yields of 3.19 t ha^{-1} in Ethiopia, more specifically 0.690 million hectares with yields of 2.78 t ha^{-1} in the Amhara Region and 0.019 million hectares with yields of 2.88 t ha^{-1} in the Awi Zone during the 2021/2022 cropping season (CSA, 2022). Wheat is currently produced through both rain-fed and irrigation systems in Ethiopia. The wheat production under rainfed is dominantly carried out during the main rainy season in Ethiopia (June to October) in the highlands of the country while irrigated wheat production is carried out from November–April in the lowlands of Ethiopia (Tadesse *et al*., 2022). Irrigation allows farmers to cultivate crops two to three times a year, which can enhance nutrition and livelihoods by diversifying and increasing income. Ethiopia boasts significant potential for wheat production under irrigation, with approximately 5.3 million hectares of land suitable for irrigated agriculture, utilizing surface, ground, and rainwater sources. However, less than 2% of this potential has been utilized (Haile, 2015). Despite the significant potential for expanding Ethiopia's wheat production both vertically and horizontally, several key challenges hinder its realization.

1.2. Wheat crop production challenges in Ethiopia

Wheat production in Ethiopia is challenged by several factors including the prevalence of biotic stresses in both rainfed and irrigated environments such as yellow rust, stem rust, septoria, and fusarium diseases, as well as abiotic stresses like soil acidity, poor soil fertility, and drought. Additionally, there are yield gaps attributed to low adoption of new technologies, high costs, and limited availability of inputs (Tadesse *et al*., 2022). Moreover, its yields are currently hampered by water scarcity, particularly during the dry season (Asmamaw *et al*., 2023*)*. Soil amendments with organic materials such as lime and biochar, along with inorganic amendments like fertilizers, have the potential to mitigate the crop production challenges mentioned above (FEKADU, 2018).

1.3. Soil amendments for wheat crop production

Soil organic and inorganic amendments play pivotal roles in enhancing crop production. Organic amendments, such as biochar, compost, and manure, improve soil structure, increase water retention, and provide essential nutrients for plant growth. They also promote microbial activity, which aids in nutrient cycling and enhances soil fertility over time. Inorganic amendments; chemical fertilizers, provide readily available nutrients to plants, stimulating rapid growth and development. They can address specific nutrient deficiencies in the soil and boost crop yields. Overall, both types of amendments contribute to soil health, fertility, and ultimately, sustainable crop production (Antonious, 2016). A diverse range of biomass materials can be effectively employed as soil amendments, each offering unique benefits for soil health and crop productivity.

1.4. Invasive water hyacinth weed wastes for soil amendments

Various types of biomasses can be utilized for soil amendments. Examples include crop residues, such as straw and husks, which enrich the soil with organic matter, improve soil structure, and enhance water retention. On the other hand, certain types of biomasses can be converted into biochar, a form of charcoal produced through pyrolysis. Biochar, produced by pyrolysis, has a porous structure that enhances soil water retention, nutrient retention, and microbial activity. Moreover, it can sequester carbon in the soil, contributing to climate change mitigation efforts (Kwapinski et al., 2010). Organic wastes like water hyacinth should be recycled not only from an ecological point of view but also for economic reasons (Seow *et al*., 2022). Therefore, the ongoing evolution of waste management strategies, namely efficient waste recycling, is one of the most challenging aims both for soil scientists and environmental engineers.

Water hyacinth (*Eichhornia crassipes*), which is one of the most invasive aquatic weeds globally including in Ethiopia, affecting socioeconomic activities and watershed ecosystems, can be a good feedstock source for biochar production. Since 2011, water hyacinth has invaded Lake Tana, Ethiopia, causing significant damage to the lake's biodiversity and livelihoods (Wondie *et al*., 2012). The Ethiopian government presently employs diverse control methods, such as mechanical and manual removal, alongside biological interventions, to tackle weed proliferation in the lake. However, the labor-intensive and uneconomical transportation and management of the collected biomass pose significant challenges. Nevertheless, this biomass represents a potentially valuable feedstock source for biochar production, offering a sustainable solution for soil enhancement.

Biochar has gained popularity as a soil amendment that improves soil physical properties, such as soil bulk density, porosity, and moisture content, as well as soil nutrient availability for plants, including ammonium-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), and available phosphorus, by reducing nutrient leaching, fixation, and nutrient recycling (Adekiya *et al*., 2020; Ginebra *et al*., 2022; Liu *et al*., 2024; Ng *et al*., 2022), thereby enhancing plant growth and yield.

In research, discrepancies have emerged regarding the effects of biochar on soil physicochemical properties and crop yield. Regarding nutrient concentrations and nitrification rates, studies present conflicting findings. Some indicate reductions in NH_4^+–N concentrations (Martí et al., 2021) post-amendment, while others report increases (Ginebra et al., 2022). Similarly, contrasting results are observed in nitrification processes, with some studies showing decreased NO_3^-–N concentration (Yao et al., 2022) and others demonstrating an increase, attributed to variations in ammonia-oxidizing bacteria abundance (Liu et al., 2024). In terms of crop yield, conflicting outcomes exist concerning optimal biochar application rates, with varying effects based on crop type and experimental conditions. While some studies suggest no significant effects of biochar rate on crop performance, others indicate improvements with specific application rates. Additionally, the impact of biochar varies between pot and field experiments, with discrepancies in its effectiveness noted.

These disparities underscore the complexity of biochar's interaction with soil and highlight the need for further research to elucidate its effects consistently across different contexts and conditions.

1.5. Objectives

Based on the above-mentioned research needs, the objectives of this dissertation were:

i. To characterize and assess the fresh and residual impact of locally produced water hyacinth biochar on soil quality and crop productivity during the rainy growing season (Chapter 2).

ii. To investigate the synergistic effects of water hyacinth biochar and inorganic fertilizer on soil physicochemical properties, as well as on crop growth and yield components, under conditions of deficit irrigation (Chapter 3).

CHAPTER TWO

2. CHARACTERIZATION OF LOCALLY PRODUCED WATER HYACINTH BIOCHAR AND ITS RESIDUAL IMPACTS ON SOIL QUALITY AND CROP PRODUCTIVITY IMPROVEMENT DURING RAINY SEASONS

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2.1. INTRODUCTION

Healthy soil is the foundation of agricultural productivity; it produces healthy crops and provides healthy food and livelihoods that improve human well-being (Wall *et al*., 2015). Poor soil conditions such as acidification, nutrient deficiency, compaction, and salinization inhibit and/or prevent plant growth and development. 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 (Yebo, 2015). Wheat crop, one of Ethiopia's most important food security crops, suffers from different challenges such as soil acidity and declining soil fertility (Tadesse *et al*., 2022).

Soil pH is often used as an indicator of soil fertility status (Hartemink and Barrow, 2023) 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 (Msimbira and Smith, 2020). It also hinders the uptake of essential nutrients by plants and increases the possibility of toxic metals being absorbed from the soil (Bolan *et al*., 2023). 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 (Haile, 2014). 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 strongly acidic (pH < 5.5). Strong acidic soils with pH < 5.5 considerably influence crop growth and require intervention (Mesfin, 2007). Crop production under such 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 (Haile, 2014). 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 (Jafer Dawid and Gebresilassie Hailu, 2017). Therefore, soil amendment using locally available resources such as biochar produced from various biomass can be one solution for poor farmers like Ethiopia.

Biochar has gained popularity as a soil amendment that enhances soil's physical and chemical properties, thereby increasing agricultural productivity through direct and indirect effects on soil quality and crop growth (Diatta *et al*., 2020; Ren *et al*., 2023; Wei *et al*., 2023). 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 (Bolan *et al*., 2023). 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.) (Hou *et al*., 2022). Crop responses to biochar application show average yield increases by 10% to 42% (Joseph *et al*., 2021) and 81.7% (Hu *et al*., 2021), with the greatest responses on acidic and sandy soils where biochar was applied along with organic and/or mineral fertilizers. However, the effect of biochar primarily depends on the biochar rate, initial soil pH, and soil textural properties (Sun *et al*., 2022), as well as the feedstock type and pyrolysis temperatures (Jalal *et al*., 2023; H. Singh *et al*., 2022). Water hyacinth-derived biochar exhibited promising basic properties, suggesting its suitability as a soil amendment for enhancing soil quality and improving crop productivity (Gezahegn *et al*., 2024).

According to (Zhang *et al*., 2016) 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 and crop performance depend on the feedstock, pyrolysis temperature, biochar application rate, and type of soil (Blenis *et al*., 2023), it is necessary to evaluate the effect of different rates of biochar produced from water hyacinth in Ethiopian acidic soil. The characteristics of the water hyacinth-derived biochar locally which is a simple grounding system that can be easily implemented at the collection site of water hyacinth for soil qualities and crop yield have not been yet studied. Moreover, studies on residual water hyacinth biochar effects on soil environment and crop production have rarely been conducted, thus recommended to evaluate the nutrient cycle in the soil (Jindo *et al*., 2020).

Therefore, this study was conducted to characterize and evaluate the residual effects of locally produced biochar derived from water hyacinth on soil nutrients and yield for bread wheat crop production in Ethiopia under two consecutive rainy seasons.

2.2. MATERIALS AND METHODS

2.2.1. Experimental site description

The field experiments were conducted during the rainy season of 2021 and 2022 (July–December). The experiments were conducted at the Injibara University research station of Awi Zone of the Amhara Region, Ethiopia (Fig.2-1). According to Habtie *et al*. (2020), the 33-year weather data showed average minimum and maximum temperatures were 10.3°C and 22.5°C, respectively. The mean annual rainfall was 1344 mm, with the main wet season occurring from June to September, followed by a less pronounced wet period extending until November.

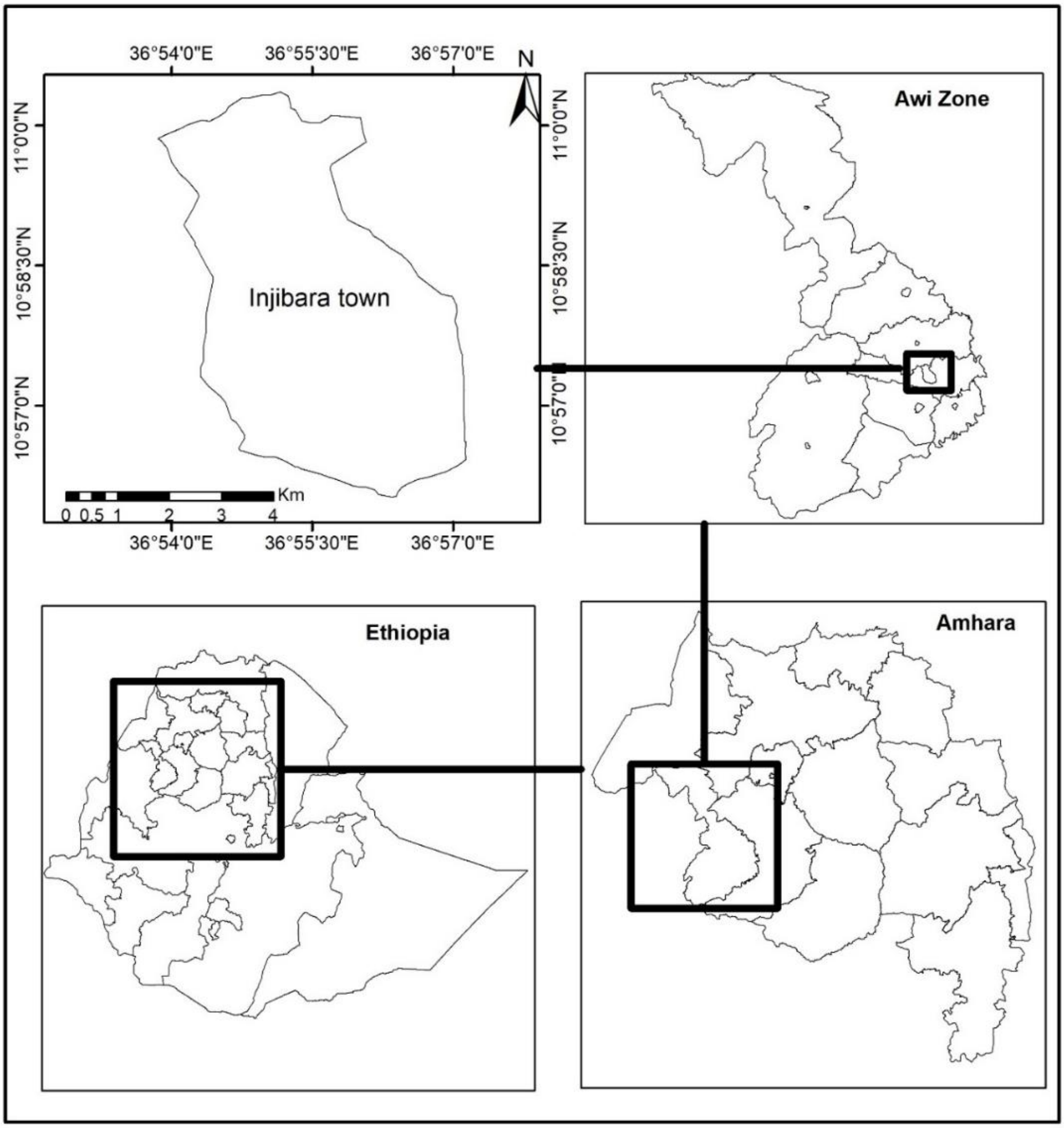

Fig. 2-1. Experimental site map

2.2.2. Experimental land/plot preparation

After land clearing, the experimental area was plowed five times using oxen. The dimensions of the plots were 1.6 m width and 2.4 m length width. The spacing between rows, plots, and replications was set at 0.2 m, 0.5 m, and 1.5 m, respectively. The same land (fixed plot) was used for a consecutive two-year open-field experiment in the rainy season.

2.2.3. Biochar production

The biochar was produced from water hyacinth collected from Lake Tana (12°03'98" N and 37°59'83" E), Ethiopia. Recognizing the challenges posed by furnace pyrolysis methods, particularly for resource-limited farmers, a simple grounding system was developed that can be easily implemented at the collection site of water hyacinth, such as Lake Tana in Ethiopia. This cost-effective solution enables farmers to convert water hyacinth biomass into biochar without the need for expensive furnaces, making it accessible and practical for small-scale agricultural operations. The stem part of the water hyacinth was gathered and sun-dried. After creating a pile of water hyacinth stems, it was covered with teff (*Eragrostis tef*) straw and a layer of soil to prevent the entrance of oxygen. Water was sprayed to cool down the biochar, and then it was sun-dried. The biochar was then sieved using <5 mm sieve after being hand-crushed.

2.2.4. Field experimentation

The plots were arranged in a randomized block design with four replications resulting in a total of 24 experimental plots. Four different rates of water hyacinth biochar (B, 0, 5, 10, and 20 t ha^{-1}), three rates of NPS inorganic fertilizer (0, 100, and 200 kg ha^{-1}) were employed, in a partially factorial treatment arrangement (Table 2-1).

The test crop was the bread wheat of “Kakaba” variety with a seedling rate of 150 kg ha^{-1}. Biochar was incorporated into the soil two days before the planting date at a depth of 20 cm. Biochar was applied only in the 2021 season for treatments received biochar. For treatments received inorganic fertilizer, all NPS and one-third of the recommended urea for the wheat crop (200 kg ha^{-1}) were applied at the time of planting (July 22, 2021, and July 20, 2022), while the remaining half of the urea was applied at the tillering stage, (September 07, 2021, and September 22, 2022).

Table 2-1. Treatments of field experiment for the 2021and 2022 rainy seasons experiment

Biochar ($t\ ha^{-1}$)	Fertilizer ($kg\ ha^{-1}$)	Treatments	Definition
0	200	0B200F	No biochar, only 200 kg ha^{-1} NPS fertilizer
5	200	5B200F	5 t ha^{-1} water hyacinth biochar with 200 kg ha^{-1} NPS fertilizer
10	200	10B200F	10 t ha^{-1} water hyacinth biochar with 200 kg ha^{-1} NPS fertilizer
20	0	20B0F	20 t ha^{-1} water hyacinth biochar only
20	100	20B100F	20 t ha^{-1} water hyacinth biochar with 100 kg ha^{-1} NPS fertilizer
20	200	20B200F	20 t ha^{-1} water hyacinth biochar with 200 kg ha^{-1} NPS fertilizer

B: Biochar derived from water hyacinth and F: NPS inorganic fertilizer

2.2.5. Soil and biochar sampling and characterization

A composite of 5 soil sub-samples was taken from the experimental land to characterize the experimental soil before preparing the experimental plots. For evaluating treatment effects, soil samples were taken from each plot on 0, 15, 30, 60, 90, and 150 days after sowing (DAS) at a depth of 0–20 cm. These samples were stored in a refrigerator until analysis.

The pH of the soil and biochar was measured from 10 g of soil and 2 g of biochar samples that had been air-dried at 45°C. For the soil sample, 25 mL of pure water was added to a 50 mL centrifuge tube, while for the biochar sample, 20 mL of pure water was added. The tubes were then shaken horizontally at 160 strokes per minute for 1 hour, allowed to stand for 30 minutes, and the pH was measured using a pH meter (LAQUA F-71, Horiba Scientific, Kyoto, Japan). Total carbon (C) and nitrogen (N) in the soil and biochar samples were measured using a CHN analyzer (Perkin Elmer, 2400 series II, Waltham, MA, USA). Five milligrams of soil and two milligrams of biochar samples were placed into tin capsules and analyzed according to the method described by Yeomans and Bremner, (1991). To determine the concentrations of NH_4^+–N and NO_3^-–N in the soil and biochar samples, 2.0 g of dry-weight equivalent soil and 2.0 g of dried biochar (45°C) were extracted with 20 mL of 2 mol L^{-1} potassium chloride solution (KCl) in a centrifuge tube. The tube was shaken horizontally at 160 strokes per minute for 1 hour. After filtration through a 0.45 μm filter membrane, the concentration of NH_4^+–N and NO_3^-–N in the extractant was determined at 670 nm and 540 nm, respectively, using a flow injection auto-analyzer 2000 (FIAlyzer-1000, FIAlab Instruments, Inc., Seattle, WA, USA) according to the methods described by Keeney and Nelson, (1983). Available phosphorus (P) was determined by extracting 2.0 g of soil and 0.5 g of biochar that had been dried at 45°C with 20 mL of Mehlich 3 extraction solution in a 50 mL centrifuge tube, according to the method described by Mehlich, (1984). The tube was shaken horizontally at 200 strokes per minute for 5 minutes, and the mixture was then filtered through a 0.45 μm pore size membrane filter. The concentration of P was determined at 870 nm using the flow injection auto analyzer 2000 (FIAlyzer-1000, FIAlab Instruments, Inc., Seattle, WA, USA). The cation exchange capacity (CEC) of the soil and biochar was determined by using 1 mol L^{-1} ammonium acetate adjusted to pH 7. Ten grams of dry soil and 1 g of biochar were mixed with the ammonium acetate solution. The mixture was shaken at 160 strokes per minute for 5 minutes for the soil and 15 hours for the biochar. After shaking, the mixture was filtered with Whatman filter paper of size 42, and the concentration of NH_4^+ was measured using the auto-analyzer to calculate the CEC of the soil and biochar by the equation (eq. 1):

$$\mathrm{CEC(cmol_c/kg)} = \frac{\mathrm{NH_4}^+ \text{ conc.(Sample}-\text{Blank)}\left(\frac{\text{mg}}{\text{L}}\right) \text{ x V(mL)}}{\text{molecular mass of } \mathrm{NH_4}^+ \text{ x W(g) x 10}} \quad (1)$$

Where V=volume of extract (i.e., 100mL) and W=biochar weight (g).

To measure soil bulk density, soil samples were collected twice: the first sample before preparing the experimental land, and then again after one year of biochar application, before the start of the 2022 experiment, from each experimental plot. It was measured by drying the core sampler soil in an oven at 105°C until it reached a constant mass. Then, it was calculated as the mass of the core sample dried at 105°C minus the mass of the core sample holder (g) divided by the volume of the core sample holder (cm^3). To determine the moisture content of the soil sample, 3 g of wet soil was measured. The samples were then placed in an aluminum dish and dried in an oven at 105°C for 24 hours. The weight of the aluminum dish and soil was recorded before and after drying. The water content was calculated by subtracting the initial wet soil mass from the final dry soil mass and dividing it by the dry soil mass. The yield of biochar was calculated by dividing the weight of the produced biochar by the dried biomass used as a feedstock and expressing the result as a percentage.

The biochar-specific surface area, pore volume, and pore size were determined using N_2 adsorption-desorption performed at 77K with the Micromeritics ASAP (Micromeritics ASAP 2020, Shimadzu, Tokyo, Japan). The specific surface area was calculated using the Brunauer Emmette Teller (BET) method (Brunauer *et al*., 1938). Fixed carbon, volatile matter, and ash content of the biochar were determined by thermal gravimetric analysis (TGA) using simultaneous differential thermogravimetry (SDT Q600, TA Instruments, Lukens Drive, New Castel, DE, USA).

2.2.6. Plant data collection

Plant height, spike length, number of spikelets per spike, and the number of grains per spike were measured from ten randomly selected plants in the central rows of each plot at the maturity stage of the crop in both the 2021 and 2022 seasons. The entire central rows were harvested to measure dry biomass and grain yield. The dry biomass was measured after sun-drying. The grain yield was also weighed after sun-drying, threshed, and separated from the straw.

2.2.7. Statistical analysis

One-way Analysis of Variance (ANOVA) was computed to compare the means of each combined treatment and two-way ANOVA was used to test for the main and interaction effects between biochar and fertilizer on soil physical and chemical properties as well as growth and yield components. All analysis of variance was conducted using the R-software program, version R–4.3.0 packages (Team, 2023). Data normality was checked by the Shapiro-Wilk procedure (Shapiro and Wilk, 1965). The difference among means of treatments was determined using Tukey's Highly Significant Difference (HSD) at the probability of 5% ($p < 0.05$).

2.3. RESULTS

2.3.1. Basic characteristics of experimental site soil and locally produced water hyacinth biochar

The soil on which the field experiments were conducted was classified as Nitisol (Schad, 2016), belonging to the silt loam texture class. The soil at the experimental site was strongly acidic with a pH of 5.23 and CEC of 19.2 $cmol_c$ kg^{-1}. The NH_4^+–N, NO_3^-–N, and available P concentrations of soil were 1.67, 11.6, and 4.19 mg kg^{-1}, respectively (Table 2-2).

The yield of the biochar was 27.4%, and it had an alkaline pH of 9.33. The concentrations of NH_4^+–N, NO_3^-–N, and available P in the soil were 2.13, 3.21, and 613 mg kg^{-1} respectively. The cation exchange capacity of the biochar was 32.2 $cmol_c$ kg^{-1}. The total carbon and organic carbon were 33.9% and 20.8% respectively. The biochar had fixed C, volatile matter, and ash contents of 17.7%, 40.2%, and 42.0%, respectively. Additionally, the biochar exhibited a specific surface area of 12.4 m^2 g^{-1}, a pore volume of 0.023 cm^3 g^{-1}, and an average pore size of 7.58 nm (Table 2-2).

Table 2-2. 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
T-C and T-N denote total carbon and nitrogen respectively.

2.3.2. Biochar and fertilizer effects on soil characteristics

Soil pH significantly increased ($p < 0.05$) with biochar application for both 2021 and 2022 cropping seasons (Fig. 2-2a) but was relatively higher in 2021 than 2022 cropping season (Fig. 2-2b). Biochar addition significantly ($p < 0.001$) increased soil pH from 5.24 (0B200F) to 5.93 (20B100F) at the beginning of the experiment (0 DAS) and continued higher pH on 15, 30, 60, 90, and 150 DAS over no biochar addition during the 2021 season (Fig. 2-2a). The residual effect of biochar application was evident at the beginning of the 2022 season (0 DAS) significantly ($p < 0.001$) increased from 5.05 (0B200F) to 5.40 (20B100F) (Fig. 2-2a). This residual liming effect of biochar continued to be significantly higher in biochar-amended plots on 30 DAS during the 2022 season. Overall, the mean effects of biochar and fertilizer throughout the year indicated significantly higher effects in the 20B100F treatment compared to the control (0B) and lower rates of biochar treatments (0, 5, and 10B) during the 2021 season (Fig. 2-2b). However, the mean residual effects of biochar applied in 2021 did not show significant effects on soil pH in the 2022 season (Fig. 2-2b).

