Effect of Biochar Application on the Improvement of Soil Properties and Buckwheat (*Fagopyrum esculentum* Moench) Yield on Two Contrasting Soil Types in a Semi-Arid Region of Inner Mongolia

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Abstract: Biochar application to soil is widely recognized as a promising agricultural management practice to increase crop production by enhancing the physical, chemical, and microbiological properties of the soil. Despite the fact that numerous studies have investigated biochar production and alterations in soil properties, the effects of biochar on contrasting soils within the same region remain poorly understood, especially for semi-arid regions. Therefore, a three-year field experiment was initiated in 2020 wherein biochar was applied once to a buckwheat field at rates of 0, 20, 40, and 60 Mg ha⁻¹ (BC0: no biochar; BC1: 20 Mg ha⁻¹; BC2: 40 Mg ha⁻¹; BC3: 60 Mg ha⁻¹) for two soil types (aeolian sandy and grey meadow soil) in the northeast of Inner Mongolia, China. The soil water storage (SWS), nutrient contents (organic matter, available nitrogen, phosphorus, and potassium), microbial biomass (carbon, nitrogen, and phosphorus), and enzyme activities (urease, invertase, and alkaline phosphatase) were assessed at a soil depth of 0–15 cm as part of the soil quality assessment, and the buckwheat grain yield was estimated for crop productivity evaluation. The results showed that biochar amendment improved selected soil physicochemical and microbiological properties and buckwheat yields for both soil types. Compared to BC0, the biochar addition increased buckwheat yields, on average, by 11.23% to 22.82% in aeolian sandy soil and by 7.36% to 14.87% in grey meadow soil across three years. The results of principal component analysis (PCA) and random forest analysis (RFA) indicate that soil available nutrients and microbiological properties were the most important factors influencing buckwheat yields in aeolian sandy soil and grey meadow soil, respectively. Based on RFA, the available potassium, phosphorus, and nitrogen were found to contribute at rates of 13.10%, 10.06%, and 8.12%, respectively, to buckwheat yields in aeolian sandy soil. In contrast, alkaline phosphatase, urease, and microbial biomass carbon contribute 20.26%, 8.48%, and 7.82%, respectively, to the buckwheat yields in grey meadow soil. Following biochar addition, there was greater improvement in soil health and buckwheat production for aeolian sandy soil than grey meadow soil. In conclusion, biochar addition is an effective practice for improving soil health and crop productivity in both aeolian sandy soil and grey meadow soil in semi-arid regions.

Keywords: biochar; buckwheat yield; soil quality; soil texture

1. Introduction

Soil is considered a living and non-renewable dynamic natural resource, supporting both food production for the increasing global population and the continued functioning of terrestrial ecosystems [1]. However, following decades of intensifying fertilization excess, urbanization, anthropic activities, and climate change, soil has been suffering due to a series of environmental concerns, including increased greenhouse gas emissions, degradation of
soil quality, and soil erosion [2]. These issues have gained significant attention from local governments and authorities, prompting proactive measures to maintain soil health and sustain soil multifunctionality.

In recent years, the widespread utilization of biochar (BC) in agriculture has been recognized as a pivotal method for enhancing soil quality and fostering sustainable agricultural practices [3]. Biochar, a carbon-rich substance derived from an extensive range of biomass or organic waste materials via thermochemical processes [4], is characterized by its high carbon content, pH, and porosity, a relatively large specific surface area, the capacity for cation exchange and nutrient retention, and structural stability [5]. There are numerous studies demonstrating that biochar addition can improve soil structure, increase soil water-holding capacity, enhance soil organic carbon, improve microbial properties, and ultimately increase crop yields [6–8]. However, some studies have also shown minor or negligible effects or, occasionally, adverse impacts [9,10]. For instance, wood biochar had only a minor effect on the yield, quality, and soil water retention of three crops—alfalfa, corn, and wheat—in a study spanning 10 site-years conducted in the western United States [9]. Similarly, reports have also revealed that biochar addition has no significant effect, or even a negative effect, on soil aggregation or aggregate stability [11], soil water availability or soil moisture content [12], nutrient (N, P) availability [13], microbial biomass C [14], and microflora abundance, biomass, and activity [15]. The varied effects of biochar addition on soil properties are constrained by the specific type of charred material, soil type, and dosage [16]. Furthermore, the pyrolysis temperature, feedstocks, and pyrolysis time associated with biochar preparation have a substantial impact on specific soil properties. For instance, greater pyrolysis temperatures (>500 °C) lead to biochars containing a significantly higher overall carbon content and having a higher specific surface area, which have been shown to promote physicochemical improvements in soil [17,18]. Additionally, studies have shown that crop-based biochar exhibits a greater cation exchange capacity than other biochars [17]. In addition, the biochar application rate and soil type play pivotal roles in driving the enhancement of soil properties and crop productivity. Some studies have indicated that there is a more pronounced improvement of soil properties and crop productivity for coarse-textured soil than fine-textured soil. Other studies have reported that higher rates of biochar application to medium-textured soils resulted in a significant increase in crop productivity, with a contrasting trend noted for coarse and fine-textured soils [19,20].

