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Modification of gasification slag-based functional soil for oat grass cultivation

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Gasification furnace slag is a substrate that can be used effectively in plant ecological restoration projects. Using this substrate can contribute to sustainable development in the ecological environment construction. This study used a gasification furnace slag sample as the matrix material of functional soil based on an evaporation experiment of functional soil and a pot experiment of oat grass. Therefore, fly ash, YJF (organic nutrient regulator), and SJJXWS (water retaining agent) amendments were applied to study the physical, chemical, and agronomic characteristics of the functional soil, such as the seedling emergence rate and plant weight. The results showed that the water evaporation capacity, pH, conductivity, bulk density, available phosphorus, available potassium, organic matter, and other relevant agronomic properties of the functional soil changed according to the amendment type used. Also, it was found that the functional soil amended with YJF and SJJXWS could promote plant growth compared to the control. The results of this study can provide a theoretical basis for further development of functional soil for ecological cycle restoration purposes.

KEYWORDS

gasification slag, functional soil, ecological restoration, physicochemical properties, plants

Introduction

Globally, there are vast extensions of land due to factors such as coal mining, climate, and other factors (Harris, 2003; Feng et al., 2022) or issues with mountain weathering. Helan Mountain is located in the transition zone between the temperate grassland and desert in China (Gu et al., 2016). The annual precipitation distribution is uneven, and the precipitation is reduced (~209.2 mm) (Wu et al., 2021). The area is dry, with low precipitation rates yearly, which is extremely unfavorable for plant growth. Recently, economic development and human overpopulation are causing serious damage to this mountain (Deng et al., 2006), so there is an urgent need for the restoration of the area. Several restoration strategies have been designed and implemented in China, but these techniques have had little effect (Jiao, 2019). On the other hand, local power plants and chemical plants produce a large amount of coal-based solid wastes, such as gasification furnace slag and fly ash. According to previous data, the global output of fly ash has exceeded the amount of 600 million tons, while the global use rate of fly ash has been only 25% (Bhattacharya et al., 2021). Additionally, China produces more than 30 million tons of gasification furnace slag (Shi et al., 2022), polluting the environment (Roy et al., 2018). Therefore, there is a need to treat these wastes such as fly ash and gasification furnace slag. Plants can repair soil by extracting, immobilizing, or volatilizing toxic metals from the soil (Liu et al., 2021a; Bai et al., 2022; Yan et al., 2022).

Minerals contain many trace elements that can be used as fertilizers to promote plant growth (Benidire et al., 2021; Zhang et al., 2021). Therefore, several studies have been performed on the planting test of gasification furnace slag. However, gasification furnace slags have been used in a small amount as amendments in soil (Liu et al., 2021b; Xiang et al., 2022), which cannot solve the accumulation and pollution problems of coal-based solid wastes. Therefore, it is particularly important to study the influence of gasification slag as the main matrix of the functional soil for mountain restoration purposes.

The basic components of the common tillage layer of the soil are SiO_2, and Al_2O_3 (Rémon et al., 2014), which are similar to the composition of the fly ash and gasification slag (Wang et al., 2022; Xuan et al., 2022). In addition, the heavy metal content of the raw materials meets the requirements of the control index of ecological restoration risk elements (Ministry of Civil Affairs of the People's Republic of China, 2021). Therefore, it is feasible to use gasification furnace slag as the main matrix of the functional soil for mountain restoration purposes. Nearly 70% of the particles in gasification slags have a size larger than 250 μm (Song et al., 2018), which is about twice as large as the general agricultural soil particle size (110 μm) (Jayarathne et al., 2020). The particle size of gasification furnace slag is extremely large, which benefits plant root respiration. On the other hand, this fact can cause more porosity, which can lead to water loss (Zhang et al., 2020). In fact, the water retention characteristics of SJJXWS (water retaining agent) can easily solve this problem, thus promoting plant growth. The nutrient content of gasification furnace slag was poor, while YJF (organic nutrient regulator) can effectively improve the organic matter and unstable organic matter contents in the soil. This event could increase the content of organic carbon and nitrogen (Yan et al., 2007), and promote plant growth. Therefore, YJF could improve the nutrients in the gasification furnace slag treatment.

