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Effects of lignite bioorganic product on sunflower growth, water and nitrogen productivity in saline-sodic farmlands at Northwest China

Zhijun Chen [a,b], Yue Li [b,c], Xuechen Zhang [b,c], Yunwu Xiong [b,c], Quanzhong Huang [b,c], Song Jin [d,e], Sun Shijun [a], Chi Daocai [a], Guanhua Huang [b,c,*]

[a] *College of Water Conservancy, Shenyang Agricultural University, Shenyang 110866, China*
[b] *Chinese-Israeli International Center for Research and Training in Agriculture, China Agricultural University, Beijing 100083, China*
[c] *Center for Agricultural Water Research, China Agricultural University, Beijing 100083, China*
[d] *Advanced Environmental Technologies LLC, Fort Collins, CO 80525, USA*
[e] *Department of Civil and Architectural Engineering, University of Wyoming, Laramie, WY 82071, USA*

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ABSTRACT

Continuous applications of lignite bioorganic fertilizer (LBF) to the field have achieved substantial improvements in soil physicochemical properties and crop yields in multiple regions throughout China. However, the effects of LBF on crop growth, and water and fertilizer productivity in saline-sodic farmlands were scarcely understood. Thus, in this study, a two-year field experiment with six treatments including a control treatment without any organic fertilizer (CK), a treatment amended with 21 t ha^{-1}sheep manure (SM), and four treatments amended with 1.5 (LBF1), 3 (LBF2), 4.5 (LBF3), and 7.5 t ha^{-1} (LBF4) LBF, was conducted in 2019 and 2020 in the Hetao Irrigation District (HID), an area known for its saline-sodic conditions located at the upper Yellow River basin, China. The results showed that the LBF2 and LBF3 treatments improved plant height, leaf area index, and dry biomass by 8–76.7 cm, 0.3–2.4, and 309–402 g plant^{-1}, respectively, in comparison with the CK treatment. The root length, root surface area, and root volume in the LBF2 and LBF3 treatment was 18.3–99.7 m, 464.6–2022.6 cm^2, and 7.6–46.4 cm^3 larger than that in the CK treatment, respectively. Average yield, water productivity, partial nitrogen productivity, and economical gain in the LBF treatments were up to 2.2 t ha^{-1}, 0.4 kg m^{-3}, 23.6 kg kg^{-1}, and 6100 Chinese Yuan ha^{-1}, respectively, substantially higher than those of the CK treatment. In addition, compared with SM treatment, the LBF2 and LBF3 treatments also significantly improved sunflower growth and water and nitrogen productivity. The results of structural equation model analysis and linear regression analysis showed that LBF2 and LBF3 treatments improved sunflower root growth mainly through improving absorption of soil nitrogen. Furthermore, the root indices had a significant positive relation with the sunflower yield, water productivity, and partial nitrogen productivity. The partial nitrogen productivity, water productivity, yield, and economic profits showed a quadratic relationship with the application rate of LBF. A comprehensive assessment of the partial nitrogen productivity, water productivity, yield, and cost versus economic suggested that an application rate of 3.0–4.0 t ha^{-1} of the lignite bioorganic fertilizer is optimal for achieving a sustainable improvement of crop yield, water productivity, and partial nitrogen productivity in saline-sodic farmlands.

1. Introduction

Soil salinization has become one of the key constraints for the sustainable development of global agriculture. Around the world, the total area of saline and sodic soil is approximately 397 and 434 million hectares, respectively (Ghosh et al., 2017). Every year about 1–2% of arable land is lost due to serious soil salinization in many regions, including Asia, Africa, North America, and other regions (Daliakopoulos et al., 2016). In saline-sodic farmlands, agricultural development was limited by soil salinization, low soil fertility and organic matter, and poor soil quality. Additionally, the loss of agricultural land is accelerating due to salination and overuse of mineral fertilizer. Therefore, ameliorative methods need to be taken to improve the crop productivity in saline-sodic soil for sustainable crop production and regenerative

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* Corresponding author at: Chinese-Israeli International Center for Research and Training in Agriculture, China Agricultural University, Beijing 100083, China.
E-mail address: ghuang@cau.edu.cn (G. Huang).

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In recent years, the application of organic amendments is considered as a promising practice to improve soil structure, hydrological functions, organic matter, microbial diversity and richness, carbon budget, and then crop production (Mahmood et al., 2017; Kalu et al., 2021). Many types of organic amendments, including farmyard manure, humic acid, and raw lignite or its products, were always applied to improve crop productivity (Amoah-Antwi et al., 2020). However, the different characteristics of those organic amendments, such as raw materials and production conditions, caused the different effects of organic amendments on crop growth. Moreover, the soil types, salinity conditions, and crops also resulted in different impacts of organic amendments on soils and crops (Erktan et al., 2020).

Farmyard manure (FYM) is one of the most widely used organic amendments, which is easily available and sustainable because it is derived from agricultural waste products without energy production processes (Siedt et al., 2021). Many studies have reported that applying FYM can increase soil organic matter and improve crop yield, and water and nitrogen productivity (Loper et al., 2010; Zhen et al., 2014; Zhang et al., 2015). For example, Iqbal et al. (2019) found that the application of poultry manure improved rice yield with high nitrogen use efficiency. Mahmood et al. (2017) evaluated the influence of FYM on maize yield and found that FYM (15 t ha^{-1}) increased soil organic carbon by 85%−90% and improved maize yield by 52%−77% in a Lyallpur soil with a pH of 7.0. However, Gai et al. (2018) had reported that the application of FYM decreased the nitrogen use efficiency in fluvo-aquic soil. In addition, Wang et al. (2021) was found that the water use efficiency of wheat was 5%−9% improved by the application of FYM, but the maize water use efficiency was decreased by 6%−10% in loam soil. Therefore, the performance of FYM on water and nitrogen use efficiency varies with soil types and crops. Moreover, the above studies had reported the influence of FYM on crop growth, water, and nitrogen productivity, but most of those studies were conducted in neutral or acid soil. There is still a lack of comprehensive analysis and understanding of if and how crop yield and water and nitrogen productivity are improved through the addition of FYM in saline-sodic soil.