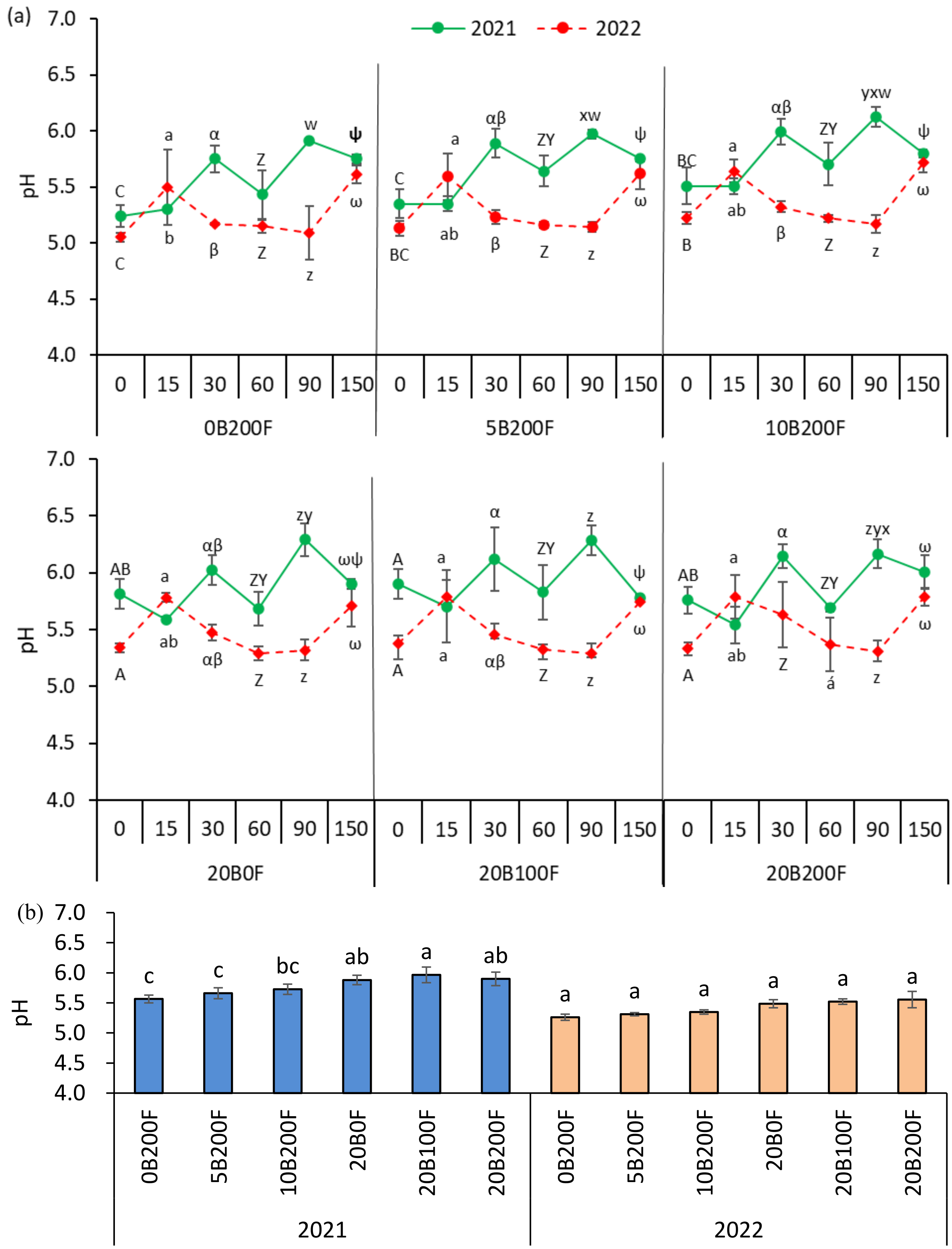

Fig. 2-2. Effects of biochar and fertilizer application on soil pH in each sampling date (a) and over year mean (b) during 2021 and 2022 cropping seasons. Mean separation was done separately for each day after sowing (DAS) among different treatments for each year. Means that do not share the same letter in each treatment were significantly different at a 5% level of significance.

The mean NH_4^+-N concentration was higher in 2021 than 2022 cropping season (Fig. 2-3a and 2-3b). The NH_4^+-N concentration was generally increased on 30 DAS and decreased afterward regardless of treatments for the 2021 season (Fig. 2-3a). Particularly on 0–30 DAS, higher fertilizer application rate (200F) caused higher NH_4^+-N, and among 200F treatments higher biochar application rates resulted in higher NH_4^+-N. On 15 DAS, NH_4^+-N in 20B200F (5.20 mg kg^{-1}) was significantly ($p < 0.05$) higher than that in 10B200F (2.69 mg kg^{-1}). NH_4^+-N in 20B200F (3.79 mg kg^{-1}) was significantly ($p < 0.01$) higher than that in 20B0F (1.54 mg kg^{-1}) on 60 DAS. On 90 DAS, NH_4^+-N in 20B0F (6.55 mg kg^{-1}) was significantly ($p < 0.05$) higher than that in 5B200F (3.58 mg kg^{-1}), and NH_4^+-N in 20B100F (2.24 mg kg^{-1}) higher ($p < 0.001$) than that in 0B200F (0.360 mg kg^{-1}) on 150 DAS in 2021 season. The residual effect of biochar applied in 2021 was seen in the 2022 season where the NH_4^+-N concentration was significantly ($p < 0.001$) higher in 20B200F (4.42 mg kg^{-1}) than in 0B200F (1.79 mg kg^{-1}) at the beginning of the season and continued higher NH_4^+-N on 15, 30, 60 and 150 DAS (Fig. 2-3a).

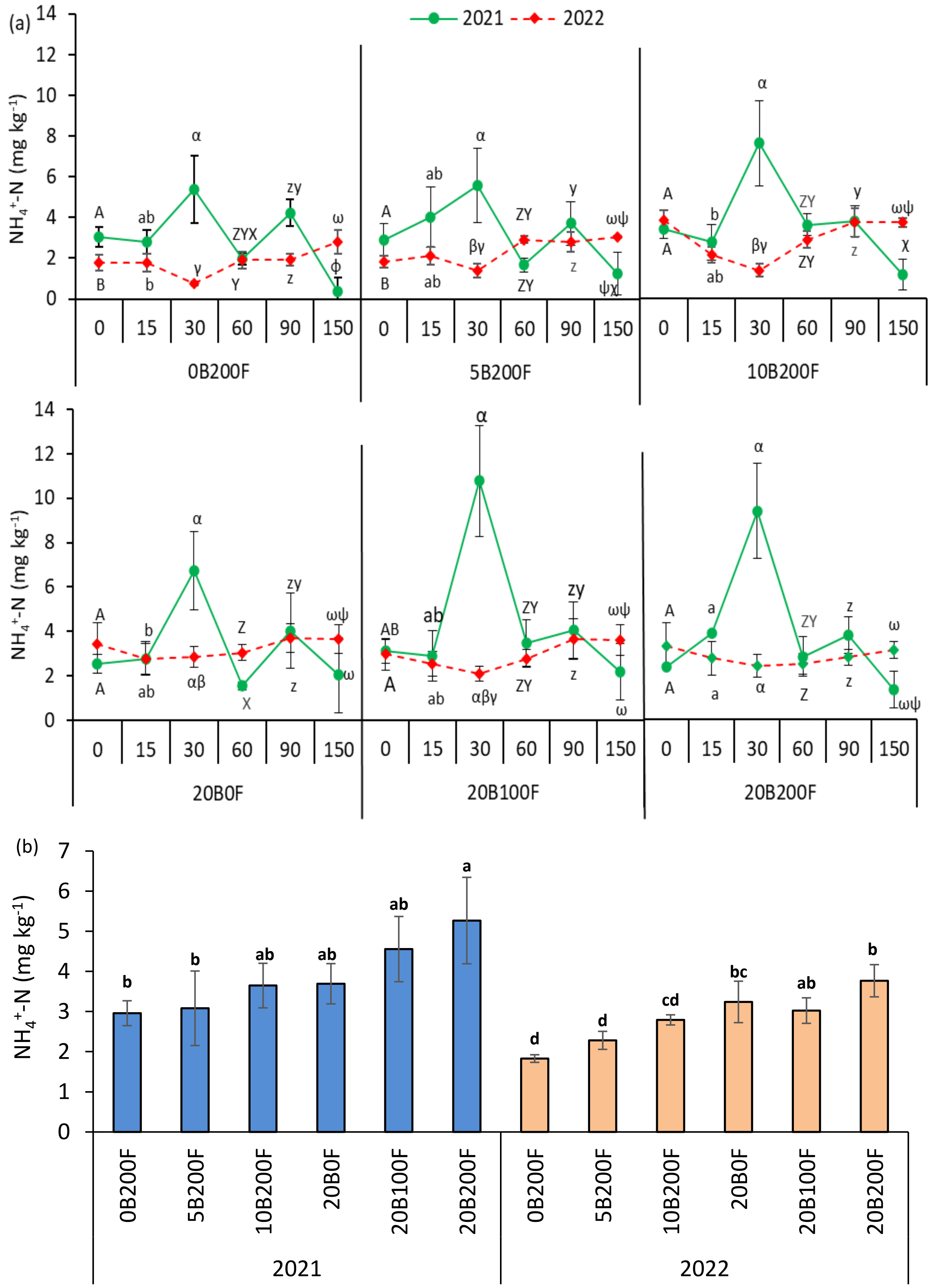

Fig. 2-3. Effects of biochar and fertilizer application on soil NH_4^+–N in each sampling date (a) and over year mean (b) during 2021 and 2022 cropping seasons. Mean separation was done separately for each day after sowing (DAS) among different treatments for each year. Means that do not share the same letter in each treatment were significantly different at a 5% level of significance.

The NO_3^--N concentration was higher in 2021 than 2022 cropping season (Fig.2-4a and 2-4b). The NO_3^--N concentration generally decreased from 0 to 30 DAS and increased on 60 DAS regardless of treatments for the 2021 season (Fig. 2-4a). Particularly on 60 DAS, NO_3^--N in 20B0F (23.0 mg kg^{-1}) was significantly ($p < 0.05$) higher than that in 5B200F (14.8 mg kg^{-1}). The NO_3^--N concentration remained low after 90 DAS in the 2021 season. The NO_3^--N concentrations were high at the beginning of the 2022 season (0 DAS), decreased after 15 DAS, and remained relatively constant until 90 DAS (Fig. 2-4a). For the residual effect of biochar in the 2022 season, NO_3^--N in 20B100F (6.28 mg kg^{-1}) was significantly higher ($p < 0.01$) than that in 5B200F (3.38 mg kg^{-1}) and control (3.81 mg kg^{-1}) on 150 DAS. In the overall mean of the yearly data, although there was no significant difference among treatments on 0–90 DAS, NO_3^--N was generally higher for the plots amended with higher biochar (20B200F) than the control (0B200F).

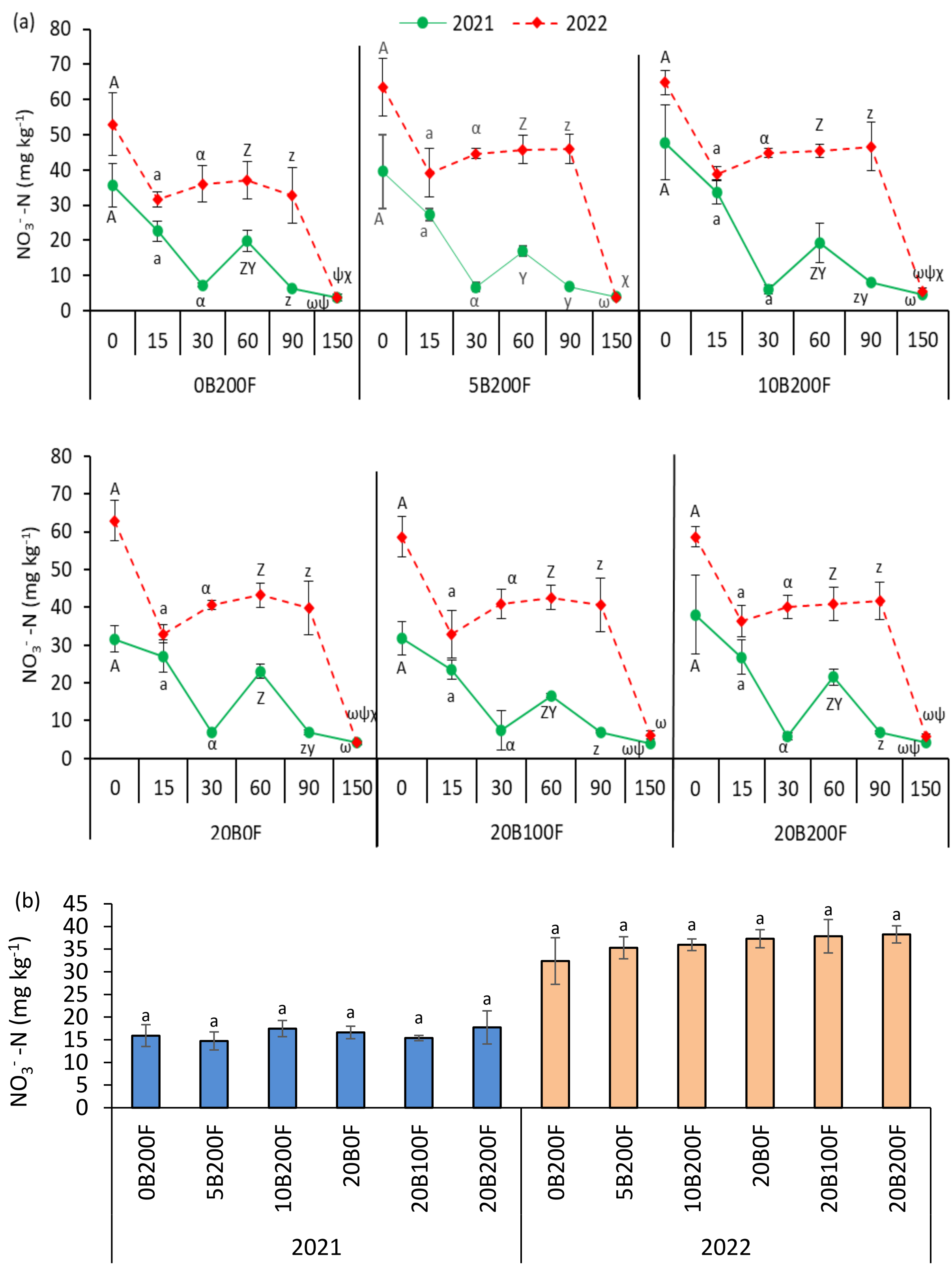

Fig. 2-4. Effects of biochar and fertilizer application on soil NO_3^-–N in each sampling date (a) and over year mean (b) during 2021 and 2022 cropping seasons. Mean separation was done separately for each day after sowing (DAS) among different treatments for each year. Means that do not share the same letter in each treatment were significantly different at a 5% level of significance.

Available P was generally higher in 2022 than 2021 cropping season (Fig. 2-5a and 2-5b). As shown in Fig. 5a both biochar and fertilizer applications did not cause much effect on soil available P during in 2021 season remaining in low concentrations during 0–90 DAS except for increases on 150 DAS. For the 2022 season, the available P concentration range was high already on 0 DAS and remained relatively constant during the season (Fig. 5a). Particularly on 30 DAS, available P was significantly ($p < 0.05$) higher in 20B100F (25.0 mg kg^{-1}) than that in 0B200F (17.9 mg kg^{-1}), and generally biochar application resulted in high available P until 60 DAS for 2022 residual effect of biochar.

The moisture content of the soil was relatively higher in 2022 than 2021 cropping season (Fig. 2-6a and 2-6b). Soil moisture remained relatively constant ranging from 28% and 37% during 0–60 DAS and decreased afterward in the 2021 season (Fig. 2-6a). The result of ANOVA showed that soil moisture content was significantly ($p < 0.01$) increased with the addition of biochar from 28% (0B200F) to 34% (20B100F) on 0 DAS. Although there was no significant difference among treatments, water content was high for the plots amended with biochar compared to those without biochar as the residual biochar effect in the 2022 season (Fig. 2-6a).

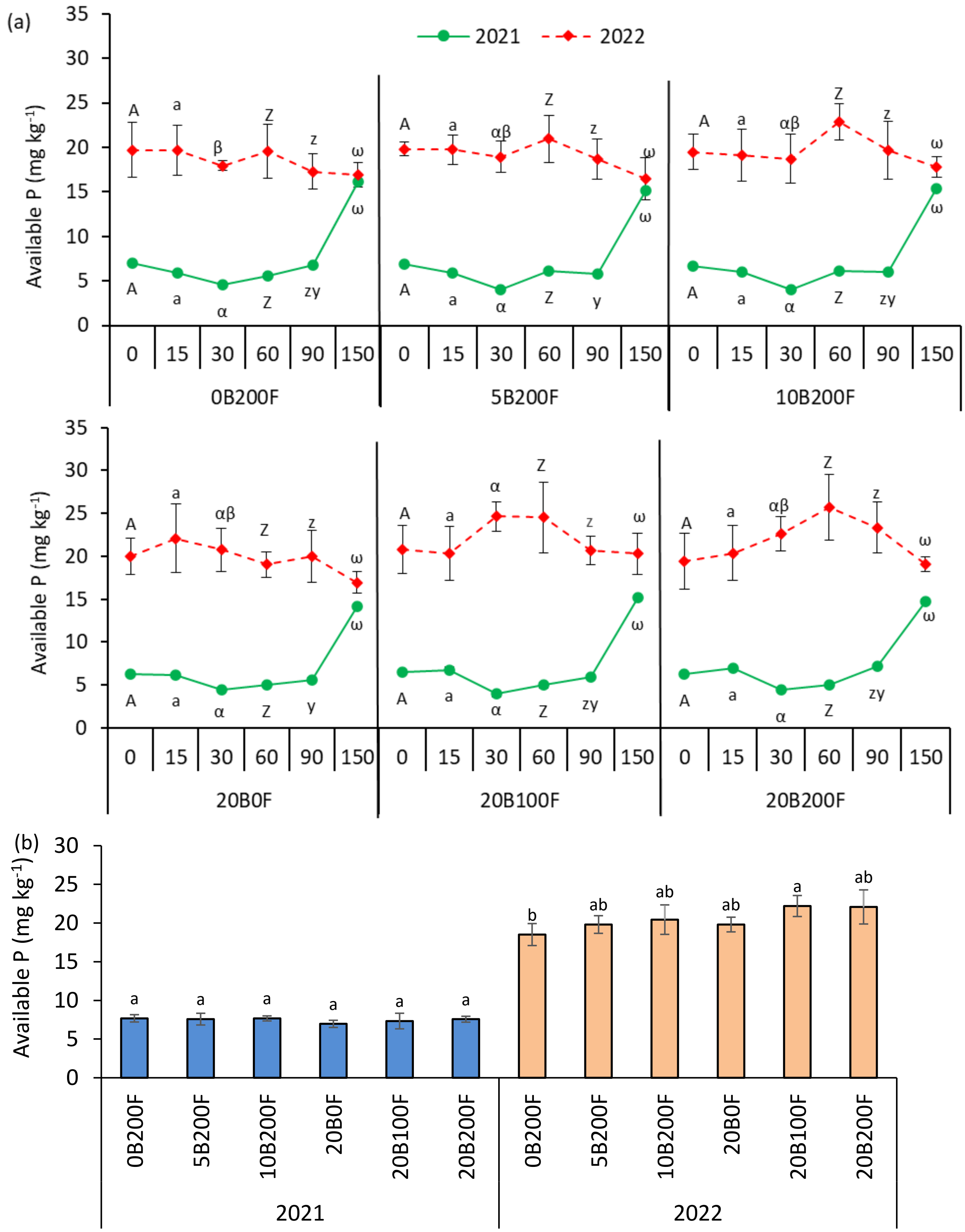

Fig. 2-5. Effects of biochar and fertilizer application on soil available P in each sampling date (a) and over year mean (b) during 2021 and 2022 cropping seasons. Mean separation was done separately for each day after sowing (DAS) among different treatments for each year. Means that do not share the same letter in each treatment were significantly different at a 5% level of significance.

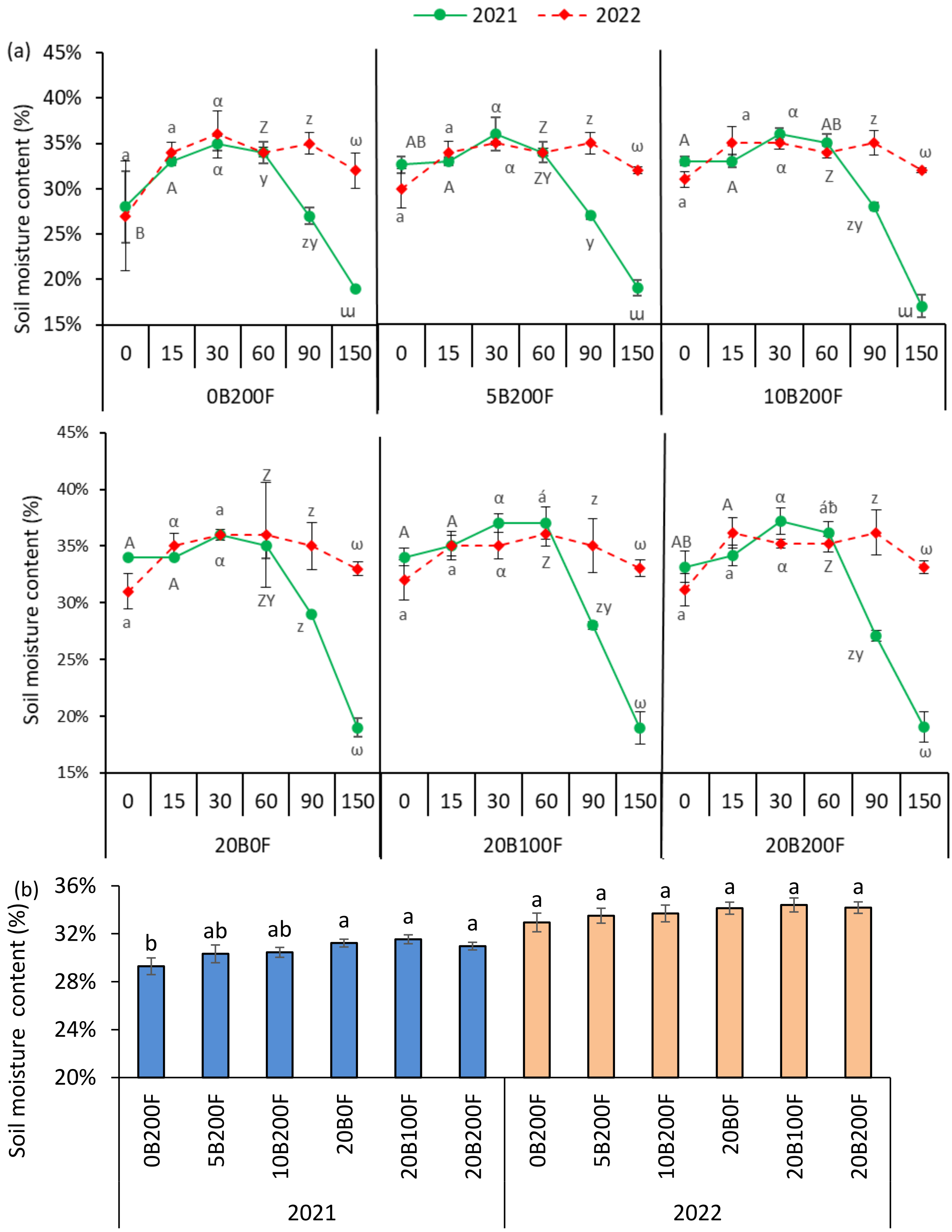

Fig. 2-6: Effects of biochar and fertilizer application on soil moisture content in each sampling date (a) and over year mean (b) during 2021 and 2022 cropping seasons. Mean separation was done separately for each day after sowing (DAS) among different treatments. Means that do not share the same letter in each treatment were significantly different at 5% level of significance.

The bulk density of the soil from the experimental plots at the beginning of the 2022 season, one year after biochar application, was 0.978, 0.907, 0.815, 0.591, 0.785, and 0.662 g cm^{-3} for 0B200F, 5B200F, 10B200F, 20B0F, 20B100F, and 20B200F, respectively. The net changes in soil bulk density due to biochar application ranged from 0.071 to 0.387 g cm^{-3}.

2.3.3. Biochar and fertilizer effects on wheat crop performance

As a general trend, the average performance of crop growth and yield components of wheat crops regardless of the treatments were greater in the 2021 season compared to those in the 2022 season (Table 2-3). The result showed that the application of biochar had positive effects, although not significant, on wheat growth and yield components in both the 2021 and 2022 years.