The raw material is also used to remove excessive heavy metals from industrial solid waste fly ash. However, its particle size (D50) is only 33.2 μm, which is smaller than the gasification furnace slag matrix (Wu et al., 2020). The small particle size of fly ash indicated that it has a large specific surface area and thus has a strong water holding capacity. Also, the nutrient content of the raw materials was higher than that of gasification furnace slag. Different proportions of fly ash and gasification slag were also selected to produce energy.

This experiment was conducted with the gasification slag as the main substrate to explore the influence of different factors and proportions on the functional soil suitable for mountain restoration. Specifically, the functional soil suitable for mountain restoration was determined according to the changes in plant growth and the physicochemical properties of the corresponding functional soil caused by adding amendments to the functional soil. The physicochemical properties of the functional soil analyzed in the present study included pH, bulk density, and organic matter, and the corresponding properties of plant growth conditions included seedling emergence rate, root length, plant height, chlorophyll, and plant weight.

Materials and methods

Raw materials

The gasifier slag and fly ash used in this experiment were supplied by Ningxia, and the YJF and SJJXWS were made in the laboratory. YJF was an organic nutrient conditioner, and SJJXWS was a water–retaining agent. The main compositions of gasification furnace slag and fly ash are shown in Table 1. The basic physicochemical properties of gasification furnace slag and fly ash are shown in Table 2. The particle size distribution diagram of gasification furnace slag and fly ash are shown in Supplementary Figure S1. The gasification slag's median particle diameter (D50) was 292.60 μm and the fly ash's median particle diameter (D50) was 39.45 μm.

Experimental design

The single-factor test method was used in this study. The characteristics of raw materials, 3 factors (YJF, SJJXWS, and fly ash), and 5 levels of experiments were considered. The experiments were done in triplicate (average and standard deviation). The test design is shown in Table 3. Table 3 shows the addition of different contents of YJF SJJXWS and fly ash additives in the gasification slag matrix.

Pot experiment

Oat grass (*Avena fatua L.*) (Gang and Zhang, 2019), a grass species with salt, alkali, cold tolerance, and drought resistance, was selected as the test grass species. This grass can grow rapidly and quickly turn the mountain slope green patches. The selected main matrix was the gasification slag after the removal of heavy metals. The content of the components is shown in Table 1. The content of heavy metals (Supplementary Table S1) met the requirements of the ecological restoration risk element control index (Supplementary Table S2). The content of heavy metals

TABLE 1 Composition analysis of the raw materials (XRF unit:%).

Raw material	SiO_2	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	Loss
Gasification slag	53.9	18.4	8.9	7.9	2.4	2.8	2.0	3.7
Fly ash	44.8	22.6	6.2	5.7	1.7	1.8	1.5	15.7

TABLE 2 Basic physicochemical characteristics of the raw materials.

Raw material	Moisture content %	pH	EC ($us\cdot cm^{-1}$)	Organic matter content ($g\cdot kg^{-1}$)	Available phosphorus content ($mg\cdot kg^{-1}$)	Available potassium content ($mg\cdot kg^{-1}$)
Gasifier slag	7.20	7.91	219.40	37.99	45.25	70.14
Fly ash	1.13	8.92	1880.00	63.40	95.11	155.34

TABLE 3 Experimental design.

Name	Experiment 1		Experiment 2		Experiment 3	
Matrix materials	Gasification slag		Gasification slag		Gasification slag	
Additive type/concentration unit	YJF/($t\cdot hm^{-2}$)		SJJXWS/($t\cdot hm^{-2}$)		Fly ash/ proportion (%)	
Number and concentration gradient	YCK	0	YCK	0	YCK	0
	YF1	10.5	YN1	0.03	YFL1-20	20
	YF2	13.5	YN2	0.06	YFL2-40	40
	YF3	16.5	YN3	0.09	YFL3-50	50
	YF4	19.5	YN4	0.12	YFL4-60	60
	YF5	22.5	YN5	0.15	YFL5-80	80