The northeast region of Inner Mongolia serves as an important base for food production, playing a vital role in upholding national food security [21]. Buckwheat (Fagopyrum esculentum Moench) is a common cultivated crop with a rich history of cultivation in China [22]. It is characterized by its tolerance to low-fertility soils and cool weather conditions. Common buckwheat, as one of the most important minor crops in China, plays a crucial role as a relief crop. It is primarily cultivated in northern China, especially in semi-arid regions such as Inner Mongolia, Gansu, Shanxi, Shaanxi, and Ningxia, promoting the self-sufficiency of these regions via food production and significantly contributing to national food security [23]. Common buckwheat has been shown to prevent diabetes in addition to having anti-inflammatory and antitumor properties. Additionally, buckwheat seeds are enriched with essential trace elements such as zinc (Zn), copper (Cu), and manganese (Mn), which are important for human health [24]. Due to its significant health benefits, such as its potential to help regulate blood pressure, blood sugar, and blood lipid levels, there is a substantial demand for this crop in both international and local markets [25]. Owing to overcultivation, excessive fertilization, and intensified agricultural practices, the soil in the regions where common buckwheat is grown has undergone a process of degradation. It is thus imperative to determine environmentally sustainable solutions to improve soil fertility and productivity toward sustaining and upholding soil health [26].

Numerous studies have extensively evaluated the impact of biochar addition on soil properties and crop yields, such as those conducted by Li et al. [27], Adekiya et al. [28], and Wei et al. [29]. However, these studies primarily focused on fertile soils. Consequently, there is a lack of research on the soil quality and crop yield of low-fertility soils affected by biochar.
addition, which requires further investigation. Moreover, the majority of these studies were conducted in temperate regions, as in the cases of Adekiya et al. [28] and Schmidt et al. [30], leaving a gap in the understanding of the effects of biochar on varying soil types in semi-arid environments within the same region. Therefore, this study aims to fill this gap by investigating the influence of different biochar rates on soil properties and productivity in a semi-arid region for different soil types. In this study, we conducted a three-year field experiment aimed at assessing the impact of four different biochar application rates (0, 20, 40, and 60 Mg ha⁻¹) on soil properties and buckwheat yields across two distinct soil types, namely, aeolian sandy soil and grey meadow soil. These two soil types represent the primary soil types in northeastern Inner Mongolia, the predominant area of cultivation that serves as the principal grain-producing zone. We hypothesize that biochar application to the two soil types will enhance the physicochemical and microbiological properties of both soils, leading to an increase in buckwheat yields. However, we also expect greater improvements with higher rates of biochar application, particularly in aeolian sandy soil. The main objectives of this study are to evaluate the effects of three different rates of biochar addition on soil physicochemical and microbiological properties and buckwheat yields in an aeolian sandy soil and grey meadow soil.

2. Material and Methods

2.1. Experimental Sites

A three-year field experiment was conducted on two different soil types (aeolian sandy soil and grey meadow soil). Both study sites are found within Horqin District, Tongliao, Inner Mongolia, China. The aeolian sandy soil field was located in Xiliaohe village (43°44′ N 122°24′ E), while the grey meadow soil was located within the Agriculture and Animal Husbandry Science and Technology Demonstration Park of Inner Mongolia Minzu University (43°65′ N 122°09′ E). The two soils were studied in separate experiments, and the field sites were approximately 50 km from each other. The basic soil properties of the two distinct soil types are shown in Table 1. The regional climate is defined as a temperate continental monsoon climate with a mean annual temperature of 6.4 °C, a mean annual precipitation of 399 mm, and a frost-free period lasting approximately 150 days. The local daily mean temperature and daily precipitation during the growing seasons of 2020, 2021, and 2022 were measured and are shown in Figure 1. Precipitation events were concentrated in July and August. The average precipitation during the buckwheat growing season (from early July to the end of September) was 241.9 mm from 2020 to 2022.

Table 1. Properties of the two soil types.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Soil Texture</th>
<th>pH</th>
<th>Organic Matter (g kg⁻¹)</th>
<th>Available Nitrogen (mg kg⁻¹)</th>
<th>Available Phosphorus (mg kg⁻¹)</th>
<th>Available Potassium (mg kg⁻¹)</th>
<th>Bulk Density (g cm⁻³)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Sand (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aeolian sandy Entisol</td>
<td>8.23</td>
<td>7.11</td>
<td>32.14</td>
<td>5.58</td>
<td>80.16</td>
<td>1.63</td>
<td>3.97</td>
<td>10.7</td>
<td>85.33</td>
<td></td>
</tr>
<tr>
<td>Grey meadow Inceptisols</td>
<td>7.2</td>
<td>11.24</td>
<td>48.52</td>
<td>15.72</td>
<td>98</td>
<td>1.45</td>
<td>10.52</td>
<td>65.44</td>
<td>24.04</td>
<td></td>
</tr>
</tbody>
</table>

2.2. Biochar

Maize stover biochar was purchased from the Jinhefu Agriculture Development Company, Liaoning, China. The biochar used in the experiments was produced via slow pyrolysis of maize stover under oxygen-limited conditions in a vertical kiln for 90 min at 450 °C; 35% of the maize stover biomass was converted to biochar [8,31]. The basic properties of the biochar were determined to be pH 8.85, total C 657.8 g kg⁻¹, total N 9.20 g kg⁻¹, total P 8.85 g kg⁻¹, total K 12.3 g kg⁻¹, available P 120 mg kg⁻¹, available K 289 mg kg⁻¹, and ash content of 16.02%. The biochar was ground to pass through a 2 mm sieve and thoroughly homogenized prior to field application.
Figure 1. Daily mean temperature and precipitation during the three buckwheat growing seasons in 2020–2022.