During the 2021 season, although no significant effect of biochar and fertilizer was observed, the plant height, spike length, spikelet number per spike, and grain number per spike were higher in treatments treated with biochar compared to those without biochar (Table 2-3). Similarly, in 2022, residual effects of biochar were observed in biochar-amended treatments, particularly in the 10B200F treatment, where higher plant height, spike length, and spikelet number per spike were recorded compared to the control (0B200F) (Table 2-3). For the 2021 season, increasing biochar application rate (0B, 5B, 10B, and 20B) among 200F treatment caused increasing dry biomass and grain yield (except for 20B200F for grain yield). Although there was no significant difference, the dry biomass with 20B200F increased by 13.1% and the grain yield with 10B200F increased by 6.4% compared to 0B200F in the 2021 season. Similarly, in the 2022 season, although no significant differences were observed between treatments, the dry biomass with the 200F treatment increased with rising biochar rates, except for 20B200F. However, biochar application had mixed effects on grain yield. Nevertheless, the highest dry biomass was with 10B200F being greater by 13.6%, and the highest grain yield was with

20B100F being greater by 11.1% compared to those with 0B200F, respectively, in the 2022 season (Table 2-3).

Table 2-3. The effects of water hyacinth biochar (B) and NPS Fertilizer (F) on wheat plant height (PH), Spike length (SL), Spikelet number per spike (SN), and Grain number per spike (GN) in 2021 and 2022 rainy seasons

Treatments	PH (cm)	SL (cm)	SN	GN	DB(t ha^{-1})	GY(t ha^{-1})
2021 season						
0B200F	85.9±1.70[a]	6.63±0.63[a]	13.9±0.63[a]	34.9±1.20[a]	13.0±0.66[a]	5.34±0.25[a]
5B200F	87.8±0.16[a]	6.68±0.15[a]	14.2±0.23[a]	36.5±3.20[a]	13.6±0.43[a]	5.57±0.20[a]
10B200F	86.6±3.20[a]	6.75±0.11[a]	14.2±0.51[a]	35.3±3.60[a]	14.2±1.13[a]	5.68±0.74[a]
20B0F	87.1±1.60[a]	6.53±0.39[a]	14.0±0.19[a]	35.3±1.80[a]	13.1±1.02[a]	5.52±0.61[a]
20B100F	88.2±0.68[a]	6.70±0.07[a]	14.0±0.16[a]	36.4±1.50[a]	13.0±0.48[a]	5.51±0.23[a]
20B200F	89.2±1.40[a]	6.68±0.26[a]	14.2±0.73[a]	36.7±1.50[a]	14.7±0.82[a]	5.44±0.84[a]
2022 season						
0B200F	73.0±10.4[a]	6.92±0.45[a]	11.2±2.26[a]	24.2±3.27[a]	9.51±0.87[a]	4.43±0.32[a]
5B200F	66.6±9.69[a]	6.70±0.48[a]	11.2±2.90[a]	25.5±6.44[a]	9.81±1.00[a]	4.85±0.50[a]
10B200F	77.1±6.45[a]	7.38±0.79[a]	13.6±1.26[a]	31.7±1.27[a]	10.8±1.84[a]	4.82±0.33[a]
20B0F	75.4±9.04[a]	6.70±0.08[a]	11.9±1.62[a]	26.3+4.57[a]	10.3±1.20[a]	4.45±0.21[a]
20B100F	74.8±6.02[a]	7.12±0.35[a]	12.8±0.40[a]	27.6±0.64[a]	10.7±1.45[a]	4.92±0.07[a]
20B200F	74.8±8.20[a]	7.15±0.42[a]	12.8±1.30[a]	32.8±2.59[a]	10.2±1.11[a]	4.56±1.16[a]

Means that sharing the same letter in each treatment were not significantly different at 5% level of significance.

2.4. DISCUSSION

2.4.1. Biochar characteristics

The biochar produced from water hyacinth biomass, collected from the same location as our collection site (Lake Tana, Ethiopia), produced using a laboratory pyrolysis furnace at the temperatures of 350, 550, and 750 ^{0}C exhibited basic properties such as biochar yield (33-51%), pH (9-11), ash content (33-52%), total carbon (TC) (28-33%), hydrogen (H) content (0.24-2.52%), nitrogen (N) content (1.37-2.14%), and carbon-to-nitrogen (C/N) ratio (15.9-20.3%) (Gezahegn *et al*., 2024). These values were relatively similar to our locally produced biochar, which was prepared using a grounding system. Our biochar had comparable characteristics in terms of yield (27.4%), pH (9.33), ash content (42.0%), TC (33.9%), H content (1.22%), N content (0.783%), and C/N ratio (43.3). Similarly, according to Li *et al*. (2016), biochar produced from water hyacinth in a furnace showed comparative values, including yield (28.2%), pH (10.96), ash content (27.2%), H content (1.1%), N content (0.73%), oxygen (O) content (42.8%), and C/N ratio (29.3%). These findings implied that locally produced biochar from water hyacinth, utilizing a cost-effective grounding system, can effectively serve as a soil amendment. This method can be particularly advantageous in areas where water hyacinth is a problem, as it offers a sustainable solution for biochar production tailored to local conditions.

2.4.2. Biochar and fertilizer effects on soil characteristics

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+} (Hailegnaw *et al*., 2019), as well as due to biochar surface properties and ability to reduce exchangeable acidic cations (Al^{3+} and H^+) (Masud *et al*., 2014). 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 (Gul *et al*., 2015). The addition of biochar in our study significantly increased soil pH at the beginning of the 2021 season and then decreased on 15 DAS (Fig.2-2a). 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 (Shi *et al.*, 2019; Zhou et al., 2014). In our study, soil pH was increased with values of 0.40–0.69 units and 0.20–0.35 units in the 2021 and 2022 seasons, as fresh and residual effects, respectively compared to those without biochar treatments. A similar finding was seen that chemical fertilizer and biochar (0.5%, 1%, 2%, and 4%) applications caused the soil pH to increase by 0.23 to 0.88 units, compared to chemical fertilizer treatment alone (Sun *et al.*, 2017). In the 2022 season experiment, the pH was higher for the plots amended with 20B than 0B, 5B, and 10B at the beginning of the experiment and remained higher in the growing season. This was mainly because of the residual effect of biochar added to the plots in the 2021 season.

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 (Hou *et al.*, 2022). In our study, the NH_4^+-N concentration in the soil at the beginning of the experiment (0 DAS) was increased from 3.03 mg kg^{-1} (0B200F) up to 3.33 mg kg^{-1} (10B200F). Then, it reached the peak on 30 DAS with values ranging from 5.37 mg kg^{-1} (0B200F) to 12.54 mg kg^{-1} (20B200F) 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 (Sun *et al.*, 2017). In our study, the application of 20B200F improved the NH_4^+-N concentration by 4.95%–408% throughout the growing stage of the wheat crop in the 2021 cropping season compared to the control (0B200F) (Figure 2-3). This trend was continued in the residual biochar 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 (Hou *et al*., 2022; Leng *et al*., 2020) (3) biochar increased microbial activity, accelerating nutrient cycling (Lehmann *et al*., 2011) and soil pH improvement which is shown in Figure 2.2 of this study.

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. Li *et al*. (2019) study 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 more NO_3^- in the soil solution (Sun *et al*., 2017). Our combined application of biochar and NPS fertilizer (20B200F) enhanced NO_3^- -N significantly by 13.8% and 17.8% on 90 and 150 DAS, respectively, compared to control (0B200F) in the 2021 season experiment. The NO_3^- -N concentration was high at the beginning of the experiment and then decreased until 30 DAS probably due to absorption by plants, denitrification, and leaching to a lesser extent. Then, NO_3^- -N was raised on 60 DAS after the split application of urea which may have been caused by nitrification. In the 2022 experiment season, the residual effect of biochar improved the NO_3^--N concentration by 64.8% (20B100F) compared to the control (0B200F) on 150 DAS. The overall increase of soil nitrification in the soil amended by biochar was possibly due to: (1) biochar promoting the conversion of NH_4^+-N to NO_2^- which was a substrate for NO_3^- -N (Nelissen *et al*., 2012) 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 (Xie *et al*., 2023). This effect is particularly attributed to the improvement of soil pH, as demonstrated in Figure 2.2 of this study, which promotes microbial population growth and activity.

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 (Syers *et al*., 2008). Soil properties such as pH, mineral and organic matter composition, CEC, and texture control plant availability of P in soils *(*Bornø *et a*l., 2018). 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 (Jindo *et al*., 2020). In our first-season experiment, there was no significant improvement in available P except on 90 DAS from the biochar application. Instead, the available P concentration from biochar amended plots was less than the control on 30 and 150 DASs. A similar finding was seen that biochar harmed soil available P in sandy clay loam and loam silty soils when the combined application of biochar with P fertilizer (Bornø *et al*., 2018). 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 (Bornø *et al*., 2018). However, for the residual effects of the biochar in the 2022 season, the available P concentration in the soil was increased with the application of biochar. Combined application of biochar with fertilizer (20B100F) increased available P by 39.7% compared to the control on 30 DAS in the 2022 season. Because of biochar could be a potential slow-release source that slowly and constantly supplied P to the soil over an extended period (Wang *et al*., 2015), the amount of available P released from biochar during our first growing season was low, but low absorption by plants and slow-release of P from biochar over time could have resulted in accumulation of residual P in the soil towards end of the 2021 growing season 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 (Suliman *et al*., 2017). The application of 20B100F in our study improved the moisture content of the soil by 2.91% to 21.4% at different growing stages of the wheat crop when compared to the plots without biochar in the season of 2021. Similarly, it was found that the moisture content of sandy loam soil was enhanced by 5.1% when biochar was applied at 1% (21.6 t ha^{-1}) versus without biochar (Yu *et al*., 2013). The bulk density of the soil was also improved with the residual effect of biochar application measured after one year (2022 cropping season). As a result of the amendment of the plots with 20B0F, the bulk density of the soil improved by 39.6% in comparison to the control plot. This was probably because of the lower density of the biochar than soil particles lowering the density of the whole soil, and the formation of soil aggregates with biochar in the long-term interaction in soil rebuilding the soil structure (Blanco-Canqui, 2021).

2.4.3. Biochar and fertilizer effects on wheat crop yield

For effective plant growth, biochar generally contains some macronutrients, micronutrients, and trace elements (Hou *et al*., 2022). It is also important to increase microbial activity, accelerate nutrient cycling, and reduce leaching and N volatilization, which are important for plant growth (Lehmann *et al*., 2011). In our study, even though there was no significant difference between the treatments, the combined application of biochar with chemical fertilizers showed a positive effect on aboveground biomass and grain yield of wheat crops 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 (Li *et al*., 2019). 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 (Agegnehu et al., 2016). In our study, the application of 20B and 10B with chemical fertilizer increased crop biomass and grain yield by 13.1% and 6.4%, respectively, in the 2021 season. Similarly, biomass increased by 13.6%, and grain yield by 11.1% in the plots amended with 10B200F and 20B200F, respectively, in the residual effects of biochar in the 2022 season. A similar finding was shown in a review of literature, the simultaneous application of biochar with inorganic fertilizers resulted in an additional 10% increase in yield compared to inorganic fertilizers alone (Bai *et al*., 2022). Another two-year biochar field trial done by Li *et al*. (2019) 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 wheat by 12.2%–13.8% compared to N fertilizer alone.

2.5. CONCLUSION

In conclusion, the study investigated the effects of water hyacinth biochar and fertilizer application on soil characteristics and wheat crop performance over two consecutive seasons. The biochar exhibited properties conducive to soil improvement, with notable impacts on soil pH, NH_4^+–N, NO_3^-–N, and available P concentrations. Biochar application as a fresh and residual increased soil pH, NH_4^+–N, and NO_3^-–N concentrations in the subsequent seasons. Additionally, biochar application improved soil moisture retention and reduced bulk density, indicating enhanced soil structure.

Furthermore, the combined application of biochar with fertilizer demonstrated positive effects on wheat crop performance, albeit not always statistically significant. Across both seasons, biochar-amended treatments generally exhibited higher plant height, spike length, spikelet number per spike, grain number per spike, dry biomass, and grain yield compared to non-amended treatments.

Overall, the study highlights the potential of locally produced water hyacinth biochar as a sustainable soil amendment, capable of improving soil characteristics and enhancing wheat crop performance. These findings suggest that biochar application, especially when combined with fertilizer, could be a valuable strategy for sustainable agricultural practices, contributing to improved soil fertility and crop productivity.

CHAPTER THREE

3. SYNERGISTIC EFFECTS OF BIOCHAR AND NPS FERTILIZER ON SOIL DYNAMICS AND WHEAT CROP YIELDS UNDER DEFICIT IRRIGATION CONDITIONS

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3.1. INTRODUCTION

Drought (deficit irrigation) stands out as the leading cause of crop yield loss among abiotic factors globally (Begna, 2020). Deficit irrigation involves applying water at levels below the maximum crop transpiration or evapotranspiration requirements, considered valuable when water availability is the limiting factor for crop cultivation and yield. It enables to enhancement of crop water productivity by reducing the amount of water applied to the crop (Baiamonte *et al*., 2020). Deficit irrigation affects soil properties, crop growth, and productivity (Iqbal *et al*., 2020). Soil acidity is also a serious problem in agricultural lands as it directly impacts the soil quality and crop production (Huang *et al*., 2023). In Ethiopia, soil acidity is increasingly becoming a widespread and severe issue, greatly limiting crop productivity. In certain regions of the Ethiopian highlands where barley, wheat, and faba beans are grown, farmers are shifting towards cultivating other crops that are more tolerant to soil acidity compared to wheat and barley (Haile *et al*., 2009). Lime is an important material for managing acidic soil, but its high transportation cost and limited availability restrict its widespread use (Huang *et al*., 2023). Hence, utilizing different biomass like water hyacinth for biochar production as a soil amendment offers a promising solution to alleviate moisture stress, soil acidity, nutrient deficiencies, and reduce the additional costs and environmental impacts associated with chemical fertilizers, particularly benefiting resource-constrained farmers.

Incorporating biochar into the soil has been demonstrated to alter certain physical properties of the soil, including bulk density, porosity, texture, and particle size distribution. As a result, soil structure is influenced, which in turn impacts crucial soil functions such as infiltration, hydraulic conductivity, water holding capacity, aeration, and redox potential. These changes ultimately affect plant growth and yield particularly under moisture deficit conditions (Ajayi and Horn, 2016; Faloye *et al*., 2019).

The ability of the combined application of biochar with inorganic fertilizer to improve soil productivity is achieved by enhancing nutrient use efficiency, as demonstrated by El-Syed *et al*. (2023), and by increasing crop water and irrigation water use efficiency under deficit irrigation conditions, as indicated by Faloye *et al*. (2019). Furthermore, through the reduction of nutrient leaching and fixation, as well as the enhancement of nutrient recycling, the synergistic effect of biochar and fertilizer can increase nutrient availability for plants. This includes ammonium-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^-–N), and available phosphorus (Adekiya *et al*., 2020; Ginebra *et al*., 2022; Liu *et al*., 2024; Ng *et al*., 2022), thereby enhancing plant growth and yield.

According to a review by Joseph *et al*. (2021), biochar amendment has been found to improve crop growth and production in several ways. It can lower soil acidity, increase dissolved and total carbon, enhance cation exchange capacity, improve nutrient availability, increase water retention, and enhance soil aggregate stability. Another review also found that the yield improvement in biochar-amended soil was particularly significant in very acidic soils ($pH \leq 5$) compared to other types of soils (Bai *et al*., 2022). A study by Baiamonte *et al*. (2020) focused on the benefits of biochar amendment for wheat crops under deficit irrigation. The study found that wheat crops experienced the greatest benefit from biochar amendment, as it increased water use efficiency and reduced irrigation frequency, especially when compared to sorghum and tomato crops. The study also found that wheat crop yield in biochar-amended soil was not significantly impacted by water deficit. This is attributed to the ability of biochar to enhance both irrigation water use efficiency (IWUE) and crop water use efficiency (CWUE) (Baiamonte *et al*., 2020). Despite these positive findings, it is important to note that there have been inconsistent outcomes reported in various research studies regarding the synergistic effects of biochar and fertilizer in soil amendment and crop productivity.

Discrepancies exist regarding the effects of biochar on soil nutrient dynamics, specifically concerning nutrient concentrations and nitrification rates. Contradictory findings are reported regarding the impact of biochar on NH_4^+–N concentrations, with some studies demonstrating reductions and others showing increases post-amendment. In a study by Martí *et al*. (2021), the incubation experiment showed a reduction of NH_4^+–N after the soil was amended by biochar. On the other hand, in a study by Ginebra *et al*. (2022), the application of biochar increased soil NH_4^+–N concentration compared to fertilizer alone. Moreover, while some studies suggest a decrease in nitrification processes and subsequent reductions in NO_3^-–N concentration with biochar application, others indicate an improvement in nitrification rates attributed to the increased abundance of ammonia-oxidizing bacteria. For example, according to Yao *et al*. (2022), biochar soil amendment decreased ammonia-oxidizing bacteria and the nitrification rate subsequently decreased NO_3^-–N concentration. Conversely, in a study by Liu *et al*. (2024) and DeLuca *et al*. (2006), biochar soil amendment showed that NO_3^-–N concentration was increased due to increasing the nitrification rate.

Additionally, discrepancies arise in the effects of biochar on crop yield, with conflicting results regarding optimal application rates and varying outcomes based on crop type and experimental conditions. According to Ye *et al*. (2020), a meta-analysis indicated that the application of biochar greater than 10 t ha^{-1} does not contribute to greater crop yield. Conversely, the combined application of 20 t ha^{-1} of biochar improved crop biomass and yield, as demonstrated by Faloye *et al*. (2019). A study by Sorensen and Lamb, (2016), on biochar soil amendment showed that the biochar rate did not exhibit either positive or negative effects on the performance of different crops. However, the effect of biochar was significant between the 5–10 t ha^{-1} and 10–20 t ha^{-1} groups on crop performance, as indicated by Ye *et al*. (2020). The effect of biochar amendment also varies for different crop types, and its impact differs between pot and field experiments, with the effect being three times higher for pot experiments compared to field experiments, as noted by Jeffery *et al*. (2011). The disparity in findings underscores the complexity of biochar's interaction with soil and highlights the need for further research to elucidate its effects consistently across different contexts and conditions.

We hypothesized that (1) locally produced biochar using a grounding system would enhance soil moisture content, thereby reducing the frequency and the amount of irrigation water requirements. This improvement in water management is crucial, especially under conditions of water deficit, and is expected to contribute significantly to improved crop performance and resilience to drought stress. (2) the application of biochar derived from water hyacinth biomass would effectively mitigate soil acidity in the acidic soils of the Ethiopian highlands, resulting in a notable increase in soil pH levels and substantial improvements in soil health under deficit moisture conditions. Consequently, this enhancement in soil conditions is anticipated to lead to a significant boost in crop productivity; (3) the synergistic combination of biochar with inorganic fertilizers soil amendment would result in a profound enhancement in soil nutrient availability and subsequent crop yield. This effect is expected to be particularly pronounced in soils with inherent nutrient deficiencies commonly found in the Ethiopian highlands. Therefore, this study aimed to ascertain the impact of the combined application of water hyacinth–derived biochar and NPS inorganic fertilizer on soil physicochemical properties and wheat crop yield in acidic soils under conditions of deficit irrigation.

3.2. MATERIALS AND METHODS

3.2.1. Experimental site description

The field experiment was conducted during the dry season of 2023, from January to May. The experiments were conducted at the Injibara University research station of Awi Zone of the Amhara Region, Ethiopia (Fig.2-1). The site's 33-year minimum and maximum temperatures were 10.3°C and 22.5°C, respectively. The mean annual rainfall was 1344 mm, with the main wet season occurring from June to September, followed by a less pronounced wet period extending until November (Habtie *et al*., 2020).

3.2.2. Experimental land/plot preparation

After land clearing, the experimental area was plowed five times using oxen. The plots were arranged with a width of 1.6 m and a length of 2 m, resulting in a total length of 29.5 m and a width of 7.8 m for the experimental site. The spacing between rows, plots, and replications was set at 0.2 m, 0.5 m, and 1.5 m, respectively.

3.2.3. Biochar production

The biochar was produced from water hyacinth collected from Lake Tana (12°72'78" N and 37°52'02" E), Ethiopia. The stem part of the water hyacinth was gathered and sun-dried. Recognizing the challenges posed by furnace pyrolysis methods, particularly for resource-limited farmers, a simple grounding system was developed that can be easily implemented at the collection site of water hyacinth, such as Lake Tana in Ethiopia. This cost-effective solution enables farmers to convert biomass into biochar without the need for expensive furnaces, making it accessible and practical for small-scale agricultural operations. After creating a pile of water hyacinth stems, it was covered with teff (*Eragrostis tef*) straw and a layer of soil to prevent the entrance of air. Water was sprayed to cool down the biochar, and then it was sun-dried. The biochar was then sieved using a < 5 mm sieve after being hand-crushed.

3.2.4. Field experimentation

The plots were arranged in a completely randomized block design with three replications resulting in a total of 36 experimental plots. Four different rates of water hyacinth biochar (B; 0, 5, 10, and 20 t ha^{-1}), three rates of NPS inorganic fertilizer (0, 100, and 200 kg ha^{-1}), and two levels of irrigation regimes (50% and 100% of crop requirement) were employed in a partially factorial treatment arrangement (Table 3-1). The experimental treatment was comprised of the full factorial arrangement for two levels of biochar rate (0 and 20 t ha^{-1}), two levels of NPS fertilizer rate (0 and 200 kg ha^{-1}), and two regimes of irrigation water (50% and 100%). Additionally, we included other rates of biochar (5 and 10 t ha^{-1}) and NPS fertilizer (100 kg ha^{-1}) as satellite treatments to minimize the number of combined treatments to use the resources efficiently (Table 3-1).

The test crop was the "Kakaba" variety of bread wheat, planted at a seedling rate of 150 kg ha^{-1}. Biochar was incorporated into the soil at a depth of 0-20 cm for treatments that received biochar, two days before the planting date (December 28, 2023). For treatments that received inorganic fertilizer, all NPS and half of the urea were applied at the time of planting (December 30, 2023), while the remaining half of the urea was applied at the tillering stage (March 09, 2023) as recommended by Derebe *et al*. (2022). To ensure uniform germination of the crop, all plots were fully irrigated two days before sowing and continued up to one week after sowing. After one week, plots were daily irrigated to meet 50% and 100% of the crop's water requirement, according to the treatment arrangement. For treatments that received 50% and 100% of full irrigation, five and ten liters of water were applied daily, respectively, until the booting stage of the crop. After the booting stage, 10 and 15 liters of water were applied daily until the physiological maturity of the crop, using a water can. This is because the water requirement of the wheat crop is higher during the later stages compared to the early stages (Deo *et al*., 2017). The amount of water applied was determined based on the irrigation water requirement of the wheat crop indicated by Desalegn *et al*. (2019) and Tewabe, (2022).

Table 3-1. Treatments of field experiment for 2023 dry season experiment

Biochar (t ha^{-1})	Fertilizer (kg ha ^{1})	Irrigation water (%)	Treatments	Definition
0	0	100	0B0F100I	No biochar +No fertilizer + 100% Full irrigation
0	200	100	0B200F100I	No biochar +200 kg ha^{-1} fertilizer + 100% Full irrigation
5	200	50	5B200F50I	5 t ha^{-1} biochar +200 kg ha^{-1} fertilizer + 50% Full irrigation
5	200	100	5B200F100I	5 t ha^{-1} biochar +200 kg ha^{-1} fertilizer + 100% Full irrigation
10	200	50	10B200F50I	10 t ha^{-1} biochar +200 kg ha^{-1} fertilizer + 50% Full irrigation
10	200	100	10B200F100I	10 t ha^{-1} biochar +200 kg ha^{-1} fertilizer + 100% Full irrigation
20	0	50	20B0F50I	20 t ha^{-1} biochar +No fertilizer + 50% Full irrigation
20	0	100	20B0F100I	20 t ha^{-1} biochar +No fertilizer + 100% Full irrigation
20	100	50	20B100F50I	20 t ha^{-1} biochar +100 kg ha^{-1} fertilizer + 50% Full irrigation
20	100	100	20B100F100I	20 t ha^{-1} biochar +100 kg ha^{-1} fertilizer + 100% Full irrigation
20	200	50	20B200F50I	20 t ha^{-1} biochar +200 kg ha^{-1} fertilizer + 50% Full irrigation
20	200	100	20B200F100I	20 t ha^{-1} biochar +200 kg ha^{-1} fertilizer + 100% Full irrigation

B: locally produced water hyacinth biochar, F: NPS fertilizer, and I: Irrigation regime

3.2.5. Soil and biochar sampling and characterization

A composite of 5 sub-samples was taken from the experimental land to characterize the experimental soil before preparing the experimental plots. For evaluating treatment effects, soil samples were taken from each plot on 7, 15, 30, 60, 90, and 130 days after sowing (DAS) at a depth of 0–20 cm. These samples were stored in a refrigerator until analysis.