Lignite, also named brown coal, was usually used for power generation, but its efficiency was very low (Akimbekov et al., 2020). However, lignite with physiochemistry properties, such as extensive surface area, complex porous structure, rich humic substances, and organic carbon, is considered a good amendment for improving crop production, especially for degraded lands (Akimbekov et al., 2020). In addition, the organic carbon in the lignite decomposed slowly and existed in soil for a long time, which could increase soil organic matter for a long time. Therefore, in recent years, lignite received attention from researchers as a potential soil conditioner to improve crop growth and water and nitrogen use efficiency (Tsetsegmaa et al., 2018; Amoah-Antwi et al., 2020). Studies have demonstrated that applying lignite or lignite fertilizer can improve soil organic matter, in turn increasing nutrient holding and water retention ability as well as crop yield and nitrogen use efficiency (Dubey et al., 2019; Sun et al., 2020). For instance, Saha et al., (2017, 2018) had reported that the application of lignite could delay the nitrogen release, and improve nitrogen retention in the soil, thus improving the nitrogen use efficiency of silver beet. Similarly, Schillem et al. (2019) reported that the application of lignite improved wheat growth, nitrogen and water use efficiency even at low application rates (5 t ha^{-1}). Although the application of lignite or lignite fertilizer has been demonstrated to improve crop and vegetable yields, water use efficiency, and nitrogen productivity, almost all those studies were conducted in normal farmland and few were conducted in saline-sodic farmland. In fact, sunflower is a widely planted crop in saline-sodic farmland. However, to the best of our knowledge, few researches on the impacts of lignite or lignite fertilizer on sunflower growth, water, and nitrogen productivity were conducted in saline-sodic farmland. Besides, the application rates of lignite or lignite fertilizer products were usually based on various recommendations by manufacturers (Little et al., 2014; Dyko et al., 2015; Tran et al., 2015). In studies of Nan et al. (2016), Schillem et al. (2019), and Akimbekov et al. (2020), the optimal application rates of lignite or lignite fertilizer were 1.5 t ha^{-1}, 5 t ha^{-1}, and 1 g kg^{-1} in a saline-sodic farmland soil without crops, in a medium sand soil with the growth of wheat in the greenhouse, and in a sandy loam soil with potato growth in the greenhouse, respectively. Therefore, the optimal application rate varies with soil types and crops. Above all, the influence of lignite or lignite fertilizer on sunflower growth, water, and nitrogen productivity, and their optimal application rates need to be further explored in saline-sodic farmland.

Thus, the purpose of this study was to investigate the effects of different organic amendments on sunflower growth, yield, and water and nitrogen productivity in saline-sodic farmlands. The experiment was conducted in the Hetao Irrigation District (HID), located in the upper Yellow River basin, China, where crop growth was severely constrained by salinization. In this study, sheep manure (SM) and lignite bioorganic fertilizer (LBF) were tested. We hypothesized that the application of LBF and SM would have a positive impact on sunflower growth and water and nitrogen productivity in saline-sodic farmlands. The specific objectives of our research are: (1) to assess the effects of LBF on sunflower growth; (2) to study the impacts of LBF on sunflower yield, water, and nitrogen productivity; and (3) to determine an effective application rate of LBF for crop yield, total economic gains, and water and nitrogen productivity in saline-sodic farmlands.

2. Materials and methods

2.1. Experimental site and experiment design

In 2019 and 2020, field experiments were conducted at Hetao Experimental Station of China Agricultural University (41°09′N, 107°39′E, 1042 ma.s.l), Bayannur city, Inner Mongolia Autonomous Region, China. The experimental site is characterized by a semiarid temperate continental climate. The annual mean temperature is 6.8 ℃, the mean annual precipitation is 160–180 mm, 50% occurring between July and September, and the mean annual potential evaporation is around 2200–2400 mm (Li et al., 2020b). In the study area, the average sunshine duration is about 3230 h and the frost-free duration is approximately 130 d with a maximum frozen depth of 1.2 m (Li et al., 2020a). According to the international soil classification system, the soil texture is silt loam in 0–60 cm soil depth and sandy loam in 60–100 cm soil depth. Basic physicochemical properties are summarized in Table S1. As shown in Table S1, the pH, exchangeable sodium saturation percentage (ESP), saturated electrical conductivity (EC$_e$), saturated sodium adsorption ratio (SAR$_e$), and soil bulk density are 9.4, 56 (mmoles l^{-1})$^{0.5}$, 9.3 dS m^{-1}, 16.3%, and 1.62 g cm^{-3}, respectively in 0–20 cm, indicating that the study area is saline-sodic farmland with poor physical and chemical properties. In 2019 and 2020, the groundwater table depth ranged from 1.3 to 2.6 m and 0.99–1.7 m, respectively. Meteorological information including rainfall, air temperature, wind speed at 2 m, and relative humidity were measured once every half an hour by an automatic weather station (HOBO U30, USA) that was placed at about 150 m from the experimental field. The details of rainfall and air temperatures during the sunflower growth period are presented in Fig. S1.

In the field experiment, six treatments: a control treatment without any organic fertilizer (CK), a treatment amended with 21 t ha^{-1} sheep manure, and four other treatments amended by lignite bioorganic fertilizer with 1.5 (LBF1), 3 (LBF2), 4.5 (LBF3), and 7.5 t ha^{-1} (LBF4), respectively. The application rate of 21 t ha^{-1} was recommended by local farmers and the rate of lignite bioorganic fertilizer was based on manufacturers' recommended value of 3 t ha^{-1}. Each treatment had three replications. All plots were arranged following a randomized block design in this study, and each plot had an area of 126 m^2 (7 m × 18 m).

The lignite bioorganic fertilizer (LBF) is a novel, biochemically processed lignite product. It has been certified by the OMRI and EU as an organic fertilizer and soil conditioner (provided by Apaxfon Bioscience and Technologies Ltd., CO, “Apaxfon”, Baotou, Inner Mongolia, China). LBF is produced with lignite through a series of physicochemical and biochemical reactions. Based on analytical data from Apaxfon, it contains a portfolio of organic compounds, ranging from large humic matter to small soluble organic acids. The basic properties of LBF and SM are listed in Table S1. The sunflower (Guaner No.1), which is the common crop planted in saline-sodic farmlands, was sowed on June 2nd and harvested on September 16th in 2019; it was sowed on June 5th and harvested on September 18th in 2020. The entire growth period of the sunflower was divided into four growth stages including seeding, budding, flowering, and maturing stage. The details regarding the growth stages of sunflower in 2019 and 2020 are listed in Table S2. The wide-narrow row alternate model with a wide-row spacing of 100 cm and narrow-row spacing of 40 cm was adopted in this study, making the average row spacing of 70 cm. Plant spacing was about 50 cm with a plant density of approximately 28,500 plants ha^{-1}. The narrow row was covered by a black plastic film with a width of 70 cm and a thickness of 0.008 mm. SM and LBF were supplied as base fertilizer prior to seeding. Specifically, the LBF and SM were spread evenly over the experimental plot, and then the tillage method was adopted to mix LBF and SM with soil in 0–20 cm depth. For chemical fertilizer, 81.0 kg ha^{-1} N, 90.3 kg ha^{-1} P, 30 kg ha^{-1} K were applied before seeding and 25.2 kg ha^{-1} N, 9.2 kg ha^{-1} P, 5.0 kg ha^{-1} K was applied during the budding stage of sunflowers. The sources for the chemical fertilizers were $(NH_4)_2HPO_4$ and K_2O, respectively. In order to reduce the limitations of salinity and sodicity on crop emergence, 1800 m^3 ha^{-1} water from the Yellow River was applied to the field before seeding. There was no irrigation during the growing period of sunflowers. After the implementation of the leaching irrigation, the average EC and pH value was 0.38 dS m^{-1} and 9.7, respectively.