2.3. Experimental Design

The field experiments began in June 2020. The biochar was applied at rates of 0 Mg ha$^{-1}$, 20 Mg ha$^{-1}$, 40 Mg ha$^{-1}$, and 60 Mg ha$^{-1}$ (BC0, BC1, BC2, and BC3, respectively). Prior to the experiment, the surface soil (0–15 cm) was evenly mixed with the biochar by a rototiller before buckwheat sowing in July 2020, with no supplementation in the following years. Each treatment was triplicated (3 m $\times$ 10 m) and separated by a ridge (30 cm wide and 10 cm high) to keep the water and nutrients from running off. All field plots were annually planted with common buckwheat (cultivar ‘Tongqiao No. 5’) in July and harvested in September. Diammonium phosphate and potassium sulfate were used as basal fertilizers at rates of 100 kg ha$^{-1}$ and 150 kg ha$^{-1}$, respectively. The fertilizers were applied once per year before sowing buckwheat. All other aspects of field management were the same for each treatment and corresponded to the local cultivation practices.

2.4. Soil Sampling and Measurements

Soil samples were collected at a depth of 0–15 cm once a year during the mature period of buckwheat (late September) using a 5 cm-diameter hand auger corer. For each plot, five points were sampled randomly in the central area, to avoid edge effects, and combined into a composite sample. The representative samples were placed into a plastic bag and transported to the laboratory for further processing. Any visible plant roots, stones, litter, and debris were removed by hand from all the collected soil samples, which were then divided into two portions: one was air-dried in the shade for two weeks for physiochemical analysis, the other was stored at 4 $^\circ$C for analysis of soil microbial biomass and enzyme activity [1].

2.4.1. Soil Physicochemical Properties

Soil water content (SWC) was determined using an oven-drying method. The bulk density (BD) was assessed following the method outlined by Zhao et al. [32]. Soil water storage was calculated following the equation detailed by Zhao et al. [32]:

$$\text{SWS} = \text{SWC} \times \text{BD} \times \frac{\text{SD}}{\text{WD}}$$  \hspace{1cm} (1)

where SWC = soil water content (% wt/wt), BD = soil bulk density (g cm$^{-3}$), SD = soil depth (mm), and WD = water density (g cm$^{-3}$). SWS content is reported as mm.
2.4.2. Soil Chemical Properties

Soil organic matter (SOM) was calculated by multiplying the soil organic carbon (SOC) by the Van Bemmelen factor of 1.72. The SOC content was quantified using the $\text{K_2Cr}_2\text{O}_7-\text{H}_2\text{SO}_4$ oxidation method [33]. The soil available nitrogen (AN, alkali-hydrolyzable N) content was quantified using the alkaline hydrolysis diffusion method [34]. The soil available phosphorus (AP, NaHCO$_3$-extractable P) content was determined using the Olsen method [35]. The soil available potassium (AK) content was measured using a flame photometer after extraction with ammonium acetate [36].

2.4.3. Soil Microbiological Properties

Soil microbial biomass carbon (SMC), nitrogen (SMN), and phosphorus (SMP) were measured using the chloroform fumigation–extraction method [37–39]. Briefly, moist soil was fumigated with chloroform (CHCl$_3$) for 24 h at 25°C. Subsequently, both fumigated and unfumigated soil samples were subjected to extraction with 0.5 mol L$^{-1}$ K$_2$SO$_4$ for SMC and SMN and with 0.5 mol L$^{-1}$ NaHCO$_3$ (pH = 8.5) for MBP. The MBC content was determined by titrating the extract with FeSO$_4$ after hot digestion with a mixture of K$_2$Cr$_2$O$_7$ and H$_2$SO$_4$. SMN was determined using a spectrophotometer at 570 nm to calculate NH$_3$–N content with the ninhydrin reagent. SMP was determined at a 700 nm wavelength on a spectrophotometer using a blended molybdenum antimony color reagent. SMC (mg kg$^{-1}$), SMN (mg kg$^{-1}$), and SMP (mg kg$^{-1}$) were then evaluated as follows:

$$\text{SM (C, N, P) = (Fum - NFum)/k}$$

where Fum and NFum are the values obtained from fumigated and non-fumigated soil and $k$ is the conversion coefficient, with values of 0.38, 0.45, and 0.4 for SMC, SMN, and SMP, respectively.

The activity of three soil extracellular enzymes related to soil C-, N-, and P-cycling, i.e., soil invertase (EC 3.2.1.26), urease (EC 3.5.1.5), and alkaline phosphatase (EC 3.1.3.1), were determined according to the methods described by Zhou et al. [40] and Guan et al. [41]. Soil urease activity was determined via colorimetric analysis of sodium phenate–sodium hypochlorite, with urea as the substrate. Soil invertase activity was assayed using indophenol blue colorimetry. Soil alkaline phosphatase activity was determined based on disodium phenyl phosphate colorimetry. Soil invertase, urease, and alkaline phosphatase activity are reported as mg glucose g$^{-1}$ 24 h$^{-1}$, mg NH$_3$–N g$^{-1}$ 24 h$^{-1}$, and µg phenol g$^{-1}$ h$^{-1}$, respectively.

2.4.4. Grain Yield

To record the grain yield, the buckwheat crop was manually harvested from three randomly selected 1 m $\times$ 2 m areas within the central area of each plot. The grain yield is expressed for 12% moisture content.