The pH of the soil and biochar was measured from 10 g of soil and 2 g of biochar samples that had been air-dried at 45°C. For the soil sample, 25 mL of pure water was added to a 50 mL centrifuge tube, while for the biochar sample, 20 mL of pure water was added. The tubes were then shaken horizontally at 160 strokes per minute for 1 hour, allowed to stand for 30 minutes, and the pH was measured using a pH meter (LAQUA F-71, Horiba Scientific, Kyoto, Japan). Total carbon (C) hydrogen (H), and nitrogen (N) in the soil and biochar samples were measured using a CHN analyzer (Perkin Elmer, 2400 series II, Waltham, MA, USA). Five milligrams of soil and two milligrams of biochar samples were placed into tin capsules and analyzed according to the method described by Yeomans and Bremner, (1991). The oxygen (O) content of biochar was obtained by the calculation of 100% − (C + H + N + Ash) %. The Willey–Black method was employed to determine organic carbon (OC). To determine the concentrations of NH_4^+–N and NO_3^-–N in the soil and biochar samples, 2.0 g of dry-weight equivalent soil and 2.0 g of dried biochar (45°C) were extracted with 20 mL of 2 mol L^{-1} potassium chloride solution (KCl) in a centrifuge tube. The tube was shaken horizontally at 160 strokes per minute for 1 hour. After filtration through a 0.45 μm filter membrane, the concentration of NH_4^+–N and NO_3^-–N in the extractant was determined at 670 nm and 540 nm, respectively, using a flow injection auto-analyzer 2000 (FIAlyzer-1000, FIAlab Instruments, Inc., Seattle, WA, USA) according to the methods described by Keeney and Nelson, (1983). Available phosphorus (P) was determined by extracting 2.0 g of soil and 0.5 g of biochar that had been dried at 45°C with 20 mL of Mehlich 3 extraction solution in a 50 mL centrifuge tube, according to the method described by Mehlich, (1984). The tube was shaken horizontally at 200 strokes per minute for 5 minutes, and the mixture was then filtered through a 0.45 µm pore size membrane filter. The concentration of P was determined at 870 nm using the flow injection auto analyzer 2000 (FIAlyzer-1000, FIAlab Instruments, Inc., Seattle, WA, USA). Cation exchange capacity (CEC) of the soil and biochar was determined by using 1 mol L^{-1} ammonium acetate adjusted to pH 7. Ten grams of dry soil and 1 g of biochar were mixed with the ammonium acetate solution. The mixture was shaken at 160 strokes per minute for 5 minutes for the soil and 15 hours for the biochar. After shaking, the mixture was filtered with Whatman filter paper of size 42, and the concentration of NH_4^+ was measured using the auto-analyzer to calculate the CEC of the soil and biochar by eq.1.

$$\mathrm{CEC(cmol_c/kg)} = \frac{\mathrm{NH_4}^+ \text{ conc.(Sample−Blank)}\left(\frac{\mathrm{mg}}{\mathrm{L}}\right) \text{ x V(mL)}}{\text{molecular mass of } \mathrm{NH_4}^+ \text{ x W(g) x 10}} \qquad \text{eq.1}$$

Where V=volume of extract (i.e., 100mL) and W=biochar weight (g).

To measure soil bulk density, we took soil samples three times: before preparing the experimental land, on 70 DAS, and at the time of crop harvesting (130 DAS: end of the experiment) from each experimental plot. It was measured by drying the core sampler soil in an oven at 105°C until it reached a constant mass. Then, we calculated it as the mass of the core sample dried at 105°C minus the mass of the core sample holder (g) divided by the volume of the core sample holder (cm^3). Soil total porosity (St) was determined by the equation:

$$\mathrm{St} = 1 - \left(\frac{\rho b}{\rho p}\right) \qquad \text{eq. 2}$$

Where ρb and ρp soil bulk density and soil particle density respectively, by considering ρp for mineral soil is 2.65 g cm^{-3} as a rule of thumb (Margesin and Schinner, 2005). To measure the moisture content of the soil sample, 3 g of wet soil was taken. The samples were weighed into an aluminum dish and then dried in an oven at 105°C for 24 hours. The weight of the aluminum dish and soil was recorded and then determined the water content by subtracting the wet soil mass from the dry soil mass and dividing it by the dry soil mass. The yield of biochar was calculated by dividing the weight of the produced biochar by the dried biomass used as a feedstock and expressing the result as a percentage. The biochar-specific surface area, pore volume, and pore size were determined using N_2 adsorption-desorption performed at 77K with Micromeritics ASAP (Micromeritics ASAP 2020, Shimadzu, Tokyo, Japan). The specific surface area was calculated using the Brunauer Emmett-Teller (BET) method (Brunauer *et al*., 1938). Fixed carbon, volatile matter, and ash content of the biochar were determined by thermal gravimetric analysis (TGA) using simultaneous differential thermogravimetry (SDT Q600, TA Instruments, Lukens Drive, New Castel, DE, USA).

3.2.6. Plant data collection

Growth and yield components of a wheat crop refer to various measurable attributes and characteristics that determine the overall development and productivity of the wheat crop. Growth components included plant height, leaf area, dry biomass, and soil plant analysis development (SPAD) value. Yield components included spike length, spikelet number per spike, grain number per spike, and grain yield.

Each plot was divided into two halves: the first half was used for frequent biomass measurements to quantify the effects of the amendments on the wheat crop biomass throughout the growth stages, while the second half was designated for the measurement of other growth and yield components of the wheat.

Dry biomass, the amount of dry plant material such as stems, leaves, and grain yield of the wheat crop is a measure of its overall growth and productivity. Biomass samples were collected at four different times during the crop growth stages. The first sample was taken on 70 DAS during the full tillering growth stage of the crop. Subsequent samplings were conducted on 90 DAS (flowering stage), 110 DAS (physiological maturity stage), and 130 DAS (harvesting stage). These samples were collected using 25cm×25cm quadrants from each plot. It was measured after drying in the sun.

Chlorophyll content measured as leaf SPAD, the concentration of chlorophyll in the leaves is indicative of the plant's photosynthetic activity and overall health. A chlorophyll meter (CY-YD, Jinan Cyeeyo Instruments Co., Ltd., China) was used to measure the chlorophyll concentration of the leaves. A leaf area meter (LAM-A, Biobase Biodustry Co., Ltd., China) was used to measure the leaf area. Measurements were taken from the central, fully matured leaves of five randomly selected plants in the central rows of each plot (Islam et al., 2014). Both leaf area and leaf chlorophyll concentration were measured three times on 70, 90, and 110 DAS, corresponding to the full tillering, flowering, and physiological maturity stages of the crop growth period, respectively. The same leaves were used for measurements during the sampling dates by marking them from five selected plant leaves in the central part of the plant.

Spike length, the component measures the length of the wheat spike or head, which contains the grains. A longer spike often indicates a higher potential for grain production and spikelet number is the number of spikelets on each spike which is a crucial determinant of the potential grain yield. The number of grains refers to the total seeds or grains produced by each wheat spike, directly impacting the final grain yield. Grain yield, the most important yield component, represents the actual amount of wheat harvested per unit area and is influenced by various growth and yield components, mentioned above. Plant height, spike length, number of spikelets per spike, and the number of grains per spike were measured from five randomly selected plants in the central rows of each plot at the maturity stage of the crop in both rainy and dry seasons. The entire central rows were harvested to measure grain yield. The grain yield was weighed after sun-drying, threshed, and separated from the wheat straw.

Liner regression model and Pearson correlation coefficient procedure were employed to determine the relationship and correlation between crop growth and yield components with grain yield of the wheat crop.

Production cost-benefit of wheat was conducted by comparing the gross return and total cost of wheat crop production. The total cost was calculated from input costs (fertilizer and biochar production) and labor costs (sowing, fertilizer application, and irrigation). The gross return was derived from the sales of wheat grain and straw at market prices. The cost of the biochar stock material (water hyacinth) was not considered since it was naturally available in Lake Tana. Only the collection and production of biochar costs were included. The total biochar production cost was divided over 5 years, considering that the biochar applied in the first year of crop production served for 5 consecutive years without much crop yield reduction (Vijay et al., 2021). All costs and returns were converted to USD (1 USD ≈ 56 Ethiopian Birr as of December 2023). The rental cost of land and plow oxen or horses were not included since most Ethiopian farmers own their land and plowing animals. Net return was computed as the difference between gross return and total cost. The cost-benefit ratio was also computed from the ratio of the gross return and total cost of production.

3.2.7. Statistical analysis

One-way Analysis of Variance (ANOVA) was computed to compare the means of each combined treatment on soil physical and chemical parameters, as well as wheat crop biomass and grain yield. Two-way ANOVA was performed to test for the interaction effects between biochar and fertilizer, biochar and irrigation, and fertilizer and irrigation, and additionally, three-way ANOVA was conducted to examine the interactive effects of biochar, fertilizer, and irrigation amount on soil physicochemical properties and crop performance. All analyses of variance were carried out using the R-software program, specifically, version R-4.3.0 packages (Team, 2023). Data normality was assessed using the Shapiro-Wilk procedure (Shapiro and

Wilk, 1965), and the difference among treatment means was determined using Tukey's Highly Significant Difference (HSD) at a 5% probability level 5% ($p < 0.05$).

3.3. RESULTS

3.3.1. Characteristics of soil and biochar

The field experiments were conducted on Nitisol soil according to Schad, (2016) soil classification, belonging to the silt loam texture class. The soil at the experimental site had strongly acidic (pH of 4.42). The concentrations of NH_4^+–N, NO_3^-–N, and available P in the soil were 1.52, 15.7, and 0.392 mg kg^{-1}, respectively (Table 3-2).

The biochar used had an alkaline (pH of 10.7). The concentrations of NH_4^+–N, NO_3^-–N, and available P in the soil were 0.748, 0.676, and 837 mg kg^{-1} respectively. The cation exchange capacity of the biochar was 33.4 $cmol_c$ kg^{-1}. The total carbon and organic carbon were 35.2% and 16.8% respectively. The biochar had fixed C, volatile matter, and ash contents of 20.3%, 59.2%, and 20.5%, respectively. Additionally, the biochar exhibited a specific surface area of 53.2 m^2 g^{-1}, a pore volume of 0.059 cm^3 g^{-1}, and an average pore size of 4.45 nm (Table 3-3).

Table 3-2. Basic characterization of soil samples

Sand	Silt	Clay	Bulk density	pH	T-C	T-N	NH_4^+-N	NO_3^--N	Available P[§]	CEC[#]
—— % ——			g cm^{-3}		—— % ——		—— mg kg^{-1} ——			$cmol_c$ kg^{-1}
20.4	65.9	13.7	1.21	4.42	3.71	0.483	1.52	15.7	0.392	18.2

Table 3-3. Basic characterization of biochar samples

Yield	pH	T-C	T-H	T-N	T-O	H/C	O/C	C/N	Organic carbon	NH_4^+-N	NO_3^--N
%		—— % ——							%	—— mg kg^{-1} ——	
28.9	10.7	35.2	0.76	0.930	42.6	0.02	1.21	37.8	16.8	0.748	0.676
Available P[§]	CEC[#]	Fix carbon	Volatile matter	Ash	S_{BET}	S_{micro}	S_{meso} & S_{macro}	V_{micro}	V_{meso} & V_{macro}	V_{total}	Pore width
mg kg^{-1}	$cmol_c$ kg^{-1}	—— % ——			—— m^2 g^{-1} ——			—— cm^3 g^{-1} ——			nm
837	33.4	20.3	59.2	20.5	53.2	25.9	27.3	0.012	0.047	0.059	4.45

[§] Mehlich 3-extraction

[#] Cation exchange capacity

S_{BET} (BET surface area), S_{micro} (micropore surface area), S_{meso} & S_{macro} (meso and macro surface area), V_{micro} (micropore volume), V_{meso} & V_{macro} (meso and macro pore volume), and V_{total} (total pore volume) of locally produced water hyacinth biochar.

3.3.2. Effects of combined application of biochar and fertilizer on soil physical properties

The bulk density of the soil generally decreased at the end of the experiment regardless of treatments. The main effect of biochar significantly ($p < 0.001$) impacted the bulk density on both 70 and 130 DAS, but not for fertilizer and irrigation (Table A4). The ANOVA results showed that the bulk density in biochar-amended plots significantly ($p < 0.001$) decreased from 0.838 and 0.750 g cm^{-3} (0 t ha^{-1}B) to 0.698 and 0.637 g cm^{-3} (20 t ha^{-1} B) on 70 and 130 DAS, respectively (Fig. 3-1). ANOVA results also revealed that the bulk density reduction was higher in the plots that received higher rates of biochar (20 t ha^{-1}) compared to those that received lower rates (5 and 10 t ha^{-1}) of biochar.

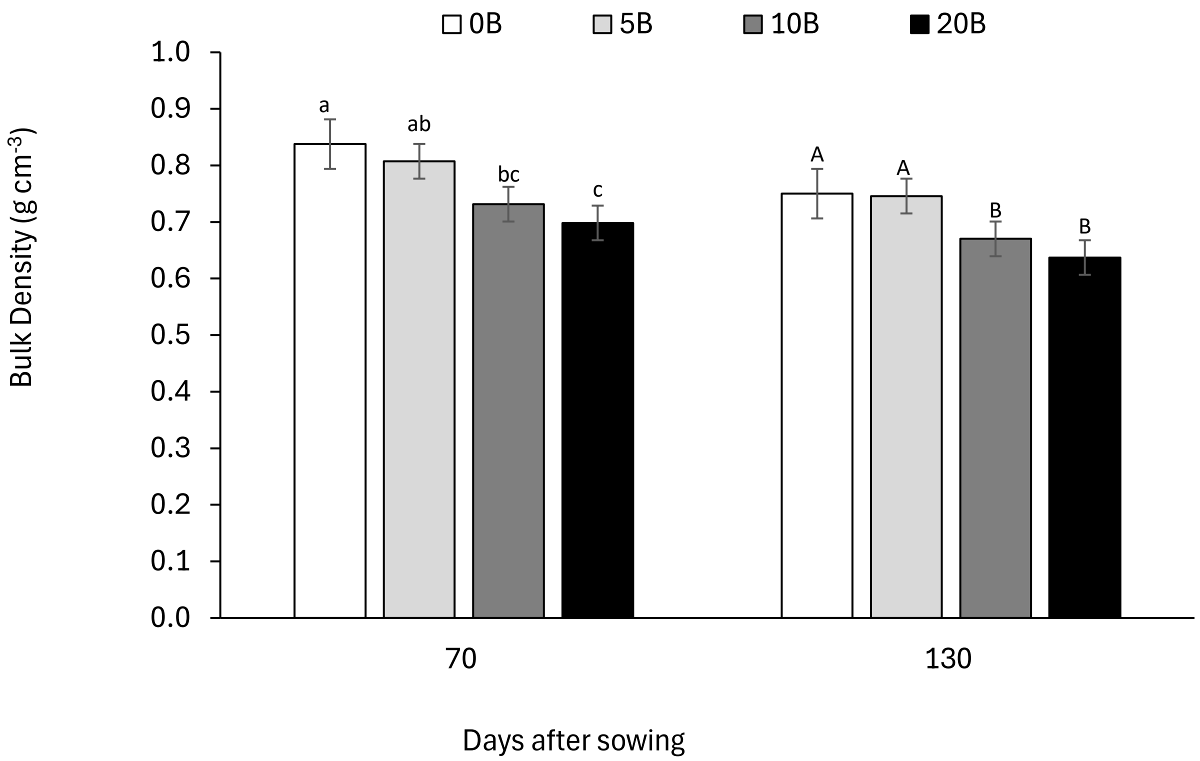

Fig. 3-1. The effect of water hyacinth biochar (B) rates (0, 5, 10, and 20 t ha^{-1}) on soil bulk density. Mean separation was done separately for each day after sowing (DAS) among different treatments. Means that do not share the same letter were significantly different at 5% level of significance. Vertical bars indicate standard deviation of means.

Total porosity at the end of the experiment (130 DAS) was higher than in the middle of the experiment period (70 DAS), regardless of the treatment. The application of biochar significantly affected soil total porosity ($p < 0.001$), while fertilizer and irrigation did not have a significant impact. Total porosity showed an increasing trend with the increase in biochar rate. It increased from 68.4% (0 t ha^{-1}B) to 73.6% (20 t ha^{-1}B) on 70 DAS and remained higher on 130 DAS (76.0%; 20 t ha^{-1}B) (Fig. 3-2).

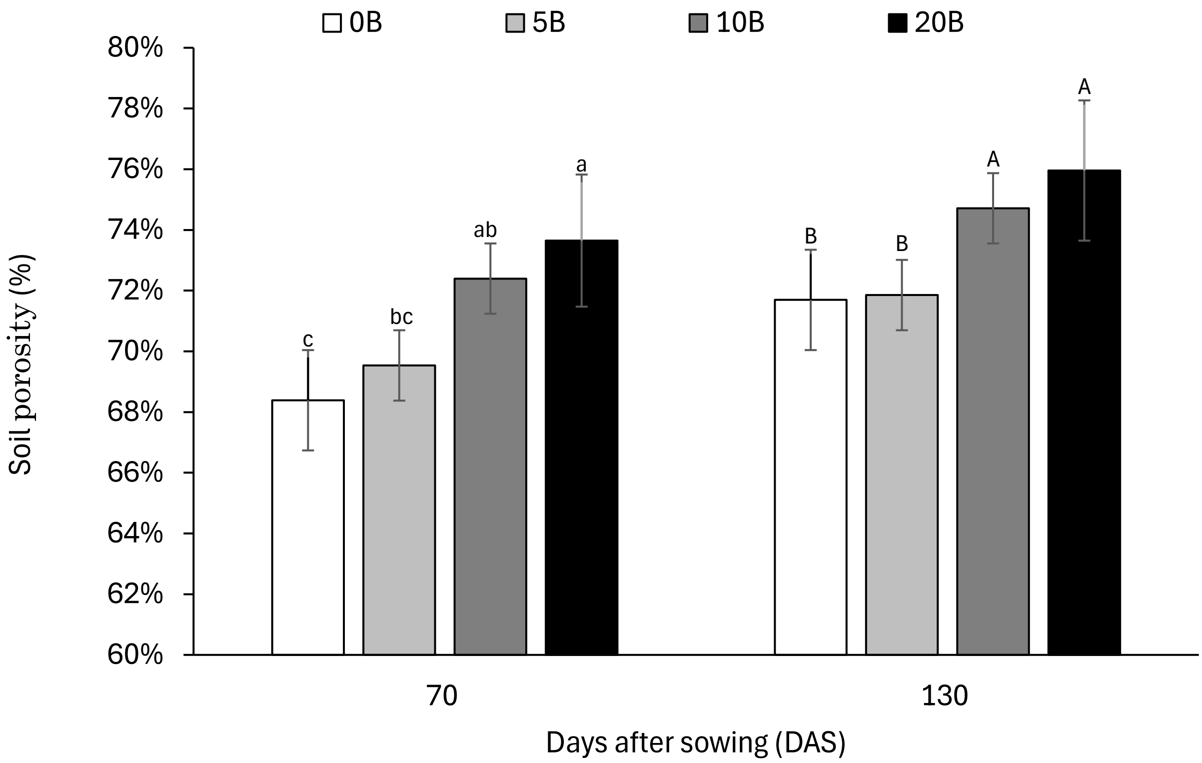

Fig. 3-2. The effect of water hyacinth biochar (B) rates (0, 5, 10 and 20 t ha^{-1}) on soil porosity. Mean separation was done separately for each day after sowing (DAS) among different treatments. Means that do not share the same letter were significantly different at 5% level of significance. Vertical bars indicate standard deviation of means.

The ANOVA result revealed that soil moisture content was positively influenced by the application of biochar compared to unamended plots. The moisture content was generally higher at the beginning and end of the experiment. Soil moisture was affected only by the main effect of biochar. The main effect of both fertilizer and irrigation and interaction effects did not affect it (Table A4). The moisture content on 15, 30, and 130 DAS was significantly ($p < 0.01$)

affected by biochar application. It increased from 26.7% (0B0F100I) to 29.5% (20B100F100I) on 15 DAS and continued to be higher on 30 (32.6%; 20B200F100I) and 130 DAS (33.9%; 20B200F100I) (Fig.3-3 and Table A1).

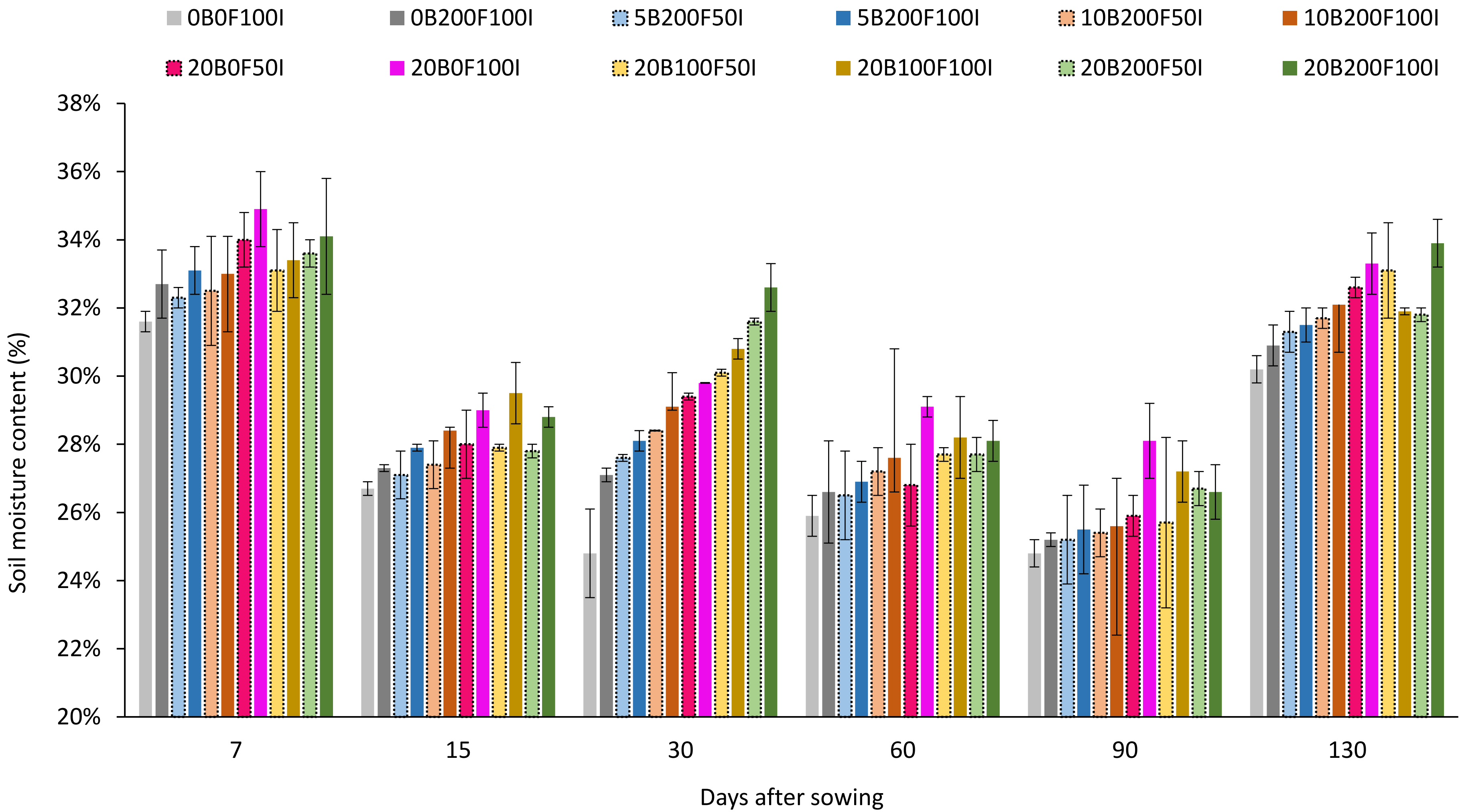

Fig. 3-3. The effect of water hyacinth biochar (B) rates (0, 5, 10, and 20 t ha^{-1}), fertilizer (F), and irrigation (I) on soil moisture content in the 2023 dry season.

3.3.3. Effects of combined application of biochar and fertilizer on soil chemical properties

The soil pH at the beginning of the experiment (7 DAS) was generally lower and higher at the end of the experiment (130 DAS), regardless of the treatments. The main effect of biochar significantly ($p < 0.001$) affected soil pH, but not fertilizer and irrigation, as well as interaction effects (Table A4). The application of biochar significantly ($p < 0.001$) affected soil pH on 7, 60, 90, and 130 DAS. The pH increased from 4.65 (0B0F100I) to 5.29 (20B100F100I) on 7 DAS and continued significantly higher in 20B100F100I (5.47) on 60 DAS, 20B20F100I (5.33), on 90 DAS, and 20B100F100I (5.90) on 130 DAS (Fig.3-4 and Table A2). Soil pH increased with the increase of biochar rate without significant differences. Treatments with a higher rate of biochar (20 t ha^{-1}) showed higher pH values compared to treatments with lower rates (5 and 10 t ha^{-1}).