2.2. Sampling and measurements

2.2.1. Water consumption and productivity

The soil water content was measured by the gravimetric method (Li et al., 2021). Soil samples were collected using an auger every 10 cm for the 20 cm upper and every 20 cm from 20 to 100 cm in the middle of the plots every ten days during the sunflower growing season. Each treatment had three replications. Soil sample of each point was divided into two parts. One was for measuring soil moisture and the other was for measuring soil nutrients. The 0–100 cm soil layer was considered to calculate total water consumption of sunflower using the soil water balance method (Eq. (1)). The water use efficiency (WUE) was calculated using Eq. (2).

$$\mathrm{ET} = P + I + \Delta \mathrm{S} - \mathrm{R} + \mathrm{F} \tag{1}$$

$$\mathrm{WP} = \frac{Y}{10ET} \tag{2}$$

where ET is the total water consumption of sunflower, mm; P and R are the rainfall and runoff, respectively, mm; $\triangle S$ is the change of soil water storage in 0–100 cm soil depth, mm; F is the vertical soil water flux in the bottom boundary. The negative value means deep percolation and the positive means capillary rise, mm. WP is the water productivity, kg m^{-3}; Y is the sunflower yield, kg ha^{-1}. P during sunflower growth period in this study is 45.5 and 123.2 mm in 2019 and 2020, respectively. There was no heavy rainfall in the study area and each plot was surrounded by a 30 cm high ridge. No runoff was observed during the experimental periods, thus $R = 0$. F is estimated using the following equations.

$$\mathrm{F} = -\mathrm{K}(\theta)\left[\frac{\psi_{m,z_2} - \psi_{m,z_1}}{\Delta Z} + 1\right] \tag{3}$$

$$K(\theta) = K_s \times \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{0.5}\left\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m}}\right]^m\right\}^2 \tag{4}$$

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \frac{1}{\left[1 + (\alpha|\psi_m|)^n\right]^m} \tag{5}$$

where F is the compensation by capillary rise, cm; $K(\theta)$ is the hydraulic conductivity at soil water content of θ, cm d^{-1}; θ_s, θ_r, n, m, and α are the parameters of van Genuchten model, and there are 0.44 cm^3cm^{-3}, 0.09 cm^3cm^{-3}, 3.05, 0.67, and 0.01 cm^{-1}, respectively. K_s is the saturated hydraulic conductivity, 4.3 cm d^{-1} in this study. The values of K_s, θ_s, θ_r, n, m, and α were estimated using the soil particles distribution (Table S1) by the RETC software. $\psi_{m,z}$ is the matric potential at depth Z, and it can be estimated using Eq. (5). In this study, Z_1 and Z_2 are the soil depth of 80 cm and 100 cm, respectively.

2.2.2. Soil nutrient content

During the initial and mature stage of sunflowers in 2019 and 2020, soil samples in 0–100 cm soil layer were selected to determine soil available nitrogen (AN), available phosphorous (AP), and available potassium (AK) in 0–100 cm soil layer. In this study, the AN was the sum of NH_4^+-N and NO_3^--N, which was determined by an ultraviolet spectrophotometer (UV-3100, China). AK was determined by the ammonium acetate extraction-flame photometry method. AP was determined by the sodium bicarbonate extraction-Mo-Sb colorimetry method (Li et al., 2021).

2.2.3. Plant growth of sunflower

In this study, main sunflower growth indexes, including the leaf area index (LAI), plant height (cm), and dry biomass (g $plant^{-1}$), were selected to represent sunflower growth conditions. Three plants in each plot were selected for measuring LAI and plant height every 10 days. In order to avoid the edge effects, the three plants were chosen based on an even growth distribution and location, in other words, randomly selected from the middle area of the plot. All the leaves of the sunflower plant were cut down and the length and width were measured by a ruler. The leaf area index was calculated using Eq. (6) (Yang, 2019). The plant height of sunflower was measured by tapeline. After the measurement of LAI and plant height, the plants were cut down and put into the oven to de-enzyme (105 ℃) for 30 min before being dried to a constant weight at 85 ℃ for measurement of dry biomass. During the late maturing stage, sunflowers from a 10 m^2 area in each plot were harvested to measure yield.

$$\mathrm{LAI} = \frac{0.75 \times \mathrm{N} \times \sum \mathrm{W} \times \mathrm{L}}{\mathrm{A}} \tag{6}$$

where LAI is the sunflower leaf area index; N is the plant density of sunflower, plants ha^{-1}; W and L are the width and length of leaf, respectively, m; A is the area, m^2.

2.2.4. Root growth of sunflower

The impacts of the application of LBF and SM on sunflower roots were also considered in this study. Since most of the sunflower roots were concentrated in the 0–40 cm soil layer, root samples in the 0–40 cm soil layer were taken in this study. Root samples within an area of 40 cm × 40 cm around the root were dug out by a spade from 0 to 40 cm soil layers during each stage of the sunflower (budding, flowering, and maturity). All root samples were carefully washed and then scanned by a scanner (Epson Perfection V700). The root length, surface area, and diameter of the sunflowers were calculated by WinRHIZOPro software 2013e (Regent Instruments, 2013).

2.2.5. Partial nitrogen productivity and net profits

The partial nitrogen productivity (PNP) was calculated based on the ratio of sunflower yield to supplied nitrogen. The net economic profits of treatments with the application of LBF and SM were calculated using Eq. (7).

$$NP = kAY - F_1 - F_2 \quad (7)$$

where k is the price of sunflower, 8.0 CNY (Chinese Yuan) kg^{-1} was used in this study for local price; AY is the achene yield of sunflower, kg ha^{-1}; F_1 is the price of LBF or SM, 3000 CNY t^{-1} for LBF and 800 CNY t^{-1} for SM; F_2 is the cost of seed, plastic film, and inorganic fertilizer, 3150 CNY ha^{-1}.

2.3. Statistical analysis

Data in this study were statistically analyzed by one-way ANOVA with randomized block design using the *agricolae* package in R language software. The principal component analysis was conducted to comprehensively evaluate the application of LBF and SM on soil quality using Origin 2021 software. Structural equation modeling (SEM) for evaluating the direct and indirect correlations between the soil nutrient and root growth was performed in AMOS v.21.0 software (AMOS, IBM, USA).

3. Results

3.1. Soil nutrients and sunflower growth

The available nitrogen in the CK treatment was 5.7–69.1 kg ha^{-1} and 16.0–90.8 kg ha^{-1} higher than those in the SM and LBF treatments in 2019 and 2020 at the mature stage, respectively (Fig. 1). For available phosphorus, at the mature stage, the LBF2 to LBF4 treatments increased soil available phosphorus in 2019 and 2020, in comparison with the CK treatment, respectively. For available potassium, there was little difference in available potassium among the LBF treatments and the CK treatment at the mature stage in 2019 and 2020.