was measured according to the specification (Ministry of ecological environment of the people's Republic of China, 1998; AQSIQ of the PRC, 2008; Ministry of Ecology and Environment of the PRC, 2019). The total required gasification slag mass was calculated based on the area (1.00 hm^2), thickness (40 cm), and density of the gasification slag in the field test. Then, some amendments could be applied to calculate the amount added in the field test. In the specific pot experiment, 1 kg of functional soil was added to each pot, and then some amendments were applied (mass/mass). The ratio of the addition of some amendments of the pot experiment was changed to "mass/area" to match the common unit of the field experiment. Different amendments were added according to the test design table (Table 3) to perform the pot experiments for the effect of the amendments. The mixed functional soil was added to the pot, and 30 seeds were sowed at about 1–2 cm depth. The pots were watered weekly to maintain a water holding capacity higher than 15%. The seedling emergence rate was the percentage of the number of seedlings in each pot after 30 days of planting.

Determination of the physicochemical characteristics of the raw materials

The water content [drying method (Ministry of Agriculture of the People's Republic of China, 2016)], accumulated evaporation (weighing method), pH value [pH electrode method (Ministry of Agriculture of the People's Republic of China, 2006)], conductivity [conductivity meter (Ministry of environmental protection of the people's Republic of China, 2016)], organic matter content [ignition reduction method (Ministry of Environmental Protection of the PRC, 2015)], available phosphorus [combined leaching method (Ministry of Agriculture of the People's Republic of China, 2010)], available potassium (counting method), seedling emergence rate, root length, and plant height (ruler method), chlorophyll (chlorophyll meter) (Xu et al., 2021), and plant weight (weighing method) were determined. Plant agronomic characteristics were measured on the 30th day of planting. A ruler was used to measure plant height and root length, a vernier