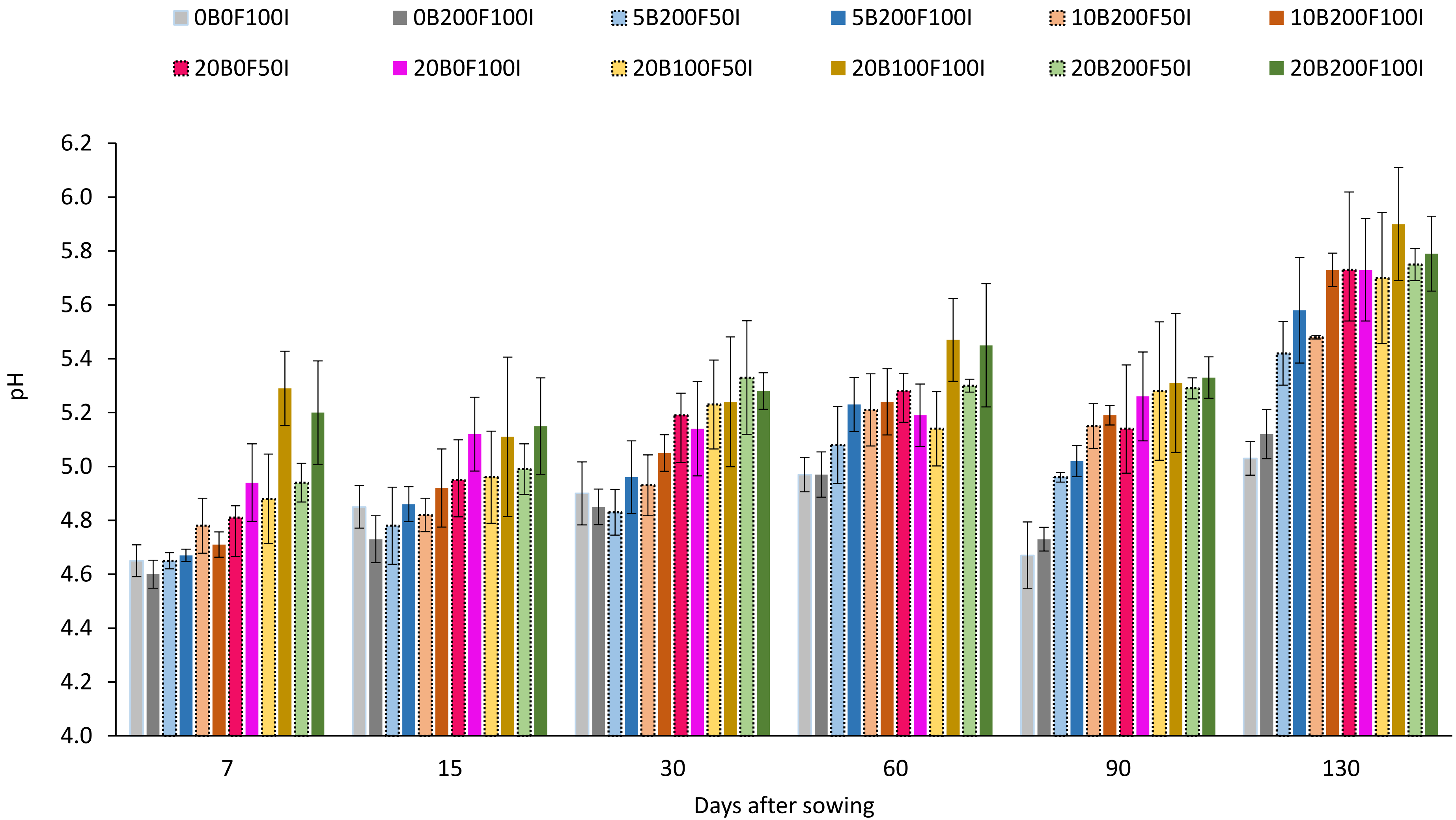

Fig. 3-4. The effect of water hyacinth biochar (B) rates (0, 5, 10, and 20 t ha^{-1}), fertilizer (F), and irrigation (I) on soil pH in the 2023 dry season.

The concentration of soil NH_4^+–N generally increased until 60 DAS and then decreased regardless of treatments. NH_4^+–N was significantly affected ($p < 0.001$) by the combined application of biochar and fertilizer throughout the crop's growth periods. It was influenced by the main effects of biochar and fertilizer on all DAS (except fertilizer on 15 DAS) and irrigation on 60 and 90 DAS. The interaction effects of biochar and fertilizer were also significant on 60, 90, and 130 DAS, while the interaction of biochar and irrigation affected NH_4^+–N on 60 and 90 DAS (Table A4). The three-way interaction effect was only significant on 60 DAS. Moreover, the NH_4^+–N concentration was higher in the plots that received a higher rate of biochar and fertilizer under full irrigation until 60 DAS. However, after that, the plots without biochar had a higher NH_4^+–N concentration. The higher NH_4^+–N concentrations were 52.2 and 194 mg kg^{-1} in 20B100F100I on 7 and 60 DAS, respectively, and 43.3 and 61.1 mg kg^{-1} in 20B200F100I on 15 and 30 DAS, respectively, compared to controls (0B0F100I and 0B200F100I) (Fig. 3-5). However, after 60 DAS, the controls had higher NH_4^+–N concentrations; 0B0F100I (58.3 mg kg^{-1}) and 0B200F100I (11.0 mg kg^{-1}) on 90 and 130 DAS, respectively. Although the concentration of soil NH_4^+–N was higher in the treatments with full irrigation (100%), it did not significantly ($p > 0.05$) affect NH_4^+–N (Table A2).

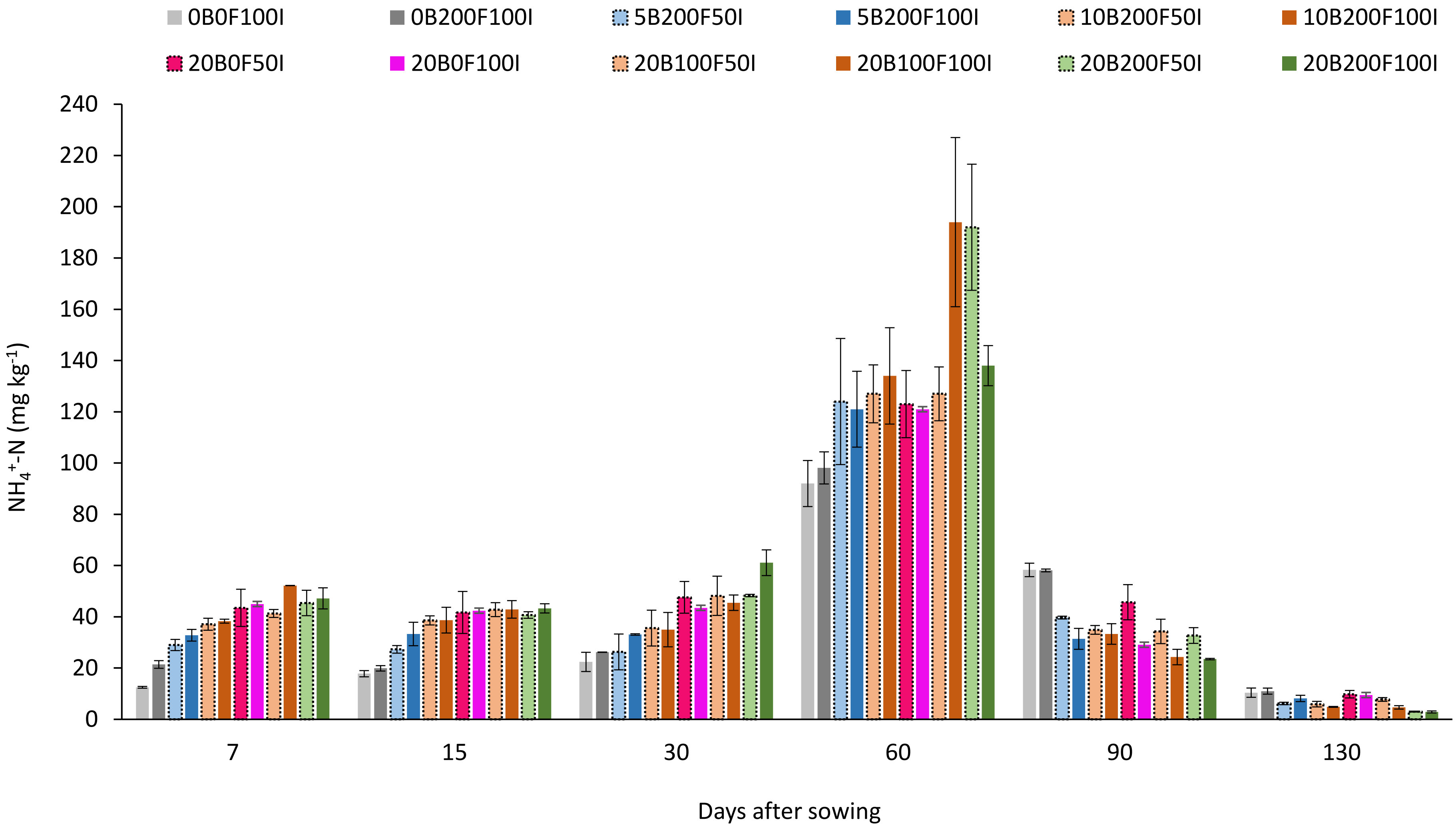

Fig. 3-5. The effect of water hyacinth biochar (B) rates (0, 5, 10, and 20 t ha–1), fertilizer (F), and irrigation (I) on soil NH_4^+–N in the 2023 dry season.

The concentration of soil NO_3^-–N increased until 90 DAS and decreased afterward regardless of treatments. The combined application of biochar and fertilizer significantly affected NO_3^-–N. Both biochar and fertilizer main effects had significant ($p < 0.001$) effects on all DAS, and irrigation had significant effects on 7, 15, and 90 DAS (Table A4). The interaction between biochar and fertilizer significantly affected NO_3^-–N on all DAS except on 130 DAS. Biochar and irrigation had a significant interaction effect on 7, 15, and 90 DAS. However, the three-way interaction was only significant on 7 and 90 DAS. The concentration of soil NO_3^-–N was higher in plots that received the highest rate of biochar and fertilizer until 60 DAS, and then, it was higher in plots without biochar. On 7 DAS, NO_3^-–N increased from 1.36 mg kg^{-1} (0B0F100I) to 10.7 mg kg^{-1} (20B200F50I) on 7 DAS and remained higher in 20B20F100I on 15 DAS (11.7 mg kg^{-1}) and 60 DAS (46.4 mg kg$^-$1) and in 20B200F100I on 30 DAS (16.3 mg kg^{-1}) compared to 0B0F100I and 0B200F100I (Fig.3-6). However, on 90 and 130 DAS, NO_3^-–N was higher in 0B0F100I (58.3 and 13.4 mg kg^{-1}, respectively) compared to 20B200F100I (21.1 and 4.31 mg kg^{-1}, respectively). Although the concentration of soil NO_3^-–N was higher in the treatments with full irrigation (100%), it did not significantly (p >0.05) affect NO_3^-–N (Table A3).

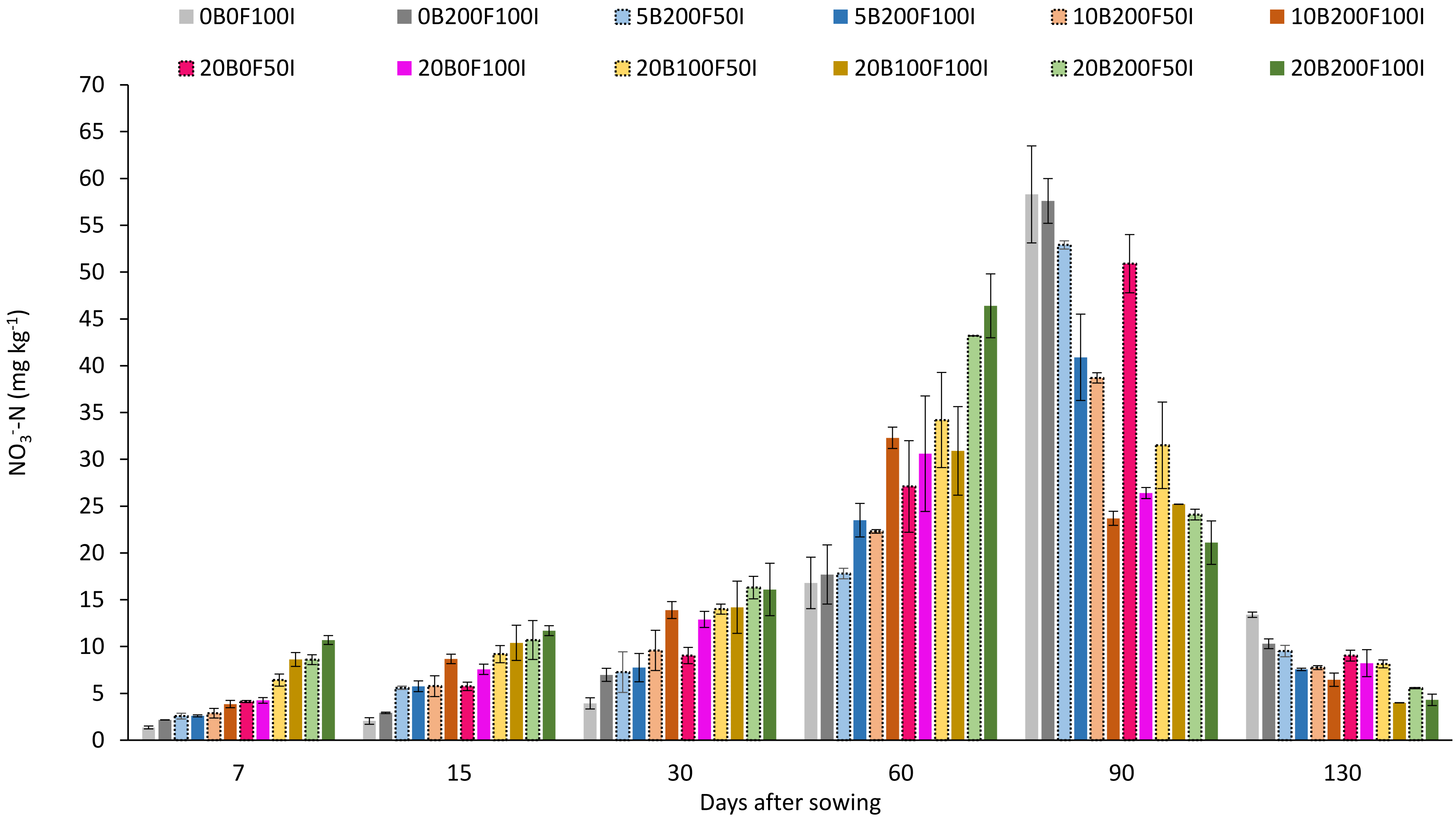

Fig. 3-6. The effect of water hyacinth biochar (B) rates (0, 5, 10, and 20 t ha–1), fertilizer (F), and irrigation (I) on soil NO_3^-–N in the 2023 dry season.

The combined application of biochar and fertilizer significantly ($p < 0.001$) increased the available phosphorus (P) during the crop's growth stage (Table A3). Both biochar and fertilizer main effects had significant effects on available P. The interaction between biochar and fertilizer also had a significant effect on the concentration of available P in the soil, particularly on 7, 60, and 130 DAS (Table A4). On 7 DAS, the 20B200F100I treatment had a higher available P concentration (2.71 mg kg^{-1}) compared to the 0B0F100I treatment (0.316 mg kg^{-1}) and the 0B200F100I treatment (0.327 mg kg^{-1}) (Fig. 3-7). This higher concentration was maintained on 15, 30, 60, 90, and 130 DAS. The application of higher rates of biochar and fertilizer led to an increase in the available P concentration in the soil. Furthermore, reducing the irrigation amount to 50% did not significantly affect the availability of P in the soil.

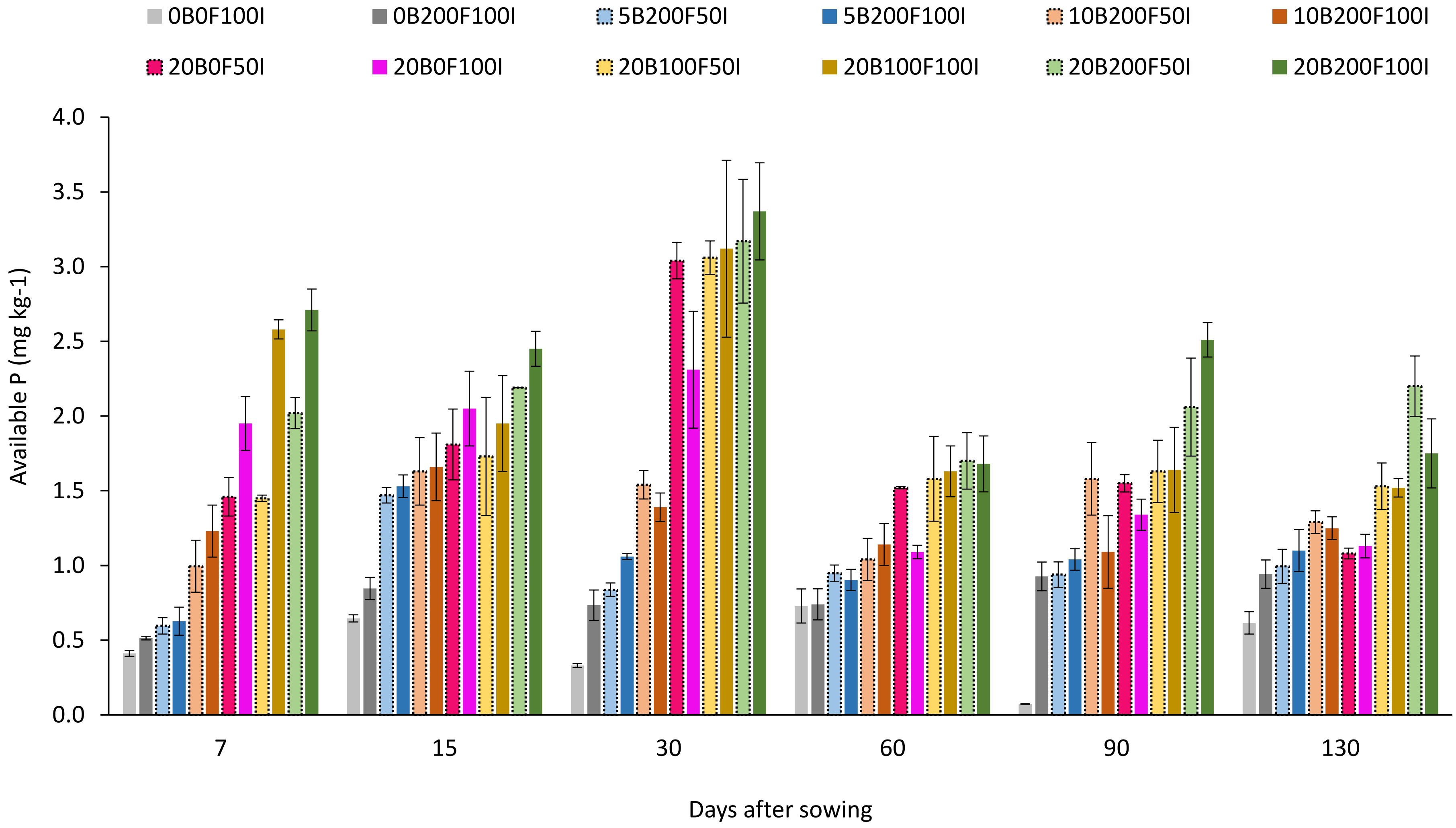

Fig. 3-7. The effect of water hyacinth biochar (B) rates (0, 5, 10, and 20 t ha^{-1}), fertilizer (F), and irrigation (I) on soil available phosphorus in 2023 dry season.

3.3.4. Effects of combined application of biochar and fertilizer on crop growth components

Amendment of the soil with biochar and fertilizer under deficit irrigation conditions exhibited positive responses in terms of wheat growth components.

Plant height was significantly more influenced by the combined application of biochar and fertilizer (Table A5). The plant height was significantly ($p < 0.001$) greater in the treatment with 20B200F100I (71.5 cm) compared to treatments without biochar, such as 0B0F100I (42.2 cm) and 0B200F100I (43.7 cm) (Table 3-3). Reducing irrigation water to 50% of the crop water requirement did not significantly affect plant height. Specifically, under 50% irrigation water of the 20B200F50I treatment, the plant height was 66.1 cm, which was not statistically different from the plant height of 71.5 cm observed under 100% irrigation water in the 20B200F100I treatment.

Leaf area generally increased on 70 DAS and decreased afterward, irrespective of the treatment (Fig. 3-8). The main effects of biochar, fertilizer, and irrigation as well as the two-way interaction of biochar and irrigation were significant ($p < 0.001$; Tables A5 and A6). Although three-way interaction was not significant ($p > 0.05$), the higher leaf area was recorded in the combination of a higher rate of biochar and fertilizer under full irrigation. Leaf area significantly ($p < 0.001$) increased with an increased amount of biochar when combined with fertilizer and irrigation. The highest leaf area (44.4 cm^2) was observed in treatments amended with 20B100F100I on 70 DAS compared to plots without biochar and those with lower biochar rates (Fig. 3-8). Leaf area significantly ($p < 0.001$) increased from 9.39 cm^2 (0B0F100I) and 12.5 cm^2 (0B200F100I) to 44.4 cm^2 (20B100F100I) on 70 DAS, maintaining higher leaf area on 90 and 110 DAS in higher biochar amended plots. The leaf area was greater in plots amended with 200 kg ha^{-1} rate of fertilizer than in plots without fertilizer, even when combined with the same amount of biochar and irrigation water.

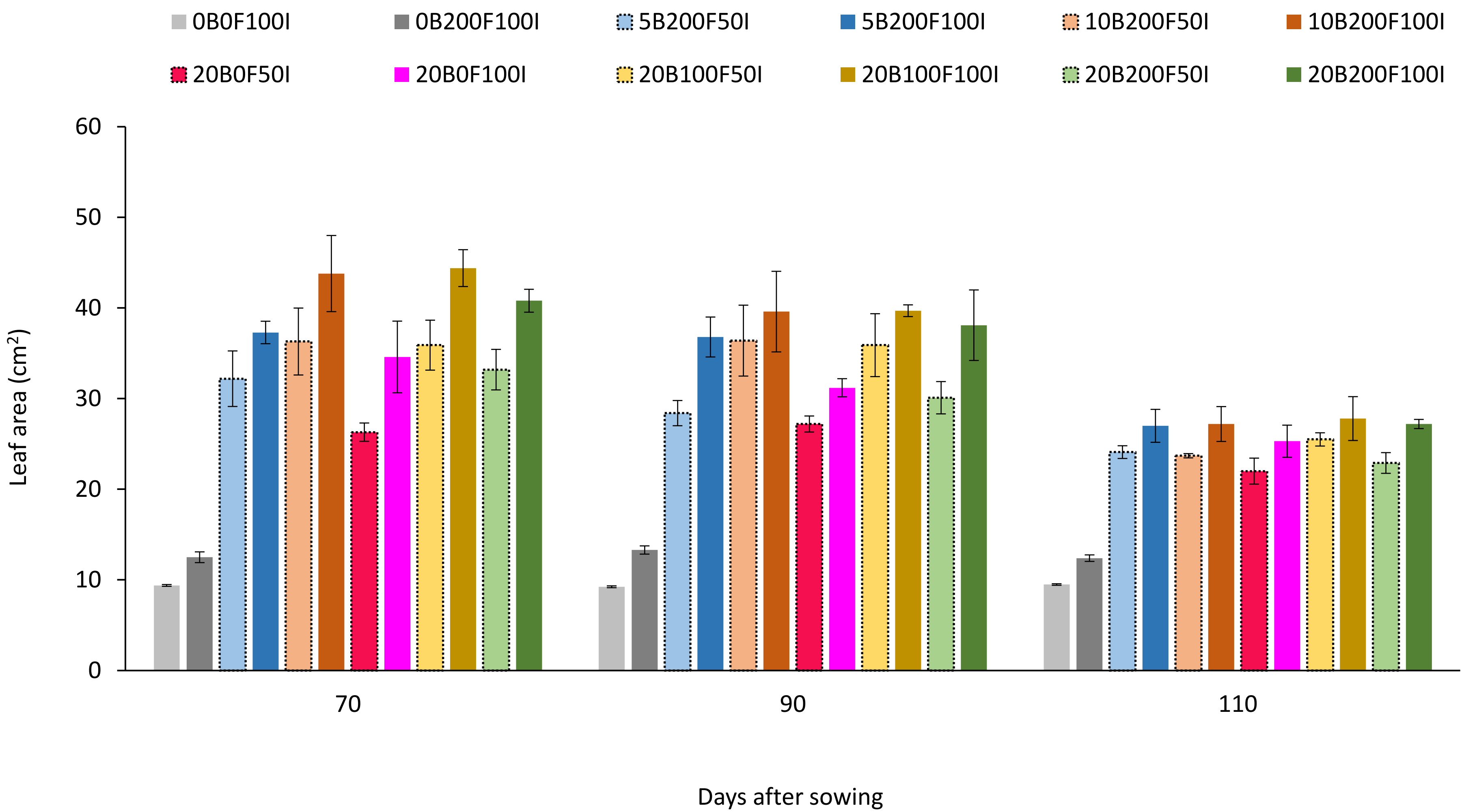

Fig. 3-8. The effect of water hyacinth biochar (B), NPS fertilizer (F), and irrigation (I) on leaf area of wheat crop in the 2023 dry season.