As shown in Fig. 2, the LBF3 treatment obtained the highest plant heights, about 16.3–32.3 cm and 19.7–76.7 cm higher than the CK treatment across all sunflower growth stages in 2019 and 2020, respectively. Following the LBF3 treatment, the LBF2 treatment had the second-largest plant height. Plant heights between the SM and CK treatments were similar. For LAI (Fig. 2C-D), the difference in LAI between the SM and CK treatments was marginally noticeable while the LBF2 and LBF3 treatments significantly increased LAI by 0.4–2.1 and 0.7–2.4 in 2019 and 0.6–2.1 and 0.3–2.4 in 2020, respectively, compared with the CK treatment. For dry biomass (Fig. 2E-F), across all growth stages of sunflower in 2019 and 2020, the dry biomass of the LBF2 and LBF3 treatments was higher than those of the CK and SM treatments. For example, at the mature stage of sunflower, compared with the CK treatment, the LBF2 and LBF3 treatments significantly increased dry biomass by 334.7 and 340.3 g plant^{-1} in 2019, and 309 and 412 g plant^{-1} in 2020, respectively. The LBF2 and LBF3 treatments markedly increased dry biomass by 181.8 and 187.4 g plant^{-1} in 2019, and 239 and 341.9 in 2020 g plant^{-1}, respectively, in comparison with the SM treatment.

As shown in Fig. 3, the highest root length was obtained in the LBF3 treatment across all sunflower growth stages in 2019 and 2020, with the sole exception of the budding stage during 2019. The root length in the LBF3 treatment was 39.2, 66.0, and 99.7 m longer than the CK treatment during the budding, flowering, and mature stages of sunflowers in 2019, respectively; those values were 22.2, 68.4, and 70.5 m in 2020, respectively. Following the LBF3 treatment, the LBF2 treatment had the second-longest root length during the growing period of sunflower in 2019 and 2020. For the root surface area, in comparison with the CK treatment, the LBF2 and LBF3 treatments significantly increased the root surface area by 636.1–717.9 cm^2 and 1031.5–1978.2 cm^2 in 2019 and 671–1215.3 cm^2 and 464.6–2022.6 cm^2 in 2020, respectively. The LBF2

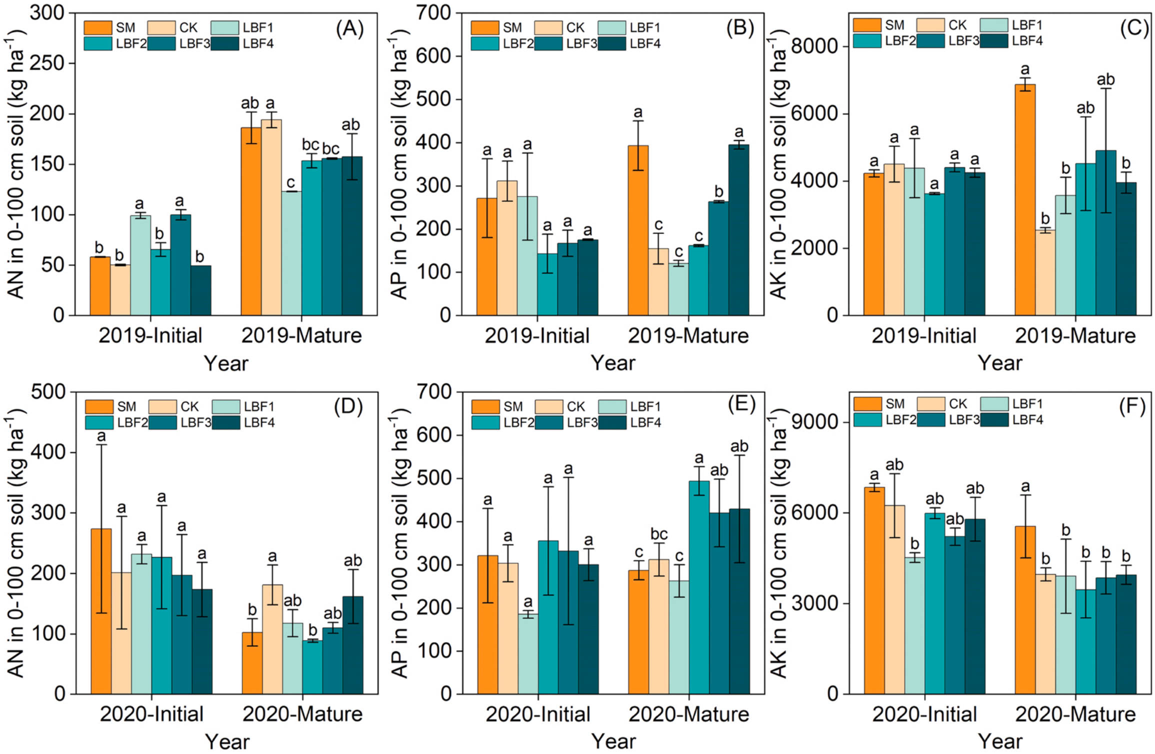

Fig. 1. Nutrients in the 0–100 cm soil varied with SM and LBF application at the initial and mature stage in 2019 and 2020. Note: CK represents the control treatment without organic fertilizer; SM represents farmyard manure treatment amended by sheep manure with 21 t ha^{-1}; LBF1-LBF4 represent four treatments amended by lignite bioorganic fertilizer with 1.5, 3, 4.5, and 7.5 t ha^{-1}, respectively; AN, AP, and AK represent available nitrogen, phosphorus, and potassium, respectively; Different letters above the columns indicate significant difference at $p < 0.05$ level; the vertical bars represent the standard error of mean (n = 3); A-C represent AN, AP, and AK in 0–100 cm soil layer in 2019, respectively; D-F represent AN, AP, and AK in 0–100 cm soil layer in 2020, respectively; Error bar represents standard error of means (n = 3).