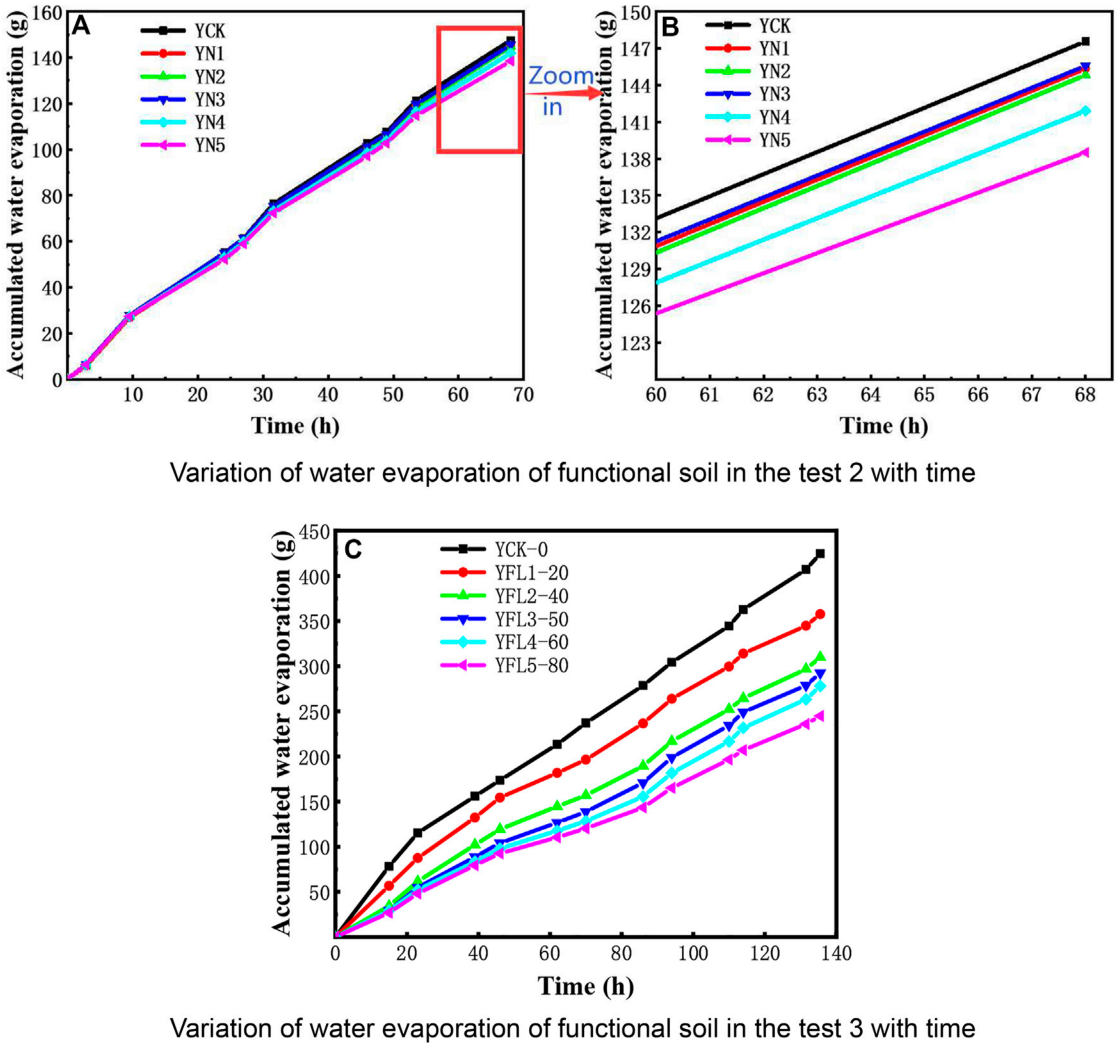

FIGURE 1
Variation of water evaporation of functional soil with time.

caliper to measure stem thickness, and analytical balances to weigh the plants.

The compositions of the gasification furnace slag and fly ash were assessed using the X–ray fluorescence (XRF) analysis, and the data was processed using the Origin (2018) software and SPSS (v. 26.0).

Results

Physicochemical characteristics of the functional soil

The water holding capacity of the soil is an important physical property. A strong water holding capacity is suitable for plant growth in arid areas (Kazen and Salar, 2022). Since the nutrient regulator in Test 1 (YJF) only affected the nutrient regulation with little effect on the water holding capacity of the functional soil, the water evaporation experiment was not performed. The difference in water evaporation capacity between different contents in the early stage of Test 2 was low, so the water evaporation experiment began when the water content was low. Specifically, Figure 1A shows the influence of SJJXWS on the evaporation characteristics of the functional soil matrix under the condition of Test 2, and Figure 1B is a partially enlarged view of the water evaporation experiment under the condition of Test 2. Figure 1C shows the effect of fly ash on the evaporation characteristics of the functional soil matrix under the conditions of Test 3.

TABLE 4 Experiment 1: Nutrient composition of the functional soil.

YJF content ($t{\cdot}hm^{-2}$)	Organic matter content/($g{\cdot}kg^{-1}$)	Available phosphorus content/($mg{\cdot}kg^{-1}$)	Available potassium content/($mg{\cdot}kg^{-1}$)
0.0	35.74 ± 1.17b	42.38 ± 3.92bc	72.42 ± 14.16b
10.5	39.64 ± 1.62a	55.183 ± 2.51a	90.91 ± 10.04b
13.5	33.04 ± 4.40b	48.42 ± 0.21ab	76.83 ± 27.82b
16.5	34.74 ± 1.54b	33.15 ± 7.99c	120.6 ± 8.17a
19.5	33.62 ± 1.45b	54.28 ± 4.17a	131.86 ± 12.42a
22.5	33.64 ± 0.77b	56.03 ± 8.12a	131.01 ± 2.60a

Different letters in the same column indicate significant differences ($p < 0.05$) based on a post-hoc test (Waller-Duncan k-ratio test).

TABLE 5 Experiment 2: Nutrient composition of the functional soil.