2.5. Data Analysis

One-way analysis of variance (ANOVA) was utilized to test the significance of biochar addition concerning the soil physiochemical and microbiological properties and the buckwheat yield separately for each year and soil type. Three-way ANOVA was employed to assess the statistical effect of biochar on soil properties and yield across two distinct soil types over the duration of the study. Principal component analysis was performed to determine the relationships between parameters and biochar treatments. Random forest analysis was performed to quantify the importance of different soil parameters in terms of buckwheat yield, which were ranked in R (’randomforest’ package).

3. Results

3.1. ANOVA of Measurements

The ANOVA for different measurements is given in Table 2. Biochar (BC), soil type (T), and year (Y) significantly influenced ($p < 0.05$) all tested parameters, except regarding
Factors | DF | Yield | SWS | SOM | AN | AP | AK | SMC | SMN | SMP | Ure | Int | Alkp
---|---|---|---|---|---|---|---|---|---|---|---|---|---
BC | 3 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | ***
T | 1 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | ***
Y | 2 | *** | *** | *** | NS | NS | *** | *** | *** | *** | *** | *** | ***
BC * T | 3 | NS | NS | *** | * | * | NS | * | ** | NS | NS | NS | ***
T * Y | 2 | *** | NS | *** | NS | *** | NS | NS | * | NS | ** | *** | ***
BC * Y | 6 | NS | NS | ** | NS | NS | ** | NS | NS | NS | NS | NS | NS
Y * T * BC | 6 | NS | NS | NS | * | NS | NS | NS | NS | * | NS | NS | NS

* , ** Significance at 0.05, 0.01, and 0.001 probability levels. NS means not significant. DF = degrees of freedom; Yield = grain yield; SWS = soil water storage; SOM = soil organic matter; AN = soil available nitrogen, AP = soil available phosphorus; AK = available potassium; SMC = soil microbial biomass carbon; SMN = microbial biomass nitrogen; SMP = microbial biomass phosphorus. Ure = urease activity; Int = invertase activity; Alkp = alkaline phosphatase activity.

3.2. Soil Physicochemical Properties

Overall, the addition of biochar significantly improved SWS for both soil types (Figure 2, Table 2), with SWS increasing with higher levels of biochar addition (BC2, BC3). However, no significant increase was observed between BC1 and BC2 in aeolian sandy soil or between BC2 and BC3 in grey meadow soil (Figure 2). Over the three-year period, the biochar treatments resulted in an average increase in SWS by 11.19% to 25.90% in aeolian sandy soil and 6.07% to 13.62% in grey meadow soil compared to their control counterparts.

![Figure 2. Soil water storage (SWS) at 0–15 cm depth under four treatments: 0 (BC0), 20 (BC1), 40 (BC2), and 60 (BC3) Mg ha⁻¹ biochar application from 2020 to 2022 in aeolian sandy and grey meadow soils. Columns for the same year (or mean of the three years) and capped with the same lower-case letter are not significantly different ($p > 0.05$), as indicated below.

The SOM showed a relatively slow increasing trend in aeolian sandy soil compared to grey meadow soil after the addition of biochar (Figure 3a). For instance, in aeolian sandy soil, only the BC3 treatment exhibited a significant increase of 13.27% in the initial year...
after biochar application compared to CK, while BC1 and BC2 exhibited a gradual increase in SOM over the subsequent years. There was greater enhancement of SOM content in grey meadow soil than in aeolian sandy soil after the application of biochar. In comparison to the control counterparts, the highest values were observed for the BC3 treatment, with an average increase of 15.07% and 25.51% in aeolian sandy and grey meadow soil, respectively.

Figure 3. Cont.
In most cases, the addition of biochar increased the soil AN, AP, and AK contents compared to the control (Figure 3b–d). The soil available nutrient content increased rapidly after biochar addition but varied depending on the soil type, biochar application rate, and duration (Figure 3b–d, Table 2). In aeolian sandy soil, each of the BC treatments contributed to an elevation in soil AN content, except for BC1 in 2022 (Figure 3b). The average increments for the years 2020, 2021, and 2022 were 14.85%, 12.59%, and 12.29%, respectively, compared to BC0. However, no statistically significant differences in AN content were observed for BC1, BC2, and BC3. As for grey meadow soil, the AN peaked in the BC2 treatment and was 16.99% higher than for BC0 on average.

In aeolian sandy soil, compared to BC0, the AP content significantly increased with the increasing rate of BC addition in the initial year, but this trend changed over the subsequent years (Figure 3c). In grey meadow soil, the BC1 and BC2 treatments showed a relatively lower increase in AP content compared to BC3. BC3 consistently had the highest AP values in both soil types. On average, the AP content was 28.79% higher in aeolian sandy soil and 13.53% higher in grey meadow soil compared to their respective control counterparts.

A noticeable increasing trend in AK was correlated with the rate of biochar addition in both aeolian sandy and grey meadow soils during the initial year following the introduction of biochar (Figure 3d, Table 2). In the years 2021 and 2022, despite certain variations indicating significant differences in biochar treatments, BC3 consistently exhibited the highest AK content, surpassing that of BC0 by 18.95% and 15.64% in aeolian sandy and grey meadow soils, respectively.