Dry biomass in the dry season generally increased until 110 DAS and decreased afterward, regardless of the treatments. The main effects of biochar, fertilizer, and irrigation were significant ($p < 0.001$) at all sampling dates (except on 110 DAS and 130 DAS of irrigation) on dry biomass (Table A5). The two-way interaction of biochar and fertilizer (70 D–110 DAS) and biochar and irrigation, as well as fertilizer and irrigation (70 DAS), affected dry biomass significantly ($p < 0.001$). Dry biomass significantly ($p < 0.001$) increased with increasing amounts of biochar even when combined with the same levels of fertilizer and irrigation water. The dry biomass was also significantly ($p < 0.001$) affected by the fertilizer rate when applied in combination with the same amount of biochar and irrigation water. Dry biomass was significantly ($p < 0.001$) higher in 20B200F100I (16.3 t ha^{-1}) than in controls of 0B0F100I and 0B200F100I (3.20 t ha^{-1}) on 70 DAS and continued to be higher on 90, 110, and 130 DAS. The highest dry biomass (36.5 t ha^{-1}) was recorded in the interaction of 20B with 200F, under full irrigation (20B200F100I) on 110 DAS (Fig. 3-9). Although dry biomass was influenced by irrigation water amount, there were no significant differences between the treatments those received 50% and 100% irrigation water (Table A6).

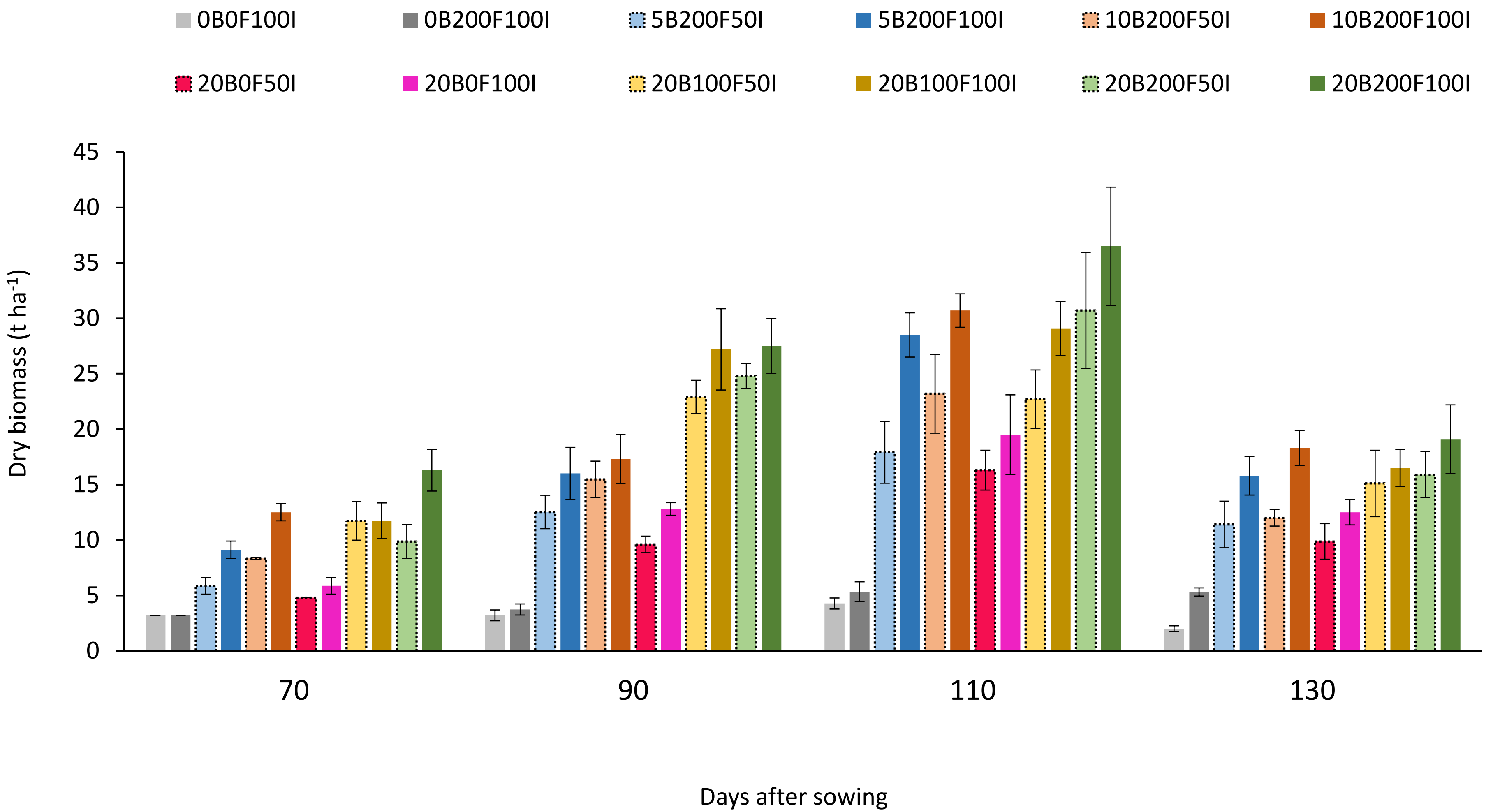

Fig. 3-9. The effect of water hyacinth biochar (B), NPS Fertilizer (F), and irrigation (I) on dry biomass of wheat crop in 2023 dry season.

The leaf SPAD value generally decreased from 70 DAS to 110 DAS, regardless of the treatments (Fig. 3-10). There was a significant ($p < 0.001$) increase in SPAD values from 28.1 (0B0F100I) to 50.4 (20B100F50I) with continued significant differences on 90 and 110 DAS. The SPAD values were significantly influenced by the main ($p < 0.001$) and interaction ($p < 0.01$) effect of biochar and fertilizer (Table A5 and A6). There was no significant difference among treatments that received different rates of biochar. Instead, a significant difference was observed between biochar-amended and unamended treatments.

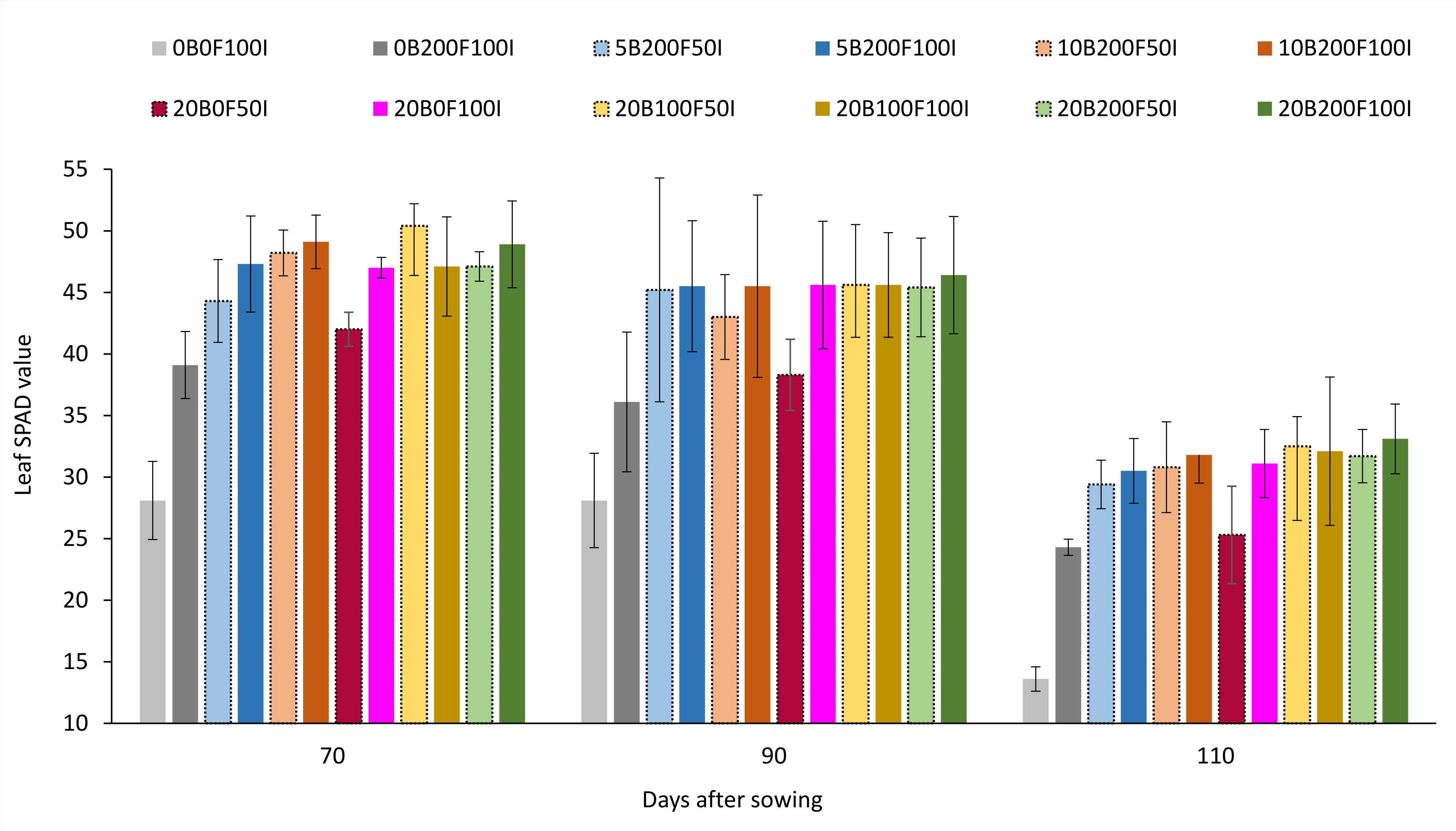

Fig. 3-10. The effect of water hyacinth biochar (B), NPS fertilizer (F), and irrigation (I) on leaf SPAD value of wheat crop in 2023 dry season.

3.3.5. Effects of combined application of biochar and fertilizer on crop yield components

The application of biochar and fertilizer under moisture deficit conditions had positive impacts on spike length, spikelet number, grain number, and grain yield.

The main effect of biochar and fertilizer significantly ($p < 0.001$) affected the spike length of the crop (Table A5). Spike length was significantly affected with biochar compared to without biochar. However, there was no significant difference between treatments that received different rates of biochar and fertilizer in spike length. Spike length significantly ($p < 0.001$) increased from 6.60 cm (0B0F100I) to 10.1 cm (20B200F100I; Table 3-3). Although there were no significant differences between treatments, spike length was higher in plots that received full irrigation water (I100) compared to 50% irrigation treatment.

The spikelet number was affected significantly ($p < 0.001$) with the main effect of biochar and fertilizer (Table A5). The highest spikelet number was observed in the treatment of 20B200F100I and 10B200F100I (16.3), while the lowest was in 0B0F100I (8; Table 3-3).

Grain number was significantly ($p < 0.001$) affected by the main effect of biochar and fertilizer (Table A5). The grain number increased significantly from 19.4 (0B0F100I) to 40.7 (20B200F100I) (Table 3-3).

Table 3-3. The effects of water hyacinth biochar (B), NPS Fertilizer (F), and irrigation (I) on average wheat plant height (PH), Spike length (SL), Spikelet number per spike (SN), and Grain number per spike (GN) in 2023 dry season

Treatments	PH (cm)	SL (cm)	SN	GN
0B0F100I	42.2±5.8^{d}	6.60±0.91^{d}	8.80±1.0^{c}	19.4±3.7^{b}
0B200F100I	43.7±4.2^{d}	7.93±0.99^{bcd}	12.2±1.2^{b}	31.8±3.5^{a}
5B200F50I	60.9±3.1^{bc}	9.27±0.41^{ab}	13.8±0.98^{ab}	38.4±4.0^{a}
5B200F100I	66.6±2.0^{abc}	9.67±0.25^{a}	15.1±0.09^{ab}	39.1±0.84^{a}
10B200F50I	63.3±1.1^{abc}	9.47±0.34^{a}	15.1±0.96^{ab}	39.2±1.8^{a}
10B200F100I	70.9±4.5^{ab}	9.87±0.34^{a}	16.3±0.41^{a}	39.2±4.5^{a}
20B0F50I	57.9±4.2^{c}	7.87±0.77^{cd}	12.5±1.4^{b}	30.3±2.8^{ab}
20B0F100I	65.1±2.5^{abc}	9.67±0.25^{a}	14.2±0.33^{ab}	33.9±3.3^{a}
20B100F50I	66.5±0.93^{abc}	8.87±0.19^{abc}	13.4±1.1^{ab}	34.8±6.1^{a}
20B100F100I	69.9±2.5^{ab}	9.47±0.50^{a}	15.7±0.61^{a}	40.3±1.8^{a}
20B200F50I	66.1±2.7^{abc}	9.47±0.19^{a}	15.7±0.84^{a}	38.8±1.3^{a}
20B200F100I	71.5±3.4^{a}	10.1±0.47^{a}	16.3±0.57^{a}	40.7±5.3^{a}

Means that do not share the same letter in each treatment were significantly different at 5% level of significance.

The grain yield of the wheat crop generally increased with an increase in the biochar rate and fertilizer in the dry season (Fig. 3-11). The main effect of biochar and fertilizer ($p < 0.001$) as well as the interaction of biochar and fertilizer showed a significant ($p < 0.01$) effect on wheat crop grain yield (Table A5). It was also influenced by irrigation water, with plots receiving full irrigation water showing higher grain yields than those with deficit irrigation but not significant. Grain yield significantly ($p < 0.001$) increased from 0.881 t ha^{-1} (0B0F100I) to 4.10 t ha^{-1} (20B200F100I). Despite experiencing yield reduction, reducing irrigation water to 50% of the crop water requirement did not significantly affect crop yield (Fig.3-11).

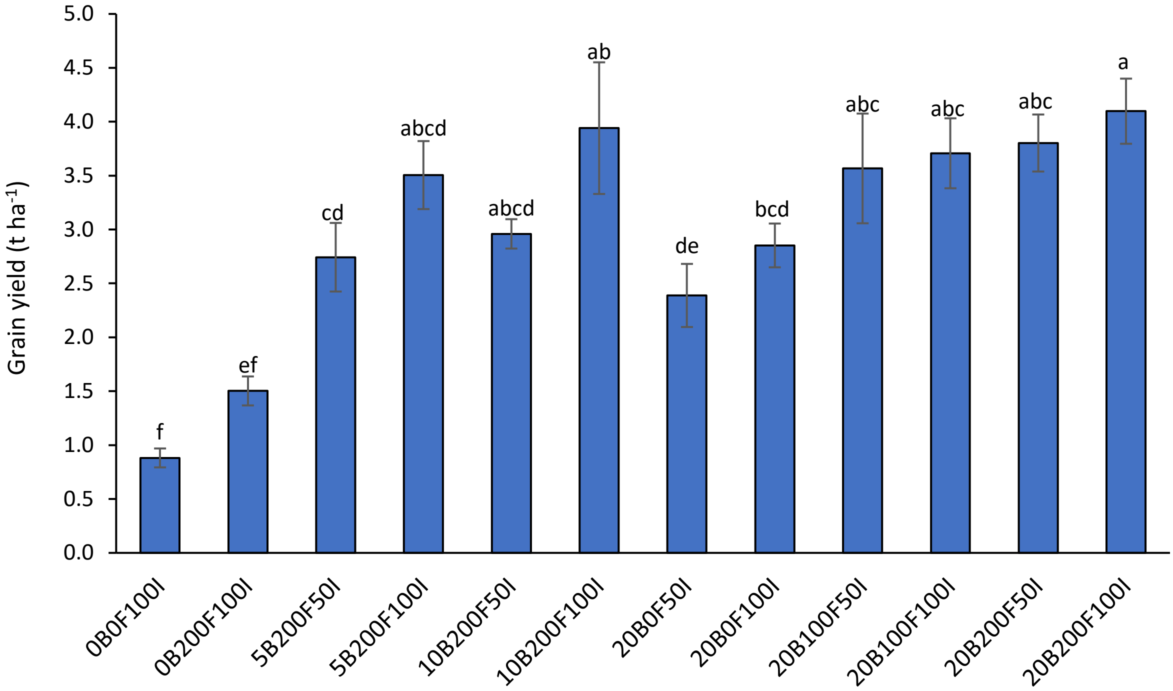

Fig. 3-11. Effects of biochar, fertilizer, and irrigation application on wheat crop grain yield in the 2023 dry season. Means that do not share the same letter in each treatment were significantly different at a 5% level of significance. Vertical bars indicate standard deviation of means.

3.3.6. Correlation analysis between growth and yield components

All growth and yield components, including dry biomass, plant height, spike length, leaf SPAD value, leaf area, and grain number, displayed positive and significant correlations with grain yield (p < 0.001). Spike length exhibited the highest contribution (0.70), followed by dry biomass (0.19) with wheat grain yield in the dry season (Fig. 3-12).

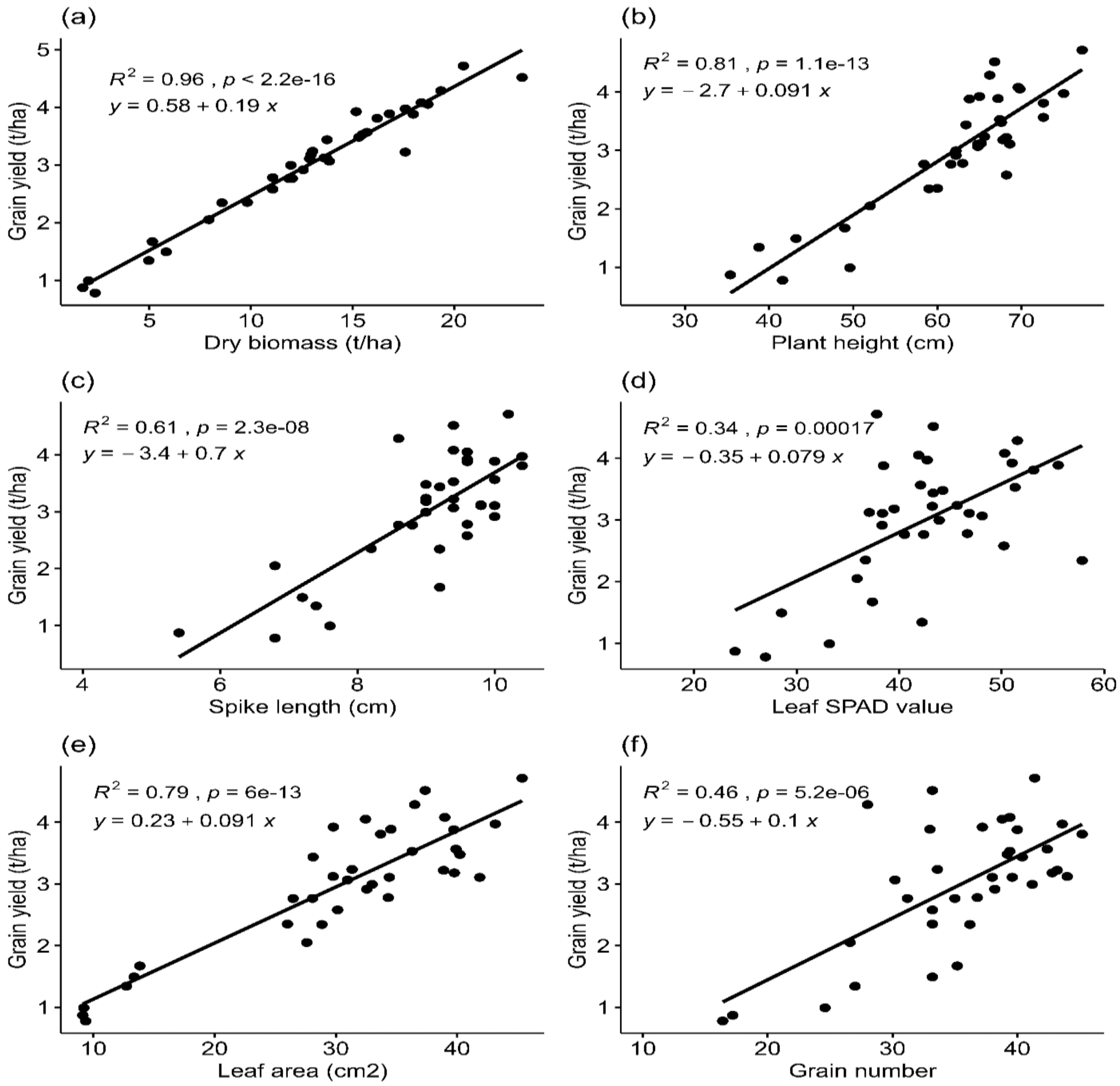

Fig.3-12. Correlation between dry biomass (a), plant height (b), spike length (c), leaf SPAD value (d), leaf area (e), and grain number (f) and wheat crop grain yield during 2023 dry season

3.3.7. Production cost-benefit analysis

The highest cost was attributed to biochar production, ranging from \$179 to \$357. Gross returns varied between \$960 and \$4598. Notably, the plots receiving 10 t ha^{-1} of biochar with 200 kg ha^{-1} of fertilizer demonstrated the highest net return, totaling \$3084 (Table 3-4).

Table 3-4. Partial budget analysis for wheat production during 2023

Farm activities	0B0F100I	0B200F100I	10B200F100I	20B100F100I	20B200F100I
			Input and labor costs (USD ha^{-1})		
NPS fertilizer	0	143	143	72	143
Urea fertilizer	145	145	145	145	145
Biochar production	0	0	179	357	357
Sowing	179	179	179	179	179
Fertilizer application	89.3	179	179	161	179
Irrigation	518	518	518	518	518
Total cost	931	1164	1343	1432	1521
			Output (t ha^{-1}) and return (USD ha^{-1})		
Output of wheat grain	0.881	1.5	3.94	3.71	4.1
Output of wheat straw	1.13	3.81	14.4	12.8	15
Gross return	960	1662	4427	4147	4598
Net return†	29.0	498	3084	2715	3077
Cost-benefit ratio‡	1.03	1.43	3.30	2.90	3.02

† Calculated as (gross return) – (total cost)

‡ Calculated as (gross return)/(total cost

3.4. DISCUSSION

3.4.1. Biochar characterization

The biochar produced from water hyacinth collected from the same location of our sample area (Lake Tana, Ethiopia) and prepared using a furnace exhibited basic properties of biochar such as biochar yield (33-51%), pH (9-11), ash content (33-52%), total carbon (TC) (28-33%), hydrogen (H) content (0.24-2.52%), nitrogen (N) content (1.37-2.14%), and carbon-to-nitrogen (C/N) ratio (15.9-20.3%) (Gezahegn et al., 2024). These properties values were relatively similar to our locally produced biochar produced in 2023, which was prepared using a grounding system. Our biochar had comparable values in terms of yield (28.9%), pH (10.7), ash content (20.5%), TC (35.2%), H content (0.76%), N content (0.930%), and C/N ratio (37.8). Similarly, Li *et al.* (2016), the study showed biochar produced from water hyacinth in a furnace showed similar properties, including yield (28.2%), pH (10.96), ash content (27.2%), H content (1.1%), N content (0.73%), oxygen (O) content (42.8%), and C/N ratio (29.3%). These findings implied that locally produced biochar from water hyacinth, utilizing a cost-effective grounding system, can effectively serve as a soil amendment. This method can be particularly advantageous in areas where water hyacinth is a problem, as it offers a sustainable solution for biochar production tailored to local conditions.