SJJXWS content ($t{\cdot}hm^{-2}$)	Organic matter content/($g{\cdot}kg^{-1}$)	Available potassium content/($mg{\cdot}kg^{-1}$)
0.00	21.74 ± 3.18b	69.75 ± 5.81ab
0.03	25.14 ± 3.09ab	53.84 ± 12.06bc
0.06	26.80 ± 4.02ab	49.81 ± 9.03c
0.09	30.20 ± 1.63a	67.50 ± 5.14bc
0.12	28.06 ± 5.27ab	63.11 ± 2.70bc
0.15	27.93 ± 3.18ab	87.59 ± 7.04a

Different letters in the same column indicate significant differences ($p < 0.05$) based on a post-hoc test (Waller-Duncan k-ratio test).

Both Test 2 and Test 3 showed that all factors had a certain impact on water evaporation. The water evaporation of the functional soil matrix increased under different factors as time increased. Test 2 (level = SJJXWS) showed that the water evaporation of functional soil matrix gradually decreases with the increase of this factor level. When the SJJXWS content reached level 5, the accumulated water evaporation was minimal. SJJXWS was a water-retaining agent and improved the water-holding capacity of the functional soil matrix. In Experiment 3 (fly ash), the accumulated evaporation of the water from the functional soil matrix generally decreased as the fly ash proportion increased. This finding implied that the water holding capacity of the fly ash was higher than that of the gasification slag due to the small particle size and large specific surface area of the former. Therefore, a large amount of fly ash could lead to a high water holding capacity of the functional soil matrix.

The physicochemical characteristics of the functional soil under different factor levels are shown in Tables 4, 5, and Figure 2. Figures 2A–C shows that the pH of the functional soil in the control group was 7.63. Under the influence of various factors, the pH change ranges of the functional soil in Test 1, Test 2, and Test 3 were 7.63–7.87, 7.63–8.25, and 7.63–8.52, respectively. Therefore, the pH of the tested functional soil showed an increasing trend. The reason is that YJF is an organic nutrient regulator with a high pH, so it can improve the pH of functional soil. SJJXWS is an alkaline water retaining agent, which can turn the soil to an alkaline condition (Yang et al., 2005; Xing and Yang, 2019). Table 2 shows that the pH of fly ash was higher than that of functional soil with the gasification slag as an amendment. In addition, the pH of the functional soil in Test 3 was gradually increasing as the fly ash proportion increased.

Figures 2A–C shows that the conductivity of functional soil in the control group was 191.53 us cm^{-1}. Under the influence of various factors, the conductivity ranges of the functional soils were 191.53–523.75 us cm^{-1} in Test 1, 191.53–280.67 us cm^{-1} in Test 2, and 191.53–1048.50 us cm^{-1} in Test 3. Therefore, the electrical conductivity of the test functional soils showed an increasing trend. In this case, the YJF acted as an organic nutrient regulator with high salt content, increasing the salt content of the functional soil and its conductivity. As mentioned before, SJJXWS is a water retaining agent. The carboxyl group with strong water absorption in the water retaining agent can exchange with the ions adsorbed in the soil after mixing with the soil, thus increasing the conductivity (Lan and Chen, 2015). Table 2 shows that the conductivity of the fly ash is higher than that of the functional soil matrix gasification slag. Consequently, the conductivity of the functional soil in Test 3 was gradually increasing with the increasing proportion of the fly ash.

Figure 2C shows that the unit weight of the control functional soil was 1.461 g cm^{-3}. In this case, the weight values of the functional soil in both Test 1 and Test 2 did not change significantly. However, the weight of the