3.3. Soil Microbiological Properties
3.3.1. Soil Microbial Biomass

Based on comparison to BC0, the biochar treatments resulted in higher SMC, SMN, and SMP contents in both soil types (Figure 4). The BC3, BC2, and BC1 treatments increased SMC by an average of 24.91%, 18.00%, and 9.41% in aeolian sandy soil and 9.54%, 7.55%, and 3.70% in grey meadow soil, respectively, compared to the BC0 treatment. Various significant effects on SMN content were observed, which increased with increasing biochar application on average, and BC treatments induced an increase of 6.12% to 13.88% in aeolian sandy soil compared to BC0. In grey meadow soil, the BC3 treatment exhibited the highest SMN value, which was 17.16% higher than for BC0. The SMP content exhibited diverse responses to the biochar addition and across different years after application in
both soil types. On average, the BC treatments increased SMP content by 6.51% to 12.72% in aeolian sandy soil compared to BC0, but no significance was observed between BC2 and BC3. Overall, the addition of biochar increased SMP content in grey meadow soil, although no significant difference between the BC treatments was found.

![Graph showing soil microbial biomass carbon (SMC), soil microbial biomass carbon (SMN), and soil microbial phosphorus (SMP) content at 0–15 cm depth under four treatments: 0 (BC0), 20 (BC1), 40 (BC2), and 60 (BC3) Mg ha\(^{-1}\) biochar application from 2020 to 2022 in aeolian sandy and grey meadow soils. Columns for the same year (or mean of the three years) and capped with the same lower-case letter are not significantly different (p > 0.05), as indicated below.

Figure 4. (a) Soil microbial biomass carbon (SMC), (b) nitrogen (SMN), and (c) phosphorus (SMP) content at 0–15 cm depth under four treatments: 0 (BC0), 20 (BC1), 40 (BC2), and 60 (BC3) Mg ha\(^{-1}\) biochar application from 2020 to 2022 in aeolian sandy and grey meadow soils. Columns for the same year (or mean of the three years) and capped with the same lower-case letter are not significantly different (p > 0.05), as indicated below.
3.3.2. Soil Enzyme Activities

The variations in soil urease, invertase, and alkaline phosphatase activities during 2020, 2021, and 2022 are shown in Figure 5. Overall, the addition of biochar substantially enhanced the activities of urease, invertase, and alkaline phosphatase. However, variations were observed depending on the soil type, biochar treatment, and duration after biochar addition (Table 2). For instance, BC3 consistently exhibited the highest urease activity in aeolian sandy soil over three years (Figure 5a). However, in grey meadow soil, substantial variations were observed for the different biochar addition rates, particularly in 2022, where no significant difference in urease activity was found between BC1, BC2, and BC3.

Biochar application had a negligible impact on soil invertase activity in grey meadow soil; only BC2 exhibited a significant increase compared to BC0 in 2021 and 2022 (Figure 5b). In aeolian sandy soil, only higher biochar addition (BC2 and BC3) increased invertase activity.

A consistent upward trend was observed for alkaline phosphatase activity in grey meadow soil during 2020 and 2021, but varied changes were induced by biochar application in aeolian sandy soil over the three years (Figure 5c). BC1 and BC2 showed a positive effect in promoting alkaline phosphatase activity in aeolian sandy soil in 2020, although this effect disappeared in 2021 and 2022. BC3 had the highest value, with an average increase of 12% compared to BC0. However, in grey meadow soil, BC2 consistently showed the highest activity over three years, with an average increase of 13.25% compared to BC0.

![Figure 5. Cont.](image-url)
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Effect in promoting alkaline phosphatase activity in aeolian sandy soil in 2020, although this effect disappeared in 2021 and 2022. BC3 had the highest value, with an average increase of 12% compared to BC0. However, in grey meadow soil, BC2 consistently showed the highest activity over three years, with an average increase of 13.25% compared to BC0.

Figure 5. (a) Soil urease, (b) invertase, and (c) alkaline phosphatase activities at 0–15 cm depth under four treatments: 0 (BC0), 20 (BC1), 40 (BC2), and 60 (BC3) Mg ha⁻¹ biochar application from 2020 to 2022 in aeolian sandy and grey meadow soils. Columns for the same year (or mean of the three years) and capped with the same lower-case letter are not significantly different (p > 0.05), as indicated below.

3.4. Buckwheat Yield

The addition of biochar resulted in a significant increase in buckwheat yields in both aeolian sandy and grey meadow soils, but the effects differed based on the soil type (Figure 6, Table 2). A stable increasing trend was observed in aeolian sandy soil, but with greater variation than observed in grey meadow soil, with an increase ranging from 2.51% to 17.02% compared to BC0 after BC addition. However, based on a three-year average, BC treatments did not yield a statistically significant difference in buckwheat yields for grey meadow soil. In contrast, a discernible increase in buckwheat yields along with the application rate was observed in aeolian sandy soil, displaying an average increase ranging from 11.23% to 22.82% compared to BC0.

Figure 6. Buckwheat grain yield under four treatments: 0 (BC0), 20 (BC1), 40 (BC2), and 60 (BC3) Mg ha⁻¹ biochar application from 2020 to 2022 in aeolian sandy and grey meadow soils. Columns for the same year (or mean of the three years) and capped with the same lower-case letter are not significantly different (p > 0.05), as indicated below.
3.5. Relationship between Soil Properties and Biochar Treatments

PCA was conducted to illustrate the relationships between selected soil parameters and treatments in aeolian sandy soil (Figure 7a) and grey meadow soil (Figure 7b), respectively. The PCA results showed that axis 1 and axis 2 together explained 81% (aeolian sandy soil) and 69% (grey meadow soil) of the total data variability. The BC2 and BC3 groups generally clustered together for both soil types. Additionally, the soil parameters positively correlated with BC2 and BC3, whereas BC0 and BC1 were clearly separated from the biochar treatments.