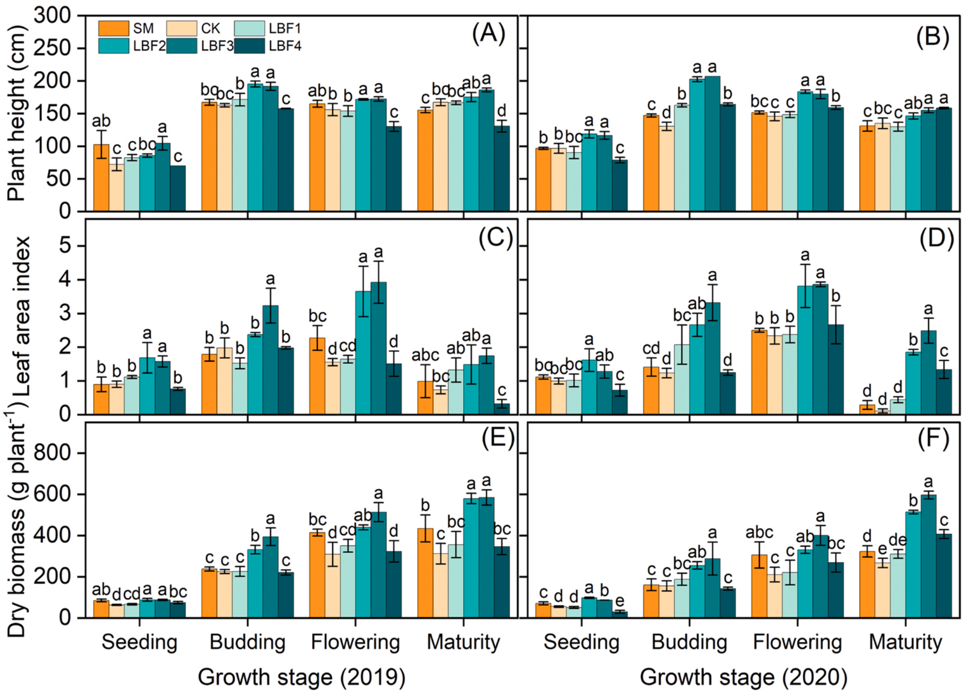

Fig. 2. Plant height (A and B), leaf area index (C and D), and dry biomass (E and F) of sunflower varied with SM and LBF application at different stages in 2019 and 2020. Note: CK represents the control treatment without organic fertilizer; SM represents farmyard manure treatment amended by sheep manure with 21 t ha^{-1}; LBF1-LBF4 represent four treatments amended by lignite bioorganic fertilizer with 1.5, 3, 4.5, and 7.5 t ha^{-1}, respectively; Different letters above the columns indicate significant differences at the $p < 0.05$ level; Error bar represents standard error of means (n = 3).

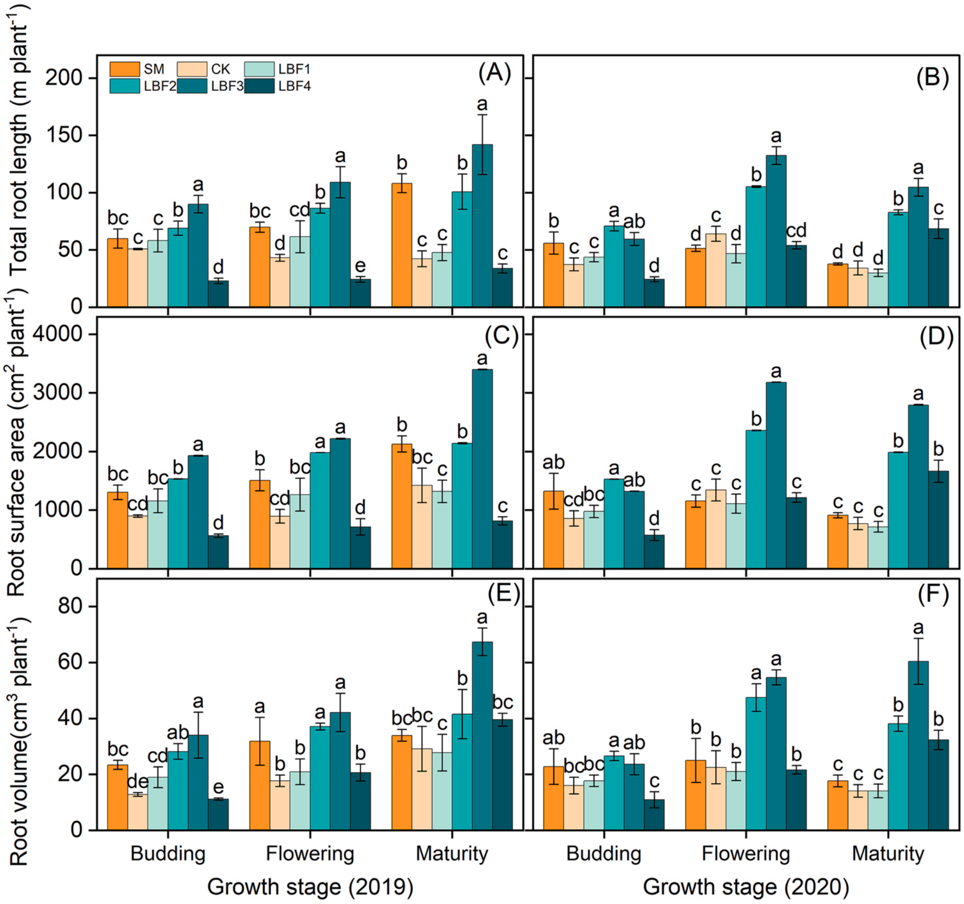

Fig. 3. Root length (A and B), root surface area (C and D), and root volume (E and F) of sunflower varied with SM and LBF application at different stages in 2019 and 2020. Note: CK represents the control treatment without organic fertilizer; SM represents farmyard manure treatment amended by sheep manure with 21 t ha^{-1}; LBF1-LBF4 represent four treatments amended by lignite bioorganic fertilizer with 1.5, 3, 4.5, and 7.5 t ha^{-1}, respectively; Different letters above the columns indicate significant differences at $p < 0.05$ level; Error bar represents standard error of means (n = 3).

and LBF3 significantly improved the root volume by 12.4–19.4 cm^3 and 21.1–38.2 cm^3 in 2019 and 10.6–24.1 cm^3 and 7.6–46.3 cm^3 in 2020, respectively, compared with the CK treatment. There was no significant difference in the root volume between the SM and CK treatments. Above all, the values of root growth indexes were the highest in the LBF3 treatment, followed closely by the LBF2 treatment.

3.2. Yield, partial nitrogen productivity, water productivity, and net profits

As shown in Table 1, compared with the CK treatment, the LBF3 treatment increased the yield by 2.5 and 1.9 t ha^{-1} in 2019 and 2020, respectively while the SM treatment only augmented the yield by 1.2 and 0.7 t ha^{-1} in 2019 and 2020, respectively. In addition, there was no significant difference in crop yield between the LBF2 and LBF3 treatment. Furthermore, the LBF2 and LBF3 treatments significantly improved the partial productivity of nitrogen by 19 and 23.6 kg kg^{-1} and 16.3 and 17.9 kg kg^{-1} in 2019 and 2020, respectively.

Table 1 also shows that compared with the CK treatment, the LBF2 and LBF3 treatments decreased sunflower water consumption by 114.5 and 273.9 mm and 95.8 and 223.5 mm in 2019 and 2020, respectively. The WP of the LBF2 and LBF3 treatment were 0.2–0.4 kg m^{-3} higher than that of the CK treatment. Compared with the SM treatment, the LBF2 and LBF3 treatments also decreased water consumption and improved the WP in 2019 and 2020. It is worth noting that the difference in sunflower yield between the CK and LBF4 treatment was scarcely noticeable, but water consumption in the LBF4 treatment was 475.4 and 123.1 mm lower than that in the CK treatment.