3.4.2. Effects of combined application of biochar and fertilizer on soil physical properties

Incorporating biochar into soils improves soil physical and hydraulic characteristics. This is because biochar has unique attributes such as high concentrations of organic carbon, significant porosity, extensive surface area, and the presence of micropores (Usevičiūtė and Baltrėnaitė-Gedienė, 2021). As a result, improvements in soil bulk density, porosity, and water-holding capacity were observed (Adekiya *et al.*, 2020).

The density of biochar is lower than that of soil particles, allowing it to decrease the overall density of the soil. When biochar is incorporated into the soil, it forms aggregates that further decrease the bulk density of the soil (Blanco-Canqui, 2021; H. Singh *et al*., 2022). In our study, biochar application resulted in a 16.7% decrease in soil bulk density on 70 DAS and a 15.1% decrease at 130 DAS, compared to the treatments without biochar. Similarly, other studies have shown that biochar amendment can improve soil bulk density by 18% (H. Singh *et al*., 2022), 14.8% (Zhang *et al*., 2020), and 7.41% (Faloye *et al*., 2019) compared to unamended soil. In our study, as the rate of biochar increased, bulk density decreased. For instance, on 70 DAS, the bulk density decreased from 0.807 g cm^{-3} (5 t ha^{-1}) to 0.731 g cm^{-3} (10 t ha^{-1}) and further decreased to 0.698 g cm^{-3} (20 t ha^{-1}). This trend continued on 130 DAS (Figure 3-1). Our findings were consistent with a study by Zhang *et al*. (2020), which also showed a decrease in soil bulk density with increasing biochar rate. However, different levels of irrigation did not have a significant effect on bulk density, which aligns with the results of our study. According to a review study by (Blanco-Canqui, 2021), biochar application lowers soil bulk density through several mechanisms. Firstly, biochar's lower density and higher porosity compared to soil particles result in dilution upon mixing, reducing the overall density. Secondly, the increased concentration of organic carbon from biochar, particularly labile carbon, enhances biological activity and soil aggregation, leading to the formation of larger pores and a decrease in bulk density. Additionally, the high cation exchange capacity and specific surface area of biochar facilitate bonding with organic matter and clay particles, thereby altering the distribution of soil pore sizes.

Biochar is highly porous, containing numerous small and large pores. When incorporated into soil, it creates a matrix of channels and spaces, which enhances overall soil porosity. Microorganisms fostered by biochar applications, such as fungi and bacteria, create networks of filaments and excrete substances that help create and maintain pore spaces within the soil structure (Jin *et al*., 2020). In our study, the application of biochar significantly improved total soil porosity compared to the treatment without biochar. Specifically, in the 20B treatments, the soil porosity was improved by 7.60% and 5.56% on 70 DAS and 130 DAS, respectively, compared to control (0B). Similarly, Omondi *et al*. (2016) demonstrated that biochar amendment significantly improved soil porosity by 8.4% compared to unamended soil by directly increasing the total pore volume. Additionally, other studies have shown that the application of biochar improved soil porosity by 12% (Toková *et al*., 2020) and 14%–64% (Blanco-Canqui, 2017) compared to the treatment without biochar.

In this study, the moisture content of the soil was significantly improved in soil amended with biochar compared to treatments without biochar. In the higher biochar application rate (20 t ha^{-1}), the soil moisture content was higher than in the lower rates (5 and 10 t ha^{-1}) and in the treatments without biochar (Figure 3-2). This is likely due to the high surface area and hydrophilic functional groups of biochar, which enable it to improve soil moisture content (Qian *et al*., 2020). Although there was no significant difference among the treatments within 20 t ha^{-1} of biochar, the highest water content was recorded in the 20B20F100I treatment (12.3%–31.5%) compared to the treatments without biochar (0B0F100I). Similarly, the field experiment conducted by Faloye *et al*. (2019) showed that the water-holding capacity of the soil was improved by 3.58%–8.70% at different soil water retentions due to biochar amendment compared to unamended soil. The study by Pandit *et al*. (2018) also demonstrated that biochar application increased water retention at field capacity from 29.9% (without biochar) to 35.3% (2% biochar). The lower soil bulk density and higher soil porosity observed in the treatment with 20 t ha^{-1} (Figures 3-1 and 3-2) of biochar in our study likely contributed to the soil's ability to retain higher soil moisture.

3.4.3. Effects of combined application of biochar and fertilizer on soil chemical properties

Amending soil with biochar has recently emerged as a method for improving soil pH in acidic agricultural soil for crop production improvement. This is because biochar is alkaline in nature and has the ability to enhance soil physical, chemical, and biological properties (Huang *et al*., 2023). In our study, the pH significantly increased with biochar amendment. The pH was improved by 5.36%–17.3% (200B100F100I) compared to the control (0B0F100I) during the crop's growth stages. Similarly, biochar soil amendments improved soil pH by 13% (Zhang *et al*., 2023) compared to no amendment. Application of different biomass-derived biochar also increased soil pH by 3.38%–14.9% (Ginebra *et al*., 2022). Mbabazize *et al*. (2023), study also showed that pH improved by 20.8% due to the combined application of 5 t ha^{-1} biochar and 500 kg ha^{-1} DAP fertilizer compared to fertilizer alone (only 500 kg ha^{-1}). Similarly, in our study, pH was improved by 8.04%–15.2% in the combined application of biochar and fertilizer (20B100F100I) compared to treatments amended with fertilizer alone (0B200F100I). The pH improvement is mainly due to biochar providing cations such as Ca, which plays a role in soil aggregate stability. Additionally, the OH^- produced from biochar neutralizes the H^+ ions, thus affecting the mobility and bioavailability of Fe^{3+} and Mn^{2+}(Huang *et al*., 2023). In our study, the observed improvement in soil pH likely facilitated the availability of essential plant nutrients, such as nitrogen and phosphorus, as these nutrients require nearly neutral soil conditions for optimal availability. This enhancement in soil pH conditions is expected to have positively influenced the solubility and accessibility of these nutrients, thereby promoting their uptake by plants.

In our study, the concentration of NH_4^+–N in the soil generally increased until 60 DAS and then decreased regardless of the treatments. This finding is consistent with the study by Yao et al. (2022), which investigated the combined application of biochar and nitrogen fertilizer and observed an initial increase followed by a decrease in NH_4^+–N concentration as the incubation time increased. This pattern may be attributed to various processes of NH_4^+–N such as nitrification, microbial fixation, and volatilization, which affect the conversion and migration of NH_4^+–N. The NH_4^+–N concentration reached its peak at 60 DAS following the supplemental application of nitrogen in the form of urea and then decreased. Similarly, Chen *et al*. (2023) observed a sharp increase in NH_4^+–N concentration in the soil after the supplemental application of nitrogen fertilizer (on 90 DAS), followed by a decrease to low concentrations, which continued until the end of the experiment (150 DAS). As demonstrated by Ginebra *et al*. (2022), the application of biochar increased the soil NH_4^+–N concentration by 10.5%–65.1% compared to NPK fertilizer alone. Similarly in our study, the NH_4^+–N concentration was significantly improved by 73.7%–144% in the 20B100F100I treatment compared to the fertilizer alone (0B200F100I) until 60 DAS (Figure 3-5). However, after 90 DAS, the opposite trend was observed. The NH_4^+–N concentration on 90 DAS and 130 DAS was higher (by 139% and 136%, respectively) in the control treatment (0B200F100I) compared to the biochar-amended treatment (20B200F100I). This is likely due to reduced nutrient absorption by the plants since the wheat biomass in the control treatment (0B200F100I) was 759 and 260% lower than in the 20B200F100I treatment on 90 and 130 DAS respectively (Fig.3-9). The observed improvement in NH_4^+–N concentration in the soil likely contributed to an increase in NO_3^-–N levels, as NH_4^+–N serves as a substrate for nitrification processes.

The concentration NO_3^-–N in this study was initially low and then increased until 60 DAS and then decreased. After 90 DAS, it decreased regardless of the treatments. Similarly, the concentration of NO_3^- –N in the soil peaked at 100 DAS and then decreased, remaining relatively low until the end of the experiment (Chen *et al*., 2023). According to a meta-analysis by Liu *et al*. (2024), the application of biochar increased the abundance of ammonia-oxidizing bacteria (AOB) by 37% and the nitrification rate by 57%, particularly in acidic soil ($pH \leq 5$), which resulted in higher NO_3^-–N concentration in the soil. In our study, the combined application of biochar and fertilizer under full irrigation increased the NO_3^-–N concentration by 131%–637% in 20B200F100I compared to the control (0B200F100I) until 60 DAS. Similarly, the soil NO_3^-–N concentration increased by 109% and 158% due to the application of 0.5% and 2% biochar on silty loam soil (Pandit *et al*., 2018). Ginebra et al. (2022) also demonstrated that the application of biochar increased soil NO_3^-–N concentration by 21.7%–139% compared to NPK fertilizer alone. However, in our study after 90 DAS, the NO_3^-–N concentration in the control (0B200F100I) was higher by 173% and 139% compared to the combined biochar and fertilizer treatments under full irrigation (20B200F100I). This is likely due to higher nutrient absorption by plants in the higher biochar-amended treatments, as the biomass was higher in the amended treatments than in the control. The application of biochar increased the concentration of NO_3^-–N in the soil by increasing soil pH, which promotes the conversion of NH_4^+ to NH_3 as a direct substrate for ammonia monooxygenase catalysis, thereby increasing the nitrification rate of the soil (Zhao *et al*., 2018). Additionally, biochar can increase soil nitrification rate by adsorbing nitrification-inhibiting compounds such as soluble phenols and terpenes (DeLuca *et al*., 2006).

Biochar application to the soil can decrease P fixation by iron and aluminum cations (Fe^{3+} and Al^{3+}) and enhance P availability in P-fertilized soils (Cui *et al*., 2011; Ng *et al*., 2022). In this study, the concentration of available P increased with an increase in biochar rate regardless of fertilizer and irrigation water amount throughout the experimental period. Application of 20 t ha^{-1} biochar combined with inorganic fertilizer (20B200F100I) improved available P by 85.8%–427% compared to fertilizer alone (0B200F100I) during different times of the crop growing periods. Similarly, the application of biochar improved soil available P by 111% and 658% (0.5% and 2% biochar respectively) compared to those without biochar treatment (Pandit *et al*., 2018). Ginebra *et al*. (2022), experiment also showed that available P was increased by 21.6%–219% (compared to unamended soil) and 102%–116% (compared to NPK alone) due to the amendment of different biomass biochar. Furthermore, the observed improvement in soil pH in our study likely contributed to an enhancement in available P levels. Optimal soil pH conditions help decrease phosphorus fixation, which occurs more prominently in acidic soils, and increase its mobility within the soil matrix and increase the availability of phosphorus, thus promoting enhanced nutrient uptake and potentially boosting crop productivity.

3.4.4. Effects of combined application of biochar and fertilizer on crop growth components

The growth components of the wheat crop were positively affected by biochar and fertilizer application.

Measuring plant height is an essential component of crop management and yield prediction, providing valuable information for optimizing agronomic practices and assessing crop health to maximize crop productivity and profitability (Wang *et al*., 2018). Plant height was affected significantly due to the combined application of biochar and fertilizer. The plant height was improved by 63.6% (20B200F100I) compared to control (0B200F100I). Similarly, in the study by Sial *et al*. (2019), wheat crop plant height was improved by 40.3% due to the amendment of the soil by 2% biochar and chemical fertilizer compared to without biochar and fertilizer. The plant height was much more affected by biochar application than by fertilizer and irrigation water. The plant height was decreased by only 3.65% when the NPS fertilizer amount was reduced by 50% (100 kg ha^{-1}), indicating that the combined application of biochar and fertilizer is a promising strategy to minimize fertilizer usage. Moreover, reducing the irrigation water to 50% did not significantly affect the plant height. In the 50% crop water requirement (20B200F50I) treatment, the plant height was improved by 51.3% compared to the control (0B200F100I), which was not statistically significant with the 100% crop water requirement

(20B200F100I) treatment effect, which showed the ability of biochar to conserve the irrigation water. Our results were consistent with the study by Kangoma *et al*. (2017), which showed that the combined application of biochar and fertilizer enhanced crop plant height by 6.40% under moderate deficit irrigation compared to flood irrigation.

Measuring plant leaf area is a fundamental aspect for the estimation of crop photosynthetic potential, assessment of plant growth and development, understanding of plant responses to the environment, and enhancing crop productivity and quality (Richards, 2000). In our study, the leaf area was improved significantly by 124–255% (20B100F100I) compared to the control (0B200F100I) during the growth period of the crop in the dry season. Lowering the irrigation amount to 50% with the same amount of biochar and fertilizer did not significantly affect leaf area compared to the full irrigation (100I) water amount. It was significantly improved by 106–187% when the irrigation amount was reduced to 50% (20B100F50I) compared to the control (0B200F100I), which was not significantly different from the full water requirement (20B100F100I). The leaf area was non-significantly affected by the rate of the biochar. This indicates the possibility of using the minimum amount (e.g., 5 t ha^{-1}) of biochar while minimizing the irrigation water to 50% with minimum effect on the leaf area of the wheat crop. This result is consistent with the study of the application of 15 t ha^{-1} biochar combined with nitrogen fertilizer that improved the wheat crop leaf area by 45.0% and 67.0% compared to fertilizer alone and without both biochar and fertilizer, respectively (Yeboah *et al*., 2017). Similarly, the combined application of biochar and fertilizer improved the leaf area of the wheat crop by 57.3% compared to without biochar and fertilizer (Sadaf *et al*., 2017).

Measuring dry biomass is a fundamental aspect of crop yield assessment and management. It provides essential information for evaluating crop performance, optimizing resource use, and making informed decisions to enhance productivity and profitability in agriculture. In our study, dry biomass was more affected by biochar and fertilizer application's main and interactive effect than the irrigation amount. The highest biomass was in the treatment of 20B200F100I (36.5 t ha^{-1}) which was not significantly different from the treatment of 20B200F50I (30.1 t/ha) on 110 DAS. Moreover, the biomass was not significantly affected by reducing the NPS fertilizer from 200 to 100 kg ha^{-1}. This is likely attributed to the ability of biochar to enhance fertilizer utilization, especially when combined with moderately reduced chemical fertilizers (Hou *et al*., 2023). It was not significantly affected by lowering the irrigation amount to 50% from the full amount. This is probably due to the ability of biochar to reduce the amount of water depletion under deficit irrigation, as a result increasing irrigation and crop water use efficiencies (Babalola *et al*., 2022). The dry biomass in 10B200F100I (12.5–30.7 t ha^{-1}) did not significantly differ from 20B200F100I (16.3–36.5 t ha^{-1}) showed the probability of using a reduced amount of biochar with minimum impact on biomass yield. (Olmo *et al*., 2014) study showed the above-ground biomass of wheat was significantly improved due to the application of biochar (13.5–15 t ha^{-1}) after 124 DAS compared to unamended soil (10.7–11.2 t ha^{-1}). Similarly, research done by Cong *et al*. (2022) on biochar application under deficit irrigation showed the highest above-ground biomass (25.7 t ha^{-1}) was in the treatment of 20 t ha^{-1} biochar with 0.8ETc compared to control with no biochar (17.7 t ha^{-1}).

The SPAD observation obtained from leaf is highly and positively correlated with leaf chlorophyll which estimates the nitrogen nutritional status of crops and provides guidance for more accurate nitrogen fertilizer management (Murdock *et al*., 1997; Schlichting *et al*., 2015) According to Mehrabi and Sepaskhah (2022), the chlorophyll concentration of wheat leaf SPAD value ranged from 28–35, 35–45, and 45–50 in no, lower, and higher rates of fertilizer plots respectively. Our findings had similar consistency with SPAD values of 28.1 (0B0F100I) and 39.1 (0B200F100I) in unfertilized and amended with fertilizer on 70 DAS, respectively. The SPAD value at the heading can provide a more accurate estimation of the final yield in wheat crop (Monostori et al., 2016). In this study, the application of biochar and fertilizer improved the SPAD value at the heading stage (90 DAS) of the crop by 28.5% (20B200F100I) compared to the control (0B200F100I). The interaction of biochar and fertilizer significantly (except on 90 DAS) affected the SPAD value. The SPAD value improved by 65.1–143% (20B200F100I) compared to without both biochar and fertilizer (0B0F100I) and 25.1–36.2% (20B200F100I) compared to with only fertilizer (0B200F100I). This is probably due to the increased soil N availability followed by a subsequent increase of foliar N concentrations due to biochar soil amendment (He *et al*., 2020). The result was consistent with the (Zulfiqar *et al*., 2022) experiment done on the effect of biochar on mitigating drought on wheat crop showed enhancement of chlorophyll a (19.3%), and chlorophyll b (22.2%) compared to the control (without biochar). Ghorbani *et al*. (2022) also showed SPAD value was significantly affected by the combined application of biochar and chemical fertilizer at the jointing and grain-filling stage of the wheat crop.

3.4.5. Effects of combined application of biochar and fertilizer on crop yield components

Combined application of biochar and NPS fertilizer positively affected wheat crop yield components under deficit irrigation.

The combined application of biochar and inorganic fertilizer has been shown to improve crop yield components. This improvement is attributed to several factors, including the enhancement of soil water holding capacity (de Jesus Duarte *et al*., 2023), irrigation water use, crop water use efficiency, and nutrient availability (Faloye *et al*., 2019). Additionally, biochar application has been reported to reduce soil bulk density and increase soil porosity (Seyedsadr *et al*., 2022), while also decreasing irrigation water loss (Wang *et al*., 2022). These combined effects contribute to increased crop growth and yield components. According to Sadaf *et al*. (2017), a study showed the combined application of biochar and NPK inorganic fertilizer improved wheat grain yield components of spike length, number of spikelets, and number of grains by 27%, 31%, and 29% respectively, compared to the control plot. In our study, the spike length improved by 53.0%, 27.4%, and 4.45% due to the combined application of biochar and fertilizer (20B200F100I) compared to 0B0F100I, 0B200F100I, and 20B0F100I, respectively. The spikelet number, grain number, and grain yield of wheat improved by 33.6%, 28.0%, and 173% in the treatment of 20B200F100I, respectively, compared to 0B200F100I. A similar finding by Hu *et al*. (2021) also showed wheat grain yield was improved by 81.7% due to the application of biochar and inorganic NP fertilizer compared to without both biochar and fertilizer. This improvement was likely due to the high surface area of biochar, which enabled it to retain more nutrients and increase its availability for crops. Additionally, the liming effect of biochar reduces the acidity of the soil, enhancing soil nutrient availability and microbial activity, thereby contributing to crop improvements (Bo *et al*., 2023). In the plots amended with the combined application of biochar and fertilizer, wheat yield components were not significantly affected by lowering the irrigation water to 50% of the full irrigation amount. This implies the possibility of growing wheat crops under deficit irrigation with biochar amendment without significant yield loss. In the treatments of 50% crop water requirement (20B200F50I) improved plant spike length (19.4%), spikelet number (28.7%), grain number (22.0%), and grain yield (153%) compared to control (0B200F100I) treatment. This result was consistent with the (Zulfiqar *et al*., 2022) study that showed biochar application substantially improved spike length (16.6%), number of grains (13.9%), and biological yield (13.1%) when compared with the control treatment, by reducing the detrimental effects of drought. The grain yield did not show a significant reduction when the amount of NPS fertilizer was decreased by 50%. The grain yield improved by 173% in the treatments that received 200 kg ha^{-1} (20B200F100I), whereas it was improved by 147% in the treatments that received 100 kg ha^{-1} (20B100F100I) of NPS fertilizer (Figure 3-11). This implied the possibility of reducing the amount of fertilizer used when combined with biochar. In the study of (Zhang *et al*., 2023), the maximum crop yield was recorded in the treatments that received 70% of chemical fertilizer combined with biochar. Moradi *et al*. (2023) also observed an increased yield of rapeseed cultivars when treated with combined biochar and 50% N application simultaneously. Similarly, in the study of Singh *et al*. (2022), the application of biochar under deficit irrigation improved crop yield components of the sweet corn crop. Soil amendment with biochar under deficit irrigation, particularly at critical growth periods of tillering, flowering, and grain filling, can improve wheat crop yield components with minimal impact (Haider *et al*., 2020). The two consecutive year study of Singh *et al*. (2022) also showed a reduction of water use to 70% of the estimated crop water requirement (ETc) maintained the plant physiology, growth, and yield similar to 100% ETc due to the amendment of biochar. This was probably due to biochar increasing irrigation water productivity by improving soil properties under water deficit conditions. According to Cakmakcı and Sahın, (2023) under 50% water deficit conditions, the biochar amendment increased the irrigation water productivity as well as water saving from 8.30–18.4% in different rates of biochar.

3.4.6. Correlation analysis between growth and yield components

Understanding the contribution of yield components to grain yield under different production environments is essential for increasing grain production (Yang *et al*., 2018). All the growth and yield components showed better contribution to grain yield. Spike length which is related to the reproductive structure of the wheat plant, exhibited the highest contribution to wheat grain yield. One unit of spike length increment could increase 0.70 units of grain yield. Longer spikes may have more florets and, therefore, more potential for grain development.

3.4.7. Production cost-benefit analysis

Economic analysis in crop production is essential for optimizing resource use, managing risks, making informed decisions, and contributing to the overall sustainability and profitability of agricultural enterprises. The biochar as soil amendment proves to be profitable and may be competitive with other soil amendments, such as lime or conventional fertilizers, particularly in the medium term (3–4 years) (Latawiec *et al*., 2021).

In this study, the production cost was higher by 15.4–30.7% in biochar-amended soil compared to unamended plots. The gross return was higher in biochar-amended plots than in unamended plots by 150–177%. This result is consistent with (Wang *et al*., 2018), where the gross production value of wheat in biochar-amended soil was 18.3–35.5% higher than in the unamended one, with the gross return ratio of wheat production to total cost ranging from 1.96–2.25. In our study, net income was higher by 519% (10B200F100I) compared to the control (0B200F) with a gross return ratio of 3.30. The higher net income was in the plots amended with a lower rate of biochar (10 t ha^{-1}) since a higher rate of biochar increased the production cost. This finding is consistent with the study by Apori *et al*. (2021) which reported a higher net income (176%) in the combined application of biochar with NPK fertilizer.

3.5. CONCLUSIONS

Water hyacinth biochar significantly improved soil bulk density, porosity, moisture content, pH, available nitrogen, and phosphorus when it was applied in combination with NPS inorganic fertilizer as compared to the sole application of fertilizer. Eventually, wheat crop growth components such as plant height, leaf area, leaf SPAD value and dry biomass as well as yield components including spike length, number of spikelets, number of grains, and grain yield of wheat crop were significantly increased. Despite an initial higher production cost, the study reveals substantial increases in gross return and net income compared to unamended plots. The economic viability of biochar as a soil amendment highlights its potential to drive sustainable agricultural practices and enhance overall profitability in crop production systems.

Due to the positive effects of water hyacinth biochar, 50% reduction of the irrigation water required for wheat production resulted in comparable wheat growth and yield components with the 100% irrigation water requirement of wheat production. Therefore, it can be concluded that water hyacinth biochar combined with NPS fertilizer can improve soil physicochemical properties as well as wheat productivity in acidic silty loam soils. Further research and field trials are warranted to explore its long-term effects and scalability across diverse agricultural landscapes.

CHAPTER FOUR

4. GENERAL DISCUSSION

4.1. Introduction

Sustainable wheat crop production often involves rotating between rainfed and irrigated cultivation throughout the year or between different growing seasons. This rotation strategy helps optimize water use, minimize environmental impacts, and reduce risks associated with climate variability. For example, farmers may plant wheat during the rainy season when natural moisture is abundant, followed by irrigated cultivation during the dry season to ensure continuous crop production. Wheat is currently produced through both rain-fed and irrigation systems in Ethiopia. Rainfed wheat production predominantly occurs during the main rainy season in Ethiopia, characterized by ample rainfall that supports crop growth without the need for supplemental irrigation (Tadesse *et al*., 2022). Irrigation allows farmers to cultivate crops two to three times a year, which can enhance nutrition and livelihoods by diversifying and increasing income. According to Eshete *et al*. (2020), a critical review study revealed an increasing demand for irrigation water among users, making efficient water use and management a major concern in Ethiopia. However, in Ethiopia, wheat production faces significant challenges due to various factors, including the prevalence of abiotic stresses like soil acidity, poor soil fertility, and drought. Among the different strategies aimed at addressing these challenges, the incorporation of biochar into the soil has gained popularity.