![Figure 7. Principal component analysis of selected soil properties and buckwheat yields under four treatments: 0 (BC0), 20 (BC1), 40 (BC2), and 60 (BC3) Mg ha\(^{-1}\) biochar application from 2020 to 2022 in (a) aeolian sandy and (b) grey meadow soils. SWS = soil water storage; SOM = soil organic matter; AN = soil available nitrogen, AP = soil available phosphorus; AK = available potassium; SMC = soil microbial biomass carbon; SMN = microbial biomass nitrogen; SMP = microbial biomass phosphorus; Ure = urease activity; Int = invertase activity; Alkp = alkaline phosphatase activity; Yield = grain yield.](image)

3.6. Buckwheat Yield and Its Relationship with Soil Properties

The results of random forest analysis showed that six variables significantly predicted buckwheat yield in aeolian sandy soil (\(p < 0.05\)), ranked in decreasing importance as AK, SMC, AP, urease, AN, and alkaline phosphatase (Figure 8), with three variables identified for grey meadow soil (\(p < 0.05\)), ranked in decreasing importance as alkaline phosphatase, urease, and SMC (Figure 8). Based on the selected soil properties, the cumulative MSE (mean square error) of soil available nutrients (AN, AP, AK) amounted to 31.27%. In aeolian sandy soil, soil microbial biomass (SMC, SMN, SMP) contributes most, at 18.33%, to the overall MSE, followed by soil enzyme activities (urease, invertase, alkaline phosphatase), at 16.96%. In contrast, the collective MSE for soil enzyme activities in grey meadow soil totaled 30.77%, with soil microbial biomass and soil available nutrients contributing 8.73% and 4.90%, respectively.
Figure 7. Principal component analysis of selected soil properties and buckwheat yields under four treatments: 0 (BC0), 20 (BC1), 40 (BC2), and 60 (BC3) Mg ha$^{-1}$ biochar application from 2020 to 2022 in (a) aeolian sandy and (b) grey meadow soils. SWS = soil water storage; SOM = soil organic matter; AN = soil available nitrogen, AP = soil available phosphorus; AK = available potassium; SMC = soil microbial biomass carbon; SMN = microbial biomass nitrogen; SMP = microbial biomass phosphorus; Ure = urease activity; Int = invertase activity; Alkp = alkaline phosphatase activity; Yield = grain yield.

3.6. Buckwheat Yield and Its Relationship with Soil Properties

The results of random forest analysis showed that six variables significantly predicted buckwheat yield in aeolian sandy soil ($p < 0.05$), ranked in decreasing importance as AK, SMC, AP, urease, AN, and alkaline phosphatase (Figure 8), with three variables identified for grey meadow soil ($p < 0.05$), ranked in decreasing importance as alkaline phosphatase, urease, and SMC (Figure 8). Based on the selected soil properties, the cumulative MSE (mean square error) of soil available nutrients (AN, AP, AK) amounted to 31.27%. In aeolian sandy soil, soil microbial biomass (SMC, SMN, SMP) contributes most, at 18.33%, to the overall MSE, followed by soil enzyme activities (urease, invertase, alkaline phosphatase), at 16.96%. In contrast, the collective MSE for soil enzyme activities in grey meadow soil totaled 30.77%, with soil microbial biomass and soil available nutrients contributing 8.73% and 4.90%, respectively.

4. Discussion

4.1. Soil Physicochemical Properties

In this study, biochar application showed positive effects on soil physical and chemical properties in aeolian sandy and grey meadow soil over three years (Table 2). Notably, a statistically significant increase ($p < 0.05$) was observed in SWS, SOM, AN, AP, and AK content in comparison to the control (Figures 2 and 3). Similar results have been reported for other studies [10,16]. These findings underscore the pronounced influence of biochar in enhancing key soil parameters, highlighting its potential role in promoting soil health and fertility.

The addition of biochar has been shown to enhance soil water retention [11]. In the present study, biochar increased SWS in both aeolian sandy and grey meadow soils, an observation supported by numerous studies. Li et al. [27] found that adding 4 Mg ha$^{-1}$ of biochar could increase SWS by 24.6% at a soil depth of 0–160 cm compared to the control after 7–8 years of biochar addition. In addition, our results revealed that the SWS increment was higher in aeolian sandy soil than in grey meadow soil, with average increases over three years of 11.21–25.91% and 6.69–13.62%, respectively, compared to the corresponding control. Our findings are consistent with those of Razzaghi et al. [42], whose global-scale meta-analysis on the effects of biochar incorporation on soil moisture retention indicated a notable augmentation in the water retention capacity of the treated soils that was particularly discernible in soils characterized by coarse textures. Additionally, the clay and silt contents are important factors that can interact with biochar to form a soil matrix, resulting in increased water-holding capacity [43]. Moreover, higher biochar application rates may be needed for soils characterized by high sand content to achieve an equivalent effect. Similarly, Mandal et al. [44] reported that more soil water was retained in sandy soil that in loamy or clay soil following biochar addition. They also found that the SWS was positively linked with the biochar application rate, as demonstrated in numerous studies [45,46]. Possible reasons for the increment in SWS are the reduction in soil bulk density and improvement in soil aggregate after biochar addition, which facilitates the soils in retaining more water [43].