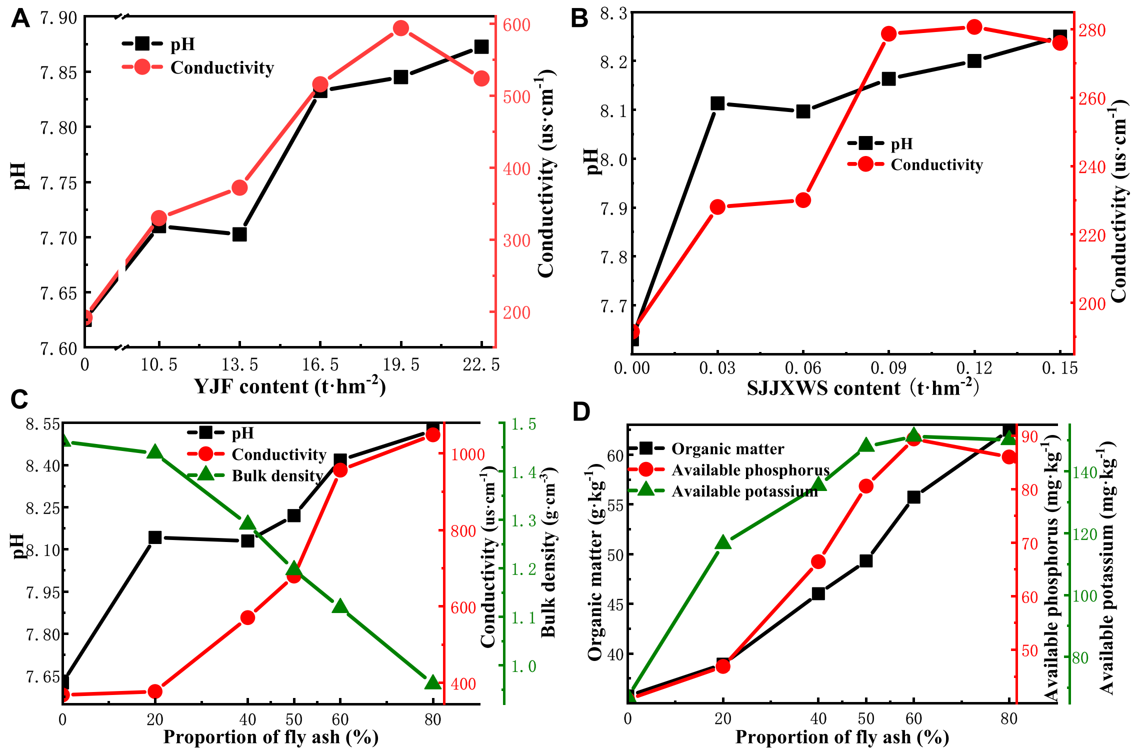

FIGURE 2
Physicochemical properties of the functional soils.

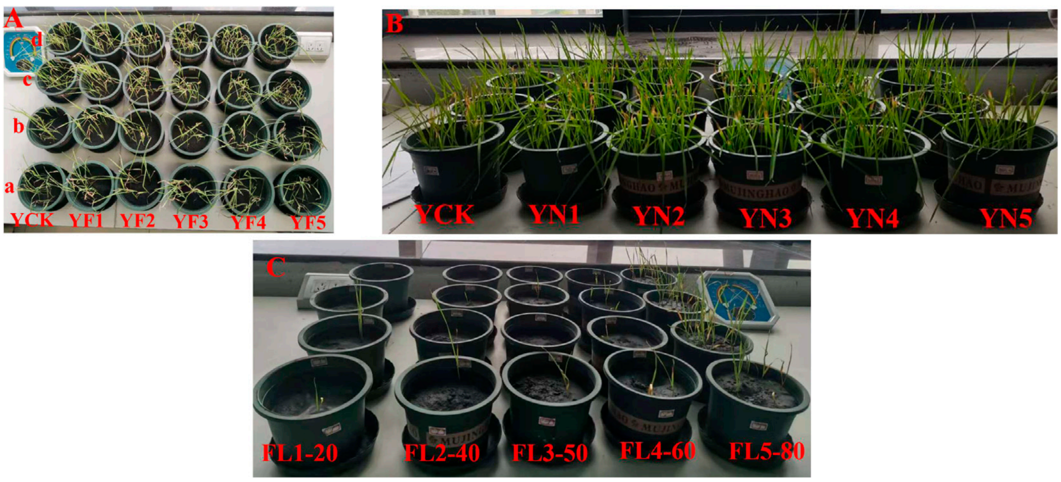

FIGURE 3
Plants used for three experiments on Day 30.

functional soil in Test 3 changed significantly, with a range of 0.961–1.461 g cm^{-3}. YJF and SJJXWS accounted for a low proportion of functional soil, so they have little effect on the bulk density of the functional soil. In Test 3, the volume density is smaller than that of gasification furnace slag