For net profits, the LBF2 treatment obtained the highest net profits with a value of 19.9 and 17.9 thousand CNY ha^{-1} respectively in 2019 and 2020, followed by the LBF3 treatment which was about 6.6 and 1.7 thousand CNY ha^{-1} higher than the CK treatment in 2019 and 2020, respectively. Compared with the CK treatment, the SM treatment reduced the net profits by 3.3 and 6.8 thousand CNY ha^{-1} in 2019 and 2020, respectively. Negative returns lied in the LBF4 treatment, implying that over-application of LBF can create a loss or deficit for farmers.

Table 1
Yield composition, partial nitrogen productivity, and net profit of sunflower in 2019 and 2020.

Year	Treatment	Yield (t ha^{-1})	ET (mm)	WP (kg m^{-3})	PNP (kg kg^{-1})	Net profit (Thousand Chinese yuan)
2019	SM	3.1 ± 0.4b	748.7 ± 26.7ab	0.4 ± 0.3 bc	28.9 ± 3.9b	9.4 ± 0.6c
	CK	2 ± 0.4c	779.3 ± 32.6a	0.3 ± 0.3c	18.7 ± 3.8c	12.7 ± 0.8 bc
	LBF1	3.1 ± 0.3b	474.8 ± 60.8c	0.7 ± 0.5a	29.5 ± 3.2b	17.4 ± 1.2ab
	LBF2	4 ± 0.7a	692.6 ± 33.3ab	0.6 ± 0.7ab	37.7 ± 6.6a	19.9 ± 1.3a
	LBF3	4.5 ± 0.4a	634.2 ± 26.7b	0.7 ± 0.7a	42.3 ± 4.2a	19.3 ± 1.3ab
	LBF4	1.9 ± 0.7c	304 ± 22.6d	0.6 ± 0.4ab	17.9 ± 6.5c	-10.4 ± −0.7d
2020	SM	2.7 ± 0.1 bc	731.2 ± 44.9a	0.4 ± 0.3a	25.1 ± 1.1 bc	6.2 ± 0.4b
	CK	2 ± 0.4c	665.5 ± 116.9a	0.3 ± 0.2a	19 ± 3.3c	13 ± 0.9a
	LBF1	2.8 ± 0.2b	537.8 ± 87.6a	0.6 ± 0.8a	26 ± 1.4b	14.4 ± 1a
	LBF2	3.8 ± 0.2a	761.3 ± 49.7a	0.5 ± 0.5a	35.3 ± 1.5a	17.9 ± 1.2a
	LBF3	3.9 ± 0.6a	840.5 ± 208.3a	0.6 ± 0.4a	36.9 ± 5.9a	14.7 ± 1a
	LBF4	2.1 ± 0.3 bc	542.5 ± 42.2a	0.4 ± 0.3a	20.2 ± 2.7 bc	-8.5 ± −0.6c

Note: Values in table are mean ± standard error of means (n = 3); Different letters in same column indicate significant difference at $p < 0.05$; ET, WP, and PNP represent water consumption, water productivity, and partial nitrogen productivity of sunflower; CK represents the control treatment without organic fertilizer; SM represents the farmyard manure treatment amended by sheep manure with 21 t ha^{-1}; LBF1-LBF4 represent four treatments amended by lignite bioorganic fertilizer with 1.5, 3, 4.5 and 7.5 t ha^{-1}, respectively.

3.3. Relationships among soil nutrients, sunflower root growth, and plant growth

The SEM was applied to evaluate the potential mechanism of soil nutrients on sunflower roots growth (Fig. 4). Fig. 4 A shows that the path coefficient between available nitrogen and root surface area was − 0.54. In addition, root surface area had significant positive path coefficients with root volume and length. Moreover, the standardized total effects of available nitrogen on root indices were all negative (Fig. 4B-D), indicating that there was a negative relationship between available nitrogen and root indices. A significant positive relationship between available phosphorus and root volume was found in the SEM, showing that available phosphorus had a significant positive influence on the root volume. Fig. 4 also shows that soil available potassium had no significant influence on root growth.

To further investigate the impact of sunflower roots growth on sunflower plant growth, the linear regression models were conducted and illustrated in Fig. S2. As shown in Fig. S2, all regression coefficients were significant at $p < 0.01$ level, indicating that root indices had significant influence on sunflower plant growth including plant height, LAI, and dry biomass. In addition, the explained variance of dry biomass, plant height, and LAI by root indices was 54–67%, 43–61%, and 27–42%, respectively, indicating that root indices had more influence on dry biomass than on plant height and LAI.

Fig. S3 shows that the root indices had significant impact on sunflower yield, water productivity, and partial nitrogen productivity. For sunflower yield and partial nitrogen productivity, the root indices explained over 50% of the variance of sunflower yield and partial nitrogen productivity, indicating that the sunflower yield and partial nitrogen productivity were largely impacted by roots growth. However, the root indices only explained 8–16% of the variance of water productivity, suggesting that root growth was not the main factor that impacted sunflower water productivity.

3.4. Relationships between application rate of LBF and Yield, NP, WP, and PNP

In this study, the yield and partial productivity of nitrogen both showed a quadratic relationship with the application rate of LBF, indicating that application of approximately 3.8 and 4.0 t ha^{-1} LBF would obtain the highest yield and partial productivities of nitrogen (Fig. 5A and D), respectively. The economical returns of the addition of LBF were calculated using the cost-benefit analysis method. The results in Fig. 5B shows that the optimal application rate of LBF to saline-sodic soil was 2.6 t ha^{-1} in which farmers could obtain 19.4 thousand CNY ha^{-1}. In this study, the quadratic function was also used to fit the water productivity versus the addition of LBF and showed that the optimal application rate of LBF was 3.3 t ha^{-1} in which the water productivity improvement was the best.

4. Discussion

4.1. Effects of lignite bioorganic fertilizer on sunflower growth

In recent years, some previous studies had explored the impacts of lignite or its commercial products on crop growth and yield (Chandrakant et al., 2019; Akimbekov et al., 2020). However, the impacts of lignite and its products on sunflower growth and yield in saline-sodic farmland were rarely evaluated. In this study, we found that the application of lignite bioorganic fertilizer with 3 and 4.5 t ha^{-1} had a significantly positive influence on plant height, leaf area index, and dry biomass in saline-sodic farmland (Fig. 2). This result indicated that the LBF also could be used for improving crops growth in saline-sodic farmland. The reason for this result was probably that application of LBF with optimal rate could increase the growth of sunflower roots. This explanation was proved by the results that the root length, surface area,