SOM serves as a key indicator of soil health, supporting multiple soil ecosystem functions crucial for terrestrial life [27]. Most studies have shown that biochar application increases soil C content, which is mainly attributed to the substantial carbon content of biochar used in these studies [27,47]. In the present study, SOM content increased by 4.85% to 15.07% in aeolian sandy soil and 9.00% to 25.51% in grey meadow soil over a three-year period after biochar addition. However, these responses are closely related to factors
such as the raw material, pyrolysis condition, application rate, and the soil types where biochar is applied [16]. El-Naggar et al. [3] found that the magnitude of SOM increases after biochar addition was greater in sandy soil (42–72%) than in loam soils (32–48%). This inconsistency may be attributed to variations in the biochar properties, addition rates, field climate conditions, and duration of biochar application. In our study, we found that SOM increased with increases in the biochar application rate over a three-year field trial. Similarly, Adekiya et al. [28] found that adding 30 Mg ha$^{-1}$ of biochar increased SOM by an average of 18% and 9% over biochar application rates of 10 Mg ha$^{-1}$ and 20 Mg ha$^{-1}$, respectively. Dong et al. [47] unveiled that after 5 years of biochar application, SOM increased by 18.8%, 42.4%, and 62.3% when biochar was applied at rates of 30, 60, and 90 Mg ha$^{-1}$, respectively, compared to the control. One potential explanation is the high organic carbon content of biochar together with the inherent recalcitrance and abundance of aromatic carbon in biochar, which prevents its rapid decomposition [16]. The recalcitrant nature of biochar, coupled with its substantial aromatic carbon content, contributes to its prolonged persistence in soil, making it less susceptible to rapid decomposition and enhancing its longevity within the soil matrix [3].

In our study, the soil available nutrients (nitrogen, phosphorus, and potassium) significantly increased after biochar addition in aeolian sandy and grey meadow soils. The possible reasons for this observation are as follows: (i) soil nutrients were released by biochar and (ii) an impact on soil diversity and the abundance of microorganisms related to N-, P-, and K- cycling, creating a favorable environment. In our study, a significant increase in soil available nutrients was observed in high biochar treatments in the third year after biochar addition. This increase may be attributed to the slow release of nutrients from biochar over time.

4.2. Soil Microbiological Properties

Soil microbial biomass and enzyme activity are commonly regarded as early indicators of alterations in soil quality. Soil enzyme activities play a crucial role in the decomposition of soil organic matter and nutrient cycling [27]. The findings of this study indicate that soil microbial biomass (C, N, and P) and three soil extracellular enzyme activities increased significantly after biochar addition in both soils.

Numerous studies have shown that adding biochar can create a favorable habitat that promotes the growth of microorganisms, thereby increasing soil microbial biomass [48,49]. In some cases, however, it was revealed that a toxic effect (chemical stress) can occur when biochar is applied at a high rate [50]. In our work, biochar addition increased soil microbial biomass in both aeolian sandy and grey meadow soils. This suggests that there were no obvious toxic effects on soil microorganisms, even at a biochar application rate of 60 Mg ha$^{-1}$. These results demonstrated that variations in soil microbial biomass can be influenced by many factors such as biochar properties, field management practices, climate conditions, and soil types.

Biochar exhibited positive impacts on soil enzymatic activities compared to the control treatment [51], which can be attributed to three main factors. Firstly, biochar can create a favorable soil water–air environment, improving water retention and oxygen levels at microsites that favor microbial and crop growth, thus promoting enzyme secretion. Secondly, biochar amendment resulted in increased SOM, providing additional substrates for soil enzymes, including labile organic C [16]. Finally, incorporating biochar promotes crop root growth, facilitating rhizodeposition [52], which acts as a catalyst for stimulating microbial growth and enhancing the excretion and activity of the studied enzymes [53].

The results of our study showed that soil enzymatic activity was highly significantly ($p < 0.001$) influenced by biochar application rates, soil type, and the duration following addition (Table 2). Considering the average across three years, we observed a more pronounced increase in microbial biomass and enzyme activities in aeolian sandy soil than in grey meadow soil. This observation was consistent with a meta-analysis highlighting that primary soil conditions, including native SOM, significantly affect microbial biomass
and enzyme activities after biochar addition where it is assumed that there is a significant increase in soils with lower SOM, where the low availability of substrate is limiting [48].

4.3. Buckwheat Yield

Numerous previous studies have demonstrated the positive impact of applying biochar, as a commonly used soil amendment, in enhancing crop yield [27,52], although this is dependent on the initial fertility status of the soil [54]. In our study, biochar addition significantly increased the buckwheat yield by 11.22–22.83% over a three-year period in aeolian sandy soil. In grey meadow soil, yield enhancement was also observed over the three tested years, although no significant influence was observed between the different biochar amendments. With considerable variations in treatments when results for the period were averaged. A similar scenario has been previously reported, where biochar exhibited a more substantial increase in yield for coarse-textured soils than fine-textured soils [55]. Some researchers have argued that the influence of biochar on crop yields is linked to soil texture. The conclusion from a meta-analysis was that grain yield is positively correlated with biological yield in sandy and loamy soils, while no significant influence was observed in fine-textured clay soils [16]. This is also supported by Hussain et al. [50] and Laghari et al. [56], who observed a greater increase in crop productivity in nutrient-deficient and degraded soils compared to fertile soils.