Although biochar has a positive effect on the physical, chemical, and biological properties of the soil, its impact depends on the biochar feedstock, application rate, and experimental conditions (Jalal *et al*., 2023). Water hyacinth, which is one of the most invasive aquatic weeds globally including in Ethiopia, affecting socioeconomic activities and watershed ecosystems, can be as a good feedstock source for biochar production. The conversion of water hyacinth biomass into biochar represents a promising avenue for soil improvement, offering tangible benefits for both soil physical structure and chemical composition (Gezahegn et al., 2024). It also reduces soil bulk density while increasing soil porosity, aggregation, and the structural stability index when compared to soil without biochar (Li et al., 2023). Incorporating biochar into the soil not only enhances soil hydrological and physical properties but also positively impacts soil chemical properties such as soil cation exchange capacity (CEC), pH, soil organic matter (SOM), total nitrogen, carbon to nitrogen (C/N) ratio, soil nutrient retention, and nutrient availability (Emile *et al*., 2023). The application of biochar under deficit irrigation has been shown to improve soil water-holding capacity and water use efficiency (Hou *et al*., 2023), ultimately resulting in increased crop production.

According to Sadaf *et al*. (2017), a study showed the combined application of biochar and inorganic fertilizer improved wheat growth and grain yield components. Furthermore, according to Baiamonte *et al*. (2020), their study also demonstrated that crop productivity, particularly wheat, under deficit irrigation, was not significantly affected in biochar-amended soil compared to soil without biochar. This lack of significant impact was attributed to biochar's ability to enhance irrigation water use efficiency (IWUE) and crop water use efficiency (CWUE). This, in turn, helps retain more water from irrigation, reducing the need for frequent irrigation and optimizing the limited water resources available for crop production.

While numerous research studies have explored the synergistic effects of soil amendment with biochar and fertilizer, there remains a notable gap in understanding the long-term and short-term impacts of locally produced biochar on soil properties and crop productivity across contrasting seasons, particularly in rainy and dry conditions. Furthermore, existing research exhibits inconsistencies in its findings, necessitating a comprehensive evaluation of biochar's effects on soil dynamics under varying environmental contexts. By addressing these knowledge gaps, future studies can provide valuable insights into the efficacy of biochar as a sustainable soil amendment, facilitating more informed agricultural practices and enhanced soil management strategies. Therefore, these studies were conducted to assess and characterize locally produced water hyacinth biochar, both its immediate and residual effects and its synergistic effects with inorganic fertilizer on soil physicochemical properties. Additionally, the aim was to evaluate its impact on wheat crop growth and yield components under contrasting environments. The goal was to optimize soil conditions and irrigation water usage for sustainable wheat crop production.

4.2. The findings and potential applications

The study during the rainy seasons, revealed that locally produced biochar through a grounding system exhibited comparable chemical and physical properties to biochar produced from water hyacinth using a furnace instrument. This finding suggests a viable solution for converting water hyacinth biomass, a pervasive aquatic weed in environments like Lake Tana, Ethiopia, into biochar for addressing soil challenges in the region. Furthermore, as outlined in Chapter 2 of this dissertation, locally produced biochar demonstrated improvements in various soil parameters essential for wheat crop production, including soil bulk density, moisture content, pH, and nutrient availability such as ammonium nitrogen, nitrate nitrogen, and available phosphorus. Notably, the residual effects of water hyacinth biochar on soil physical and chemical properties remained significant one year after application, as indicated in Chapter 2. This highlights the potential for long-term benefits associated with locally produced biochar. These findings underscore the promising role of biochar as a sustainable soil amendment, offering both immediate improvements and lasting impacts on soil health and crop productivity in Ethiopia's agricultural landscapes.

During the dry season, as discussed in Chapter 3, the study revealed notable enhancements in soil physical and chemical properties, including reduced soil bulk density, increased porosity, and improved moisture content, attributed to biochar amendments. Additionally, the application of water hyacinth biochar, combined with NPS inorganic fertilizer (as detailed in Chapter 3 of Figures 3-4 to 3-7), led to significant improvements in soil pH and nutrient levels, such as ammonium nitrogen, nitrate nitrogen, and available phosphorus. These enhancements in soil conditions had profound positive effects on various wheat crop growth parameters, including increased plant height, dry biomass, leaf SPAD value (indicating chlorophyll content), and leaf area, as well as yield components such as spike length, spikelet number, grain number, and overall grain yield. Interestingly, despite a reduction in irrigation water to 50% of crop water requirements, there was no significant decrease observed in wheat crop growth or yield components. This resilience is likely attributable to the synergistic effects of biochar and fertilizer, which enhance crop water use efficiency and irrigation water use efficiency. These findings underscore the importance of the combined application of water hyacinth biochar and NPS fertilizer, especially in regions where water scarcity poses challenges to sustainable wheat crop production.

The study's overarching findings highlight the feasibility of locally converting water hyacinth biomass into biochar using a grounding system, offering a practical solution for regions afflicted by water hyacinth infestations and economically viable for local farmers. Notably, biochar derived from water hyacinth demonstrated the capacity to enhance both soil chemical and physical properties, exhibiting beneficial effects both immediately after application and in residual form across various seasons. Furthermore, the application of water hyacinth biochar particularly 20 t ha^{-1} exhibited potential in reducing the quantity and frequency of irrigation water needed for sustainable wheat crop production, particularly in areas vulnerable to climate change impacts like Ethiopia. This indicates a promising avenue for mitigating the challenges posed by erratic weather patterns and water scarcity in agricultural systems.

In essence, the study underscores the dual benefits of biochar derived from water hyacinth: remediation of invasive biomass and improvement of soil quality for enhanced crop productivity. Such interventions hold significant promise for fostering resilience and sustainability in agricultural landscapes grappling with environmental and economic pressures.

4.3. Future research directions

Throughout this dissertation, extensive efforts were made to characterize the properties of locally produced water hyacinth biochar and assess its impact on soil properties and crop performance, both immediately after application and in residual form across varying seasons. However, there remains a crucial need for further evaluation of water hyacinth biochar over prolonged periods, across diverse soil types, and in varying environmental conditions.

Expanding the scope of research to include long-term studies would provide valuable insights into the enduring effects of water hyacinth biochar on soil health and crop productivity. Additionally, investigating its performance across different soil types and environmental contexts would offer a more comprehensive understanding of its efficacy and applicability across diverse agricultural settings.

Therefore, it is recommended to conduct comprehensive, extended-duration studies that encompass a range of soil conditions and environmental variables to fully elucidate the potential benefits and limitations of water hyacinth biochar as a sustainable soil amendment. Such research endeavors would contribute significantly to advancing our knowledge and informing practical applications of water hyacinth biochar in agricultural systems.

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Appendix

Table A1. The effect of water hyacinth biochar (B), NPS fertilizer (F), and irrigation (I) on soil moisture content in 2023 dry season.

Treatments	Soil moisture content (%)					
	7	15	30	60	90	130
	Days after sowing (DAS)					
0B0F100I	$0.316±0.003^{a}$	$0.267±0.002^{c}$	$0.248±0.013^{h}$	$0.259±0.006^{a}$	$0.248±0.004^{a}$	$0.302±0.004^{c}$
0B200F100I	$0.327±0.010^{a}$	$0.273±0.001^{bc}$	$0.271±0.002^{g}$	$0.266±0.015^{a}$	$0.252±0.002^{a}$	$0.309±0.006^{bc}$
5B200F50I	$0.323±0.003^{a}$	$0.271±0.007^{bc}$	$0.276±0.001^{g}$	$0.265±0.013^{a}$	$0.252±0.013^{a}$	$0.313±0.006^{abc}$
5B200F100I	$0.331±0.007^{a}$	$0.279±0.001^{abc}$	$0.281±0.003^{fg}$	$0.269±0.006^{a}$	$0.255±0.013^{a}$	$0.315±0.005^{abc}$
10B200F50I	$0.325±0.016^{a}$	$0.274±0.007^{bc}$	$0.284±0.000^{efg}$	$0.272±0.007^{a}$	$0.254±0.007^{a}$	$0.317±0.003^{abc}$
10B200F100I	$0.330±0.017^{a}$	$0.284±0.011^{abc}$	$0.291±0.001^{def}$	$0.276±0.010^{a}$	$0.256±0.032^{a}$	$0.321±0.014^{abc}$
20B0F50I	$0.340±0.008^{a}$	$0.280±0.010^{abc}$	$0.294±0.001^{cdef}$	$0.268±0.012^{a}$	$0.259±0.006^{a}$	$0.326±0.003^{abc}$
20B0F100I	$0.349±0.011^{a}$	$0.290±0.005^{ab}$	$0.298±0.000^{cde}$	$0.291±0.003^{a}$	$0.281±0.011^{a}$	$0.333±0.009^{ab}$
20B100F50I	$0.331±0.012^{a}$	$0.279±0.001^{abc}$	$0.301±0.001^{cd}$	$0.277±0.002^{a}$	$0.257±0.025^{a}$	$0.331±0.014^{ab}$
20B100F100I	$0.334±0.011^{a}$	$0.295±0.009^{a}$	$0.308±0.003^{bc}$	$0.282±0.012^{a}$	$0.272±0.009^{a}$	$0.319±0.001^{abc}$
20B200F50I	$0.336±0.004^{a}$	$0.278±0.002^{abc}$	$0.316±0.001^{ab}$	$0.277±0.005^{a}$	$0.267±0.005^{a}$	$0.318±0.002^{abc}$
20B200F100I	$0.341±0.017^{a}$	$0.288±0.003^{ab}$	$0.326±0.007^{a}$	$0.281±0.006^{a}$	$0.266±0.008^{a}$	$0.339±0.007^{a}$

Table A2. The effect of water hyacinth biochar (B), NPS fertilizer (F), and irrigation (I) on soil pH and NH_4^+-N in the 2023 dry season.

Treatments	**Soil pH**						**NH_4^+-N (mg kg^{-1})**					
	7	**15**	**30**	**60**	**90**	**130**	**7**	**15**	**30**	**60**	**90**	**130**
	-------Days after sowing (DAS) -------						**-------Days after sowing (DAS) -------**					
0B0F100I	4.65±0.059^{c}	4.85±0.079^{a}	4.90±0.117^{a}	4.97±0.064^{b}	4.67±0.124^{c}	5.03±0.062^{c}	12.5±0.345^{f}	17.8±1.21^{d}	22.4±3.75^{d}	92.0±8.98^{b}	58.3±2.62^{a}	10.4±1.81^{a}
0B200F100I	4.60±0.052^{c}	4.73±0.087^{a}	4.85±0.066^{a}	4.97±0.084^{b}	4.73±0.044^{bc}	5.12±0.091^{bc}	21.4±1.49^{ef}	19.9±1.06^{cd}	26.2±0.070^{cd}	98.1±6.26^{b}	58.1±0.542^{a}	11.0±1.19^{a}
5B200F50I	4.65±0.030^{c}	4.78±0.143^{a}	4.83±0.085^{a}	5.08v0.143^{ab}	4.96±0.018^{abc}	5.42±0.118^{abc}	29.0±2.18^{de}	27.3±1.48^{bcd}	26.3±6.99^{cd}	124±24.6^{b}	39.7±0.543^{bc}	6.19±0.473^{bcde}
5B200F100I	4.67±0.023^{c}	4.86±0.065^{a}	4.96±0.135^{a}	5.23±0.100^{ab}	5.02±0.058^{abc}	5.58±0.196^{ab}	32.8±2.28^{cde}	33.3±4.57^{abc}	33.1±0.283^{bcd}	121±14.8^{b}	31.4±4.08^{cd}	8.15±1.23^{abcd}
10B200F50I	4.78±0.102^{c}	4.82±0.062^{a}	4.93±0.113^{a}	5.21±0.134^{ab}	5.15±0.083^{ab}	5.48±0.0067^{abc}	37.1±2.34^{bcd}	38.6±1.77^{ab}	35.6±6.99^{bcd}	127v11.3^{b}	34.9±1.70^{bcd}	5.92±1.08^{cde}
10B200F100I	4.71±0.047^{c}	4.92±0.145^{a}	5.05±0.068^{a}	5.24±0.123^{ab}	5.19±0.036^{ab}	5.73±0.062^{a}	38.3±0.773^{bcd}	38.7±5.02^{ab}	35.0±6.70^{bcd}	134±18.8^{b}	33.3±4.02^{cd}	4.86±0.168^{de}
20B0F50I	4.81±0.044^{c}	4.95±0.149^{a}	5.19±0.082^{a}	5.28±0.066^{ab}	5.14±0.237^{ab}	5.73±0.289^{a}	43.5±7.26^{abc}	41.7±8.20^{ab}	47.6±6.19^{ab}	123v13.1^{b}	45.7±6.86^{b}	9.81±1.46^{ab}
20B0F100I	4.94±0.144^{abc}	5.12±0.137^{a}	5.14±0.175^{a}	5.19±0.116^{ab}	5.26±0.165^{a}	5.73±0.190^{a}	45.0±2.14^{ab}	42.4±4.75^{a}	43.5±7.37^{abc}	121±5.29^{b}	29.1±0.962^{cd}	9.48±0.578^{abc}
20B100F50I	4.88±0.166^{bc}	4.96±0.171^{a}	5.23±0.165^{a}	5.14±0.138^{ab}	5.28±0.257^{a}	5.70±0.243^{a}	41.3±1.55^{abc}	42.8±2.71^{a}	48.2±7.66^{ab}	127±10.5^{b}	34.3±4.76^{bcd}	7.76±0.729^{abcd}
20B100F100I	5.29±0.138^{a}	5.11±0.296^{a}	5.24±0.241^{a}	5.47±0.154^{a}	5.31±0.258^{a}	5.90±0.332^{a}	52.2±1.08^{a}	42.9±3.42^{a}	45.5±3.01^{ab}	194±33.0^{a}	24.3±3.01^{d}	4.66±0.662^{de}
20B200F50I	4.94±0.072^{abc}	4.99±0.094^{a}	5.33±0.211^{a}	5.30±0.024^{ab}	5.29v0.039^{a}	5.75±0.060^{a}	45.4±4.96^{ab}	40.7±1.28^{ab}	48.3v0.469^{ab}	192±24.6^{a}	32.7±3.07^{cd}	3.02±0.180^{e}
20B200F100I	5.20±0.192^{ab}	5.15±0.179^{a}	5.28±0.068^{a}	5.45±0.229^{a}	5.33±0.077^{a}	5.79±0.139^{a}	47.2±4.11^{ab}	43.3±1.80^{a}	61.1±5.02^{a}	138±7.82^{b}	23.5±0.280^{d}	2.87±0.405^{e}

Table A3. The effect of water hyacinth biochar (B), NPS fertilizer (F), and irrigation (I) on soil NO_3^- -N and Available P in the 2023 dry season.

Treatments	NO_3^- -N (mg kg^{-1})						Available P (mg kg^{-1})					
	7	**15**	**30**	**60**	**90**	**130**	**7**	**15**	**30**	**60**	**90**	**130**
	Days after sowing (DAS)						**Days after sowing (DAS)**					
0B0F100I	1.36±0.15^{g}	2.05±0.35^{f}	3.93±0.60^{d}	16.8±2.75^{d}	58.3±5.18^{a}	13.4±0.28^{a}	0.412±0.02^{f}	0.646±0.02^{e}	0.331±0.01^{e}	0.729±0.11^{d}	0.073±0.00^{e}	0.616±0.08^{e}
0B200F100I	2.17±0.01^{fg}	2.92±0.07^{ef}	6.98v0.70^{d}	17.7±3.16^{d}	57.6±2.39^{a}	10.3±0.52^{b}	0.514±0.01^{f}	0.846±0.07^{de}	0.734±0.10^{de}	0.740±0.10^{d}	0.927±0.10^{d}	0.942±0.10^{de}
5B200F50I	2.57±0.31^{efg}	5.60±0.18^{de}	7.27±2.17^{cd}	17.8±0.56^{d}	52.9±0.44^{a}	9.52±0.61^{bc}	0.596±0.06^{f}	1.47±0.05^{cd}	0.838±0.05^{de}	0.947±0.06^{d}	0.939±0.09^{d}	0.994±0.11^{de}
5B200F100I	2.60±0.10^{efg}	5.76±0.58^{d}	7.75±1.51^{cd}	23.5±1.79^{cd}	40.9±4.61^{bc}	7.56±0.13^{cde}	0.627±0.09^{ef}	1.53±0.08^{bcd}	1.06±0.02^{de}	0.903±0.07^{d}	1.04±0.07^{cd}	1.10±0.14^{cd}
10B200F50I	2.88±0.52^{def}	5.77±1.1^{d}	9.59±2.15^{bcd}	22.3±0.19^{cd}	38.7±0.55^{c}	7.75±0.21^{cde}	0.995±0.17^{de}	1.63±0.23^{bc}	1.54±0.10^{cd}	1.04±0.14^{d}	1.58±0.24^{bc}	1.29±0.08^{cd}
10B200F100I	3.86±0.39^{de}	8.68±0.51^{bc}	13.9±0.90^{ab}	32.3±1.14^{bc}	23.7±0.75^{de}	6.46±0.71^{def}	1.23±0.14^{cd}	1.66±0.26^{bc}	1.39±0.20^{cd}	1.14±0.07^{bcd}	1.09±0.20^{cd}	1.25±0.05^{cd}
20B0F50I	4.13±0.11^{d}	5.75±0.45^{d}	9.04±0.87^{bcd}	27.1±4.89^{cd}	50.9±3.11^{ab}	9.03±0.58^{bc}	1.46±0.13^{c}	1.81±0.24^{abc}	3.04±0.12^{ab}	1.52±0.01^{abc}	1.55±0.06^{bcd}	1.08±0.04^{cd}
20B0F100I	4.25±0.30^{d}	7.57±0.55^{cd}	12.9v0.86^{abc}	30.6±6.17^{c}	26.4±0.59^{de}	8.23±1.44^{bcd}	1.95±0.18^{b}	2.05±0.25^{abc}	2.31±0.39^{bc}	1.09±0.05^{cd}	1.34±0.10^{cd}	1.13±0.08^{cd}
20B100F50I	6.42±0.65^{c}	9.19±0.92^{abc}	14.0±0.54^{ab}	34.2±5.08^{abc}	31.5±4.62^{cd}	8.15±0.42^{bcd}	1.45±0.02^{c}	1.73±0.40^{bc}	3.06±0.11^{ab}	1.58±0.28^{ab}	1.63±0.21^{bc}	1.53±0.16^{bc}
20B100F100I	8.62±0.74^{b}	10.4±1.88^{ab}	14.2±2.79^{ab}	30.9±4.73^{c}	25.2±0.00^{de}	4.0±0.01^{g}	2.58±0.06^{a}	1.95±0.32^{abc}	3.12±0.59^{ab}	1.63±0.17^{a}	1.64±0.29^{bc}	1.52±0.06^{bc}
20B200F50I	8.6±0.52^{b}	10.7±2.08^{ab}	16.3±1.20^{a}	43.2±0.00^{ab}	24.1±0.57^{de}	5.56±0.06^{efg}	2.02±0.10^{b}	2.19±0.00^{ab}	3.17±0.41^{ab}	1.70±0.19^{a}	2.06±0.33^{ab}	2.20±0.20^{a}
20B200F100I	10.7±0.47^{a}	11.7±0.53^{a}	16.1±2.80^{a}	46.4±3.41^{a}	21.1±2.32^{e}	4.31±0.61^{fg}	2.71±0.14^{a}	2.45±0.12^{a}	3.37±0.31^{a}	1.68±0.19^{a}	2.51±0.16^{a}	1.75±0.23^{ab}

Table A4. The main and interaction effects of biochar (B), fertilizer (F), and irrigation (I) on treatments in each day after sowing (DAS) in the 2023 dry season.

	pH						**NH_4^+-N**						**NO_3^--N**					
	7	**15**	**30**	**60**	**90**	**130**	**7**	**15**	**30**	**60**	**90**	**130**	**7**	**15**	**30**	**60**	**90**	**130**
Effects	DAS						DAS						DAS					
B	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
F	ns	ns	ns	ns	ns	ns	**	ns	**	***	**	***	***	***	***	***	***	***
I	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	***	ns	*	**	ns	ns	***	ns
B*F	*	ns	ns	ns	ns	ns	ns	ns	ns	**	**	***	***	***	*	***	***	ns
B*I	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	***	ns	*	**	ns	ns	***	ns
F*I	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	**	ns	ns	ns	**	ns
B*F*I	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	ns	**	ns	ns	ns	**	ns

	Available P						**Soil moisture content**						**Bulk Density**		**Soil porosity**	
	7	**15**	**30**	**60**	**90**	**130**	**7**	**15**	**30**	**60**	**90**	**130**	**70**	**130**	**70**	**130**
Effects	DAS						DAS						DAS		DAS	
B	***	***	***	***	***	***	***	***	***	**	***	***	**	**	**	**
F	***	***	***	**	***	***	ns	ns	***	ns	ns	ns	ns	ns	ns	ns
I	***	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	*	ns	ns	ns	ns
B*F	***	ns	ns	**	ns	***	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B*I	***	ns	ns	ns	ns	ns	ns	*	ns	ns	ns	*	ns	ns	ns	ns
F*I	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
B*F*I	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

*, **, and *** denote significant differences by $p < 0.05$, 0.01, and 0.001, respectively, among different treatment.

Table A5. The main and interaction effects of biochar (B), fertilizer (B), and irrigation (I) on wheat growth and yield components during the dry season

	Plant height	Spike length	Spikelet number	Grain number	Grain yield	Leaf area			Leaf SPAD value			Dry biomass			
						70	90	110	70	90	110	70	90	110	130
						Days after sowing (DAS)									
B	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***
F	ns	**	***	***	***	***	***	***	***	**	***	***	***	***	***
I	ns	ns	ns	ns	ns	***	***	***	ns	ns	ns	***	**	ns	ns
B*F	ns	ns	ns	ns	**	ns	ns	ns	**	ns	**	***	***	***	ns
B*I	ns	ns	ns	ns	ns	***	ns	***	ns	ns	ns	***	**	ns	ns
F*I	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns
B*F*I	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	**	ns	ns	ns

Where *, **, and *** denote significant differences by $p < 0.05$, 0.01, and 0.001, respectively, among different treatment.

Table A6. The effect of water hyacinth biochar (B), NPS fertilizer (F), and irrigation (I) on wheat leaf area, leaf SPAD value, and dry biomass in the 2023 dry season.

Parameter	DAS	0B0F100I	0B200F100I	5B200F50I	5B200F100I	10B200F50I	10B200F100I	20B0F50I	20B0F100I	20B100F50I	20B100F100I	20B200F50I	20B200F100I
Leaf area (cm^2)	70	9.39^{e}	12.5^{e}	32.2^{cd}	37.3^{abc}	36.3^{abc}	43.8^{a}	26.3^{d}	34.6^{bcd}	35.9^{abc}	44.4^{a}	33.2^{bcd}	40.8^{ab}
	90	9.24^{e}	13.3^{e}	28.4^{cd}	36.8^{ab}	36.4^{ab}	39.6^{a}	27.2^{d}	31.2^{bcd}	35.9^{abc}	39.7^{a}	30.1^{abc}	38.1^{ab}
	110	9.49^{d}	12.4^{d}	24.1^{abc}	27.0^{ab}	23.7^{abc}	27.2^{ab}	22.0^{c}	25.3^{abc}	25.5^{abc}	27.8^{a}	22.9^{bc}	27.2^{a}
Leaf SPAD value	70	28.1^{c}	39.1^{b}	44.3^{ab}	47.3^{ab}	48.2^{ab}	49.1^{a}	42.0^{ab}	47.0^{ab}	50.4^{a}	47.1^{ab}	47.1^{ab}	48.9^{a}
	90	28.1^{b}	36.1^{ab}	45.2^{a}	45.5^{a}	43.0^{a}	45.5^{a}	38.3^{ab}	45.6^{a}	45.6^{a}	45.6^{a}	45.4^{a}	46.4^{a}
	110	13.6^{b}	24.3^{a}	29.4^{a}	30.5^{a}	30.8^{a}	31.8^{a}	25.3^{a}	31.1^{a}	32.5^{a}	32.1^{a}	31.7^{a}	33.1^{a}
Dry biomass ($t\ ha^{-1}$)	70	3.20^{f}	3.20^{f}	5.87^{def}	9.13^{bcd}	8.33^{cde}	12.5^{ab}	4.80^{ef}	5.87^{def}	11.73^{bc}	11.7^{bc}	9.87^{bc}	16.3^{a}
	90	3.20^{f}	3.73^{ef}	12.53^{cd}	16.0^{c}	15.47^{cd}	17.3^{bc}	9.60^{de}	12.8^{cd}	22.9^{ab}	27.2^{a}	24.8^{a}	27.5^{a}
	110	4.27^{g}	5.33^{fg}	17.9^{de}	28.5^{abcd}	23.2^{bcde}	30.7^{ab}	16.3^{ef}	19.5^{cde}	22.7^{bcde}	29.1^{abc}	30.7^{ab}	36.5^{a}
	130	2.01^{e}	5.31^{de}	11.4^{cd}	15.8^{abc}	12.0^{bcd}	18.3^{ab}	9.87^{cd}	12.5^{abc}	15.1^{abc}	16.5^{abc}	15.9^{abc}	19.1^{a}

Where DAS denotes days after sowing