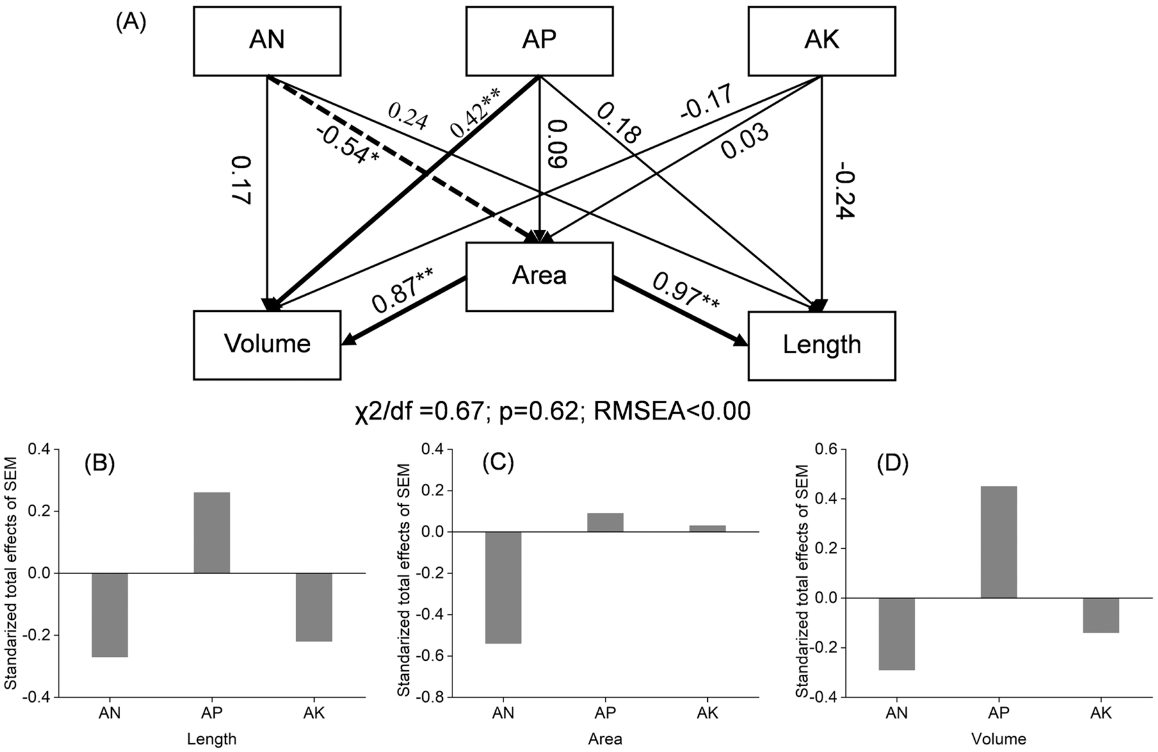

Fig. 4. The structural equation model showing the direct and indirect effects of soil nutrient on root growth. Note: AN, AP, and AK represent soil available nitrogen, phosphorous, and potassium, respectively; Volume, Area, and Length represent root volume, root surface area, and root length, respectively; The thick and thin lines arrows indicate significant and nonsignificant effects, respectively, and values next to the arrows represent the path coefficients; The solid and dashed lines arrows indicate positive and negative effects, respectively; SEM represents the structure equation model.

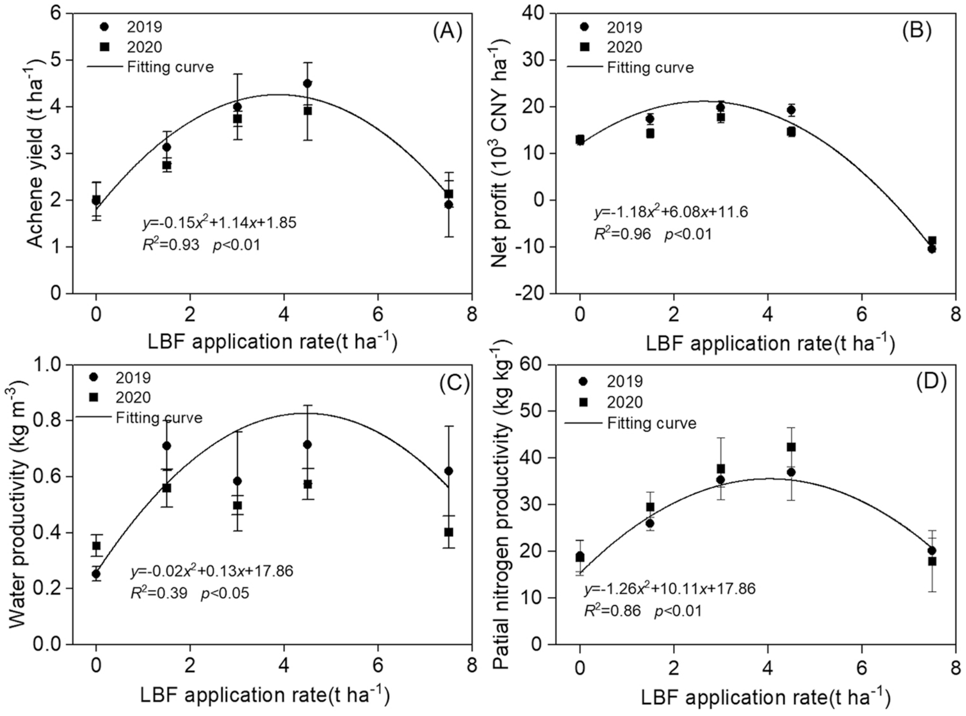

Fig. 5. Yield, net profit, water productivity, and partial nitrogen productivity varied with lignite bioorganic fertilizer application rate.

and volume had a significant positive relation with sunflower plant height, LAI and dry biomass (Fig. S2). However, previous studies about the effects of lignite or its products on crop growth scarcely focused on crop root growth. In this study, the results confirmed that the root traits, including root length, surface area, and volume, were all promoted by the application of the lignite bioorganic fertilizer with 3 and 4.5 t ha^{-1} (Fig. 2). There were two mechanisms for improved sunflower growth by amendment of LBF with optimal rate. Firstly, the application of LBF with an optimal rate could improve soil physicochemical properties, i.e., improving soil porosity and water stable aggregation, increasing soil organic matter, and decreasing salinity (Tsetsegmaa et al., 2018; Amoah-Antwi et al., 2020). Application of LBF with optimal rate improved soil physicochemical properties, because the LBF contains high organic matter, which could increase soil water stable aggregation and soil cation exchange capacity (Shao, 2006). The complex interpore structure of LBF also created pores between the lignite bio-organic fertilizer particles and surrounding soil aggregations, which could decrease soil bulk density and increase soil porosity structure (Li et al., 2021). All those improved soil physicochemical properties will inevitably affect crop root growth (Tsetsegmaa et al., 2018). Secondly, the nitrogen release rate is delayed by the application of LBF, which could increase the nitrogen uptake of sunflower roots (Saha et al., 2017, 2018; Amoah-Antwi et al., 2020). We found that soil available nitrogen content had a significant negative relation with sunflower root growth (Fig. 4). The reason for the negative relationship between soil available nitrogen content and sunflower root growth was probably that the sunflower roots increased the absorption of soil available nitrogen, which resulted in lower soil available nitrogen in the soil.