The increase in yield resulting from biochar addition can be attributed to the improvements in soil water storage, available nutrients, and soil microbiological properties, all of which benefit buckwheat growth. Additionally, biochar is rich in available nutrients, and adding 20 Mg ha\(^{-1}\), 40 Mg ha\(^{-1}\), and 60 Mg ha\(^{-1}\) of biochar to the soil is equivalent to adding 184, 368, and 552 N kg ha\(^{-1}\); 180, 360, and 540 P kg ha\(^{-1}\); and 252, 504, and 756 K kg ha\(^{-1}\). These additional nutrients may be released from the biochar into the soil, promoting crop growth and leading to increased yields.

For our three-year experiment, we observed a consistently positive impact on buckwheat yields, possibly linked to the steady increase in soil water storage, available nutrients, and microbiological properties. This enhances the soil physicochemical and biological environment and contributes to improved crop growth and yields [7]. Similarly, Haider et al. [57] reported that aged biochar had more effective nutrient capture effects, leading to increased crop yields over time. Other possible reasons could be the gradual release of additional nutrients (N, P, K, Ca, and Mg) to plants over time [58] or the gradual formation of an organic coating on the surface of biochar, which significantly enhances its nutrient retention capacity after aging in compost media [59]. However, some previous studies reported biochar addition had limited or even adverse impacts on crop yields, as evidenced by pot and field trials [29,30]. These findings may be linked with various factors, including the types and properties of biochar, its application rate and frequency, soil texture, and climate conditions [54].

The rate of biochar addition is also a crucial factor in determining crop yields. Generally, for moderate biochar application rates, a consistently positive impact on crop yield is demonstrated. Conversely, a relatively low application rate may have no obvious effect, while excessive amounts of biochar may lead to negative effects on yield. However, precisely delineating the effects of low, medium, and high rates of biochar application remains a challenging task, sparking ongoing controversy and debate in this field. For instance, Yang et al. [60] reported that treatment with 30 Mg ha\(^{-1}\) resulted in a higher maize yield than treatment with 45 Mg ha\(^{-1}\). Yao et al. [61] found that rice yields increased with biochar applied at rates of 33.75 Mg ha\(^{-1}\), 67.5 Mg ha\(^{-1}\), and 101.25 Mg ha\(^{-1}\) in a two-year field experiment, although no significant difference between the biochar treatments was found. On the other hand, Rondon et al. [62] reported that 165 Mg ha\(^{-1}\) of biochar application in poor soils (low organic content or salinized soils) decreased crop yields. In our study, under the current experimental conditions in a semi-arid region of China, a biochar application rate of 60 Mg ha\(^{-1}\) resulted in the highest buckwheat yield in both aeolian sandy and grey meadow soils, despite the yield variations observed over three years in grey meadow soil.
Therefore, further research should focus on determining the optimal biochar addition rates and assessing their long-term effects on soil properties and productivity in this region.

The results of the random forest analysis indicated that the yield increase in aeolian sandy and grey meadow soil is a result of differences in the changes to soil properties induced by biochar addition. This can be primarily attributed to the distinct characteristics of each soil type. The complex interactions between changes in soil properties and subsequent yield improvements highlight the nuanced interplay between biochar-induced alterations and the inherent characteristics of different soil types. These insights are valuable in terms of understanding the complex dynamics influencing agricultural productivity.

Although low, medium, and high rates of biochar addition were found to have positive effects on soil properties and crop yields in our three-year experiment, further investigation is recommended to explore the ameliorative effects of biochar application on the two types of soil studied. This could involve increasing the frequency of biochar applications and extending the duration of the experiment, for example, to five years, to comprehensively evaluate long-term effects.

5. Conclusions

In this three-year study, biochar addition enhanced SWS, increased SOM and soil available nutrients (AN, AP, AK), promoted microbiological properties (SMC, SMB, SMP, and urease, invertase, and alkaline phosphatase activities), and increased buckwheat yields along with the increase in biochar application rates in both aeolian sandy and grey meadow soils. The BC3 treatment (60 Mg ha\(^{-1}\)) showed the highest improvement of soil properties and buckwheat yields for both soils. The buckwheat yield increased by 21.84%, 24.48%, and 21.21% in sandy aeolian soil and by 17.02%, 15.30%, and 11.92% in grey meadow soil in the BC3 treatment compared to their control groups in 2020, 2021, and 2022, respectively. The increase in buckwheat yield in aeolian sandy soil was found to be primarily driven by the enhancement of soil available nutrients, while in grey meadow soil, the soil microbiological properties play a significant role in influencing buckwheat yield. However, the positive effects were stronger in aeolian sandy soil than in grey meadow soil. The incorporation of biochar appears to be a sustainable approach for enhancing soil quality in both degraded aeolian sandy and grey meadow soils, particularly in regions with a semi-arid climate worldwide. Given the complex interactions between soil types and biochar application rates regarding the residual effects of biochar, further investigation involving interdisciplinary collaboration is recommended to assess long-term changes in soil quality and productivity.

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Abbreviations

The following abbreviations are used in this manuscript:

- SWS: Soil water storage
- SOM: Soil organic matter
- AN: Available nitrogen
AP  Available phosphorus
AK  Available potassium
SMC  Microbial biomass carbon
SMN  Microbial biomass nitrogen
SMP  Microbial biomass phosphorus
Ure  Urease activity
Int  Invertase activity
Alkp  Alkaline phosphatase activity
Yield  Grain yield

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