4.2. *Effects of lignite bioorganic fertilizer on sunflower yield and water and nitrogen productivity*

Studies had showed that the application of LBF had significant positive impacts on crop yield (Chandrakant et al., 2019). In this study, compared with the CK treatment, application of LBF with proper rate significantly improved sunflower yield. This result was similar to the result of Akimbekov et al. (2020) who found that the application of lignite-based fertilizer improved potato yield by 66.4%. However, in the saline-sodic farmland, the influence of LBF on sunflower nitrogen productivity and water use efficiency was scarcely explored. As expected, in this study, we found that the amendment of LBF with 3.0–4.5 t ha^{-1} significantly improved the partial productivity of nitrogen and water productivity in comparison with the CK treatment. The reason for this result was probably that application of LBF improved the sunflower roots growth. This explanation could be proved by the result in Fig. S3, in which the root length, root surface area, and root volume had a significant positive relation with sunflower yield, water productivity, and partial nitrogen productivity, and those three root indices could explain 55–67% and 56–68% variance of yield and partial nitrogen productivity, respectively. It is worth noting that the root growth only explained 8–16% of the variance of water productivity. This result showed that the water productivity was not mainly impacted by root growth in this study. It is reasonable because the root growth might directly impact sunflower transpiration, but soil evaporation was also impacted by soil properties in saline-sodic farmlands. Therefore, the influence of root growth on water productivity was lower than that on sunflower yield and partial nitrogen productivity.

Furthermore, in this study, we found that the water consumption of sunflower in the LBF3 treatments were significantly lower than that in the CK treatment in 2019 and there was no significant difference of water consumption of sunflower among the CK and LBF treatments. This result was reasonable because the total water consumption of sunflower was composed of evaporation and transpiration. The application of LBF with proper rate could improve sunflower growth and thus increased transpiration of sunflower in comparison with the CK treatment. In contrast, it also could result in more reduction of evaporation than the CK treatment did through increasing plant height and LAI (Fig. 2). Thus, there is a trade-off relation between sunflower transpiration and soil evaporation. The ultimately impacts of LBF on water consumption of sunflower may vary with different weather condition. It is worth noting that the difference in sunflower yield between the CK and LBF4 treatment was scarcely noticeable, but water consumption in the LBF4 treatment was lower than that in the CK treatment. A possible reason for this was that the LBF4 treatment increased soil salinity, in comparison with the CK treatment, which increased more accumulation of salinity on the soil surface that prevented soil evaporation. Moreover, the sunflower was rainfed in this study. This is similar to the study of Zhen et al. (2014). In fact, irrigation is necessary for crop production in the study area due to the semiarid temperate continental climate with an annual rainfall of 160 mm. However, according to our previous studies, most sunflower plants were heavily injured or died after irrigation during the growing season. The reason was probably that in heavy saline-sodic soils, the salt accumulated on the soil surface was dissolved by irrigation water, which caused serious salt stress in the root zone and this stress lasted for a long time due to the poor pore structure of saline-sodic soils. Therefore, no irrigation during the growing season has been widely adopted as common practice for sunflower growing in saline-sodic soils in the study area. The shallow ground water can provide enough water to meet the requirements of plant growth. However, to achieve high production, irrigation is still required for sunflowers planted in non-saline and slight saline-sodic soils in this study area. Moreover, in this study, compared with CK treatment, the SM treatment significantly improved the sunflower yield and nitrogen productivity (Table 1). However, the performance of SM for improving sunflower yield and nitrogen productivity in the saline-sodic farmland was more ineffective than that of LBF2 and LBF3 treatments. We attributed the improved performance of LBF to large stable organic matter and soluble organic acids, which improved soil quality and then improved absorption of soil nutrients (Nan et al., 2016; Pritchett et al., 2011). It is necessary to note that the LBF4 did not have a positive impact on sunflower growth, yield, and nitrogen and water productivity in the saline-sodic farmland. The reason for this result was probably that the LBF contains higher electrical conductivity than soil (Table S1). When the LBF was overused, it would increase soil salinity, which suppressed the growth of sunflower (Li et al., 2020).

4.3. *Appropriate lignite bioorganic fertilizer addition strategy*

Although it is often claimed that the application of lignite or its products could improve soil quality and thus increase crop growth and soil productivity, the application rate of lignite or its products was always recommended by manufacturers in many studies (Little et al., 2014). The appropriate application rate of those additions widely varied with crops and soils (Amoah-Antwi et al., 2020), and to our knowledge, few researchers studied the influence of LBF on sunflower growth in saline-sodic soils. In this study, we found that partial nitrogen productivity, economic returns, and water productivity all showed a quadratic relationship with the application rate of LBF. This is reasonable because inadequate application of LBF may have no significant influence on soil physicochemical properties, while overuse of LBF may increase soil electrical conductivity (Amoah-Antwi et al., 2020). The reason for improved partial fertilizer productivity, yield, economic returns, and water productivity by application of LBF with the optimal rate was mentioned above. Nevertheless, the higher pH and electrical conductivity of fertilizer itself could increase soil salinity and then decreased the partial productivity of nitrogen, yield, economic returns, and water productivity when it was overused (Li et al., 2021). In this study, we further found that from the relationships between the application rate of LBF and partial nitrogen productivity, yield, economic returns, and water productivity, the optimal application rate of LBF was 4.0, 3.8, 2.6, and 3.3 t ha^{-1}, respectively. Therefore, comprehensively considering the partial productivity of nitrogen, sunflower yield, economic profits, and water productivity, the appropriate application rate of LBF to saline-sodic soils was about 3.0–4.0 t ha^{-1} in this study. In addition, the LBF contains a rich humic substances, organic carbon, and complex pore structure, which continuously affect soil physicochemical properties (Amoah-Antwi et al., 2020). Therefore, the long-term application of LBF may obtain more effective impacts on soil physicochemical properties and crop growth.

5. Conclusion

In conclusion, the sunflower root growth and plant growth indices, including the root length, root surface area, root volume, plant height, leaf area index, and dry biomass, were significantly improved by the application of the lignite bioorganic fertilizer with 3.0 and 4.5 t ha^{-1}. Ultimately, average yield, water productivity, partial nitrogen productivity, and economical gain were improved by the application of lignite bioorganic fertilizer with 3.0 and 4.5 t ha^{-1} in comparison with the CK treatment. Although the addition of the farmyard manure improved sunflower growth, the improvement of sunflower growth in the treatments with bioorganic fertilizer of 3.0 and 4.5 t ha^{-1} was more beneficial than those in the treatments with farmyard manure. In addition, the partial nitrogen productivity, water productivity, yield, and economic profits showed a quadratic relationship with the application rate of Lignite bioorganic fertilizer. Based on the field data and a comprehensive assessment of the cost versus economic and water and nitrogen productivity, an application rate of about 3.0–4.0 t ha^{-1} of the lignite bioorganic fertilizer appears to be cost-effective and achieves a sustainable improvement of crop yield, economic returns, and water and partial nitrogen productivity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2022.107806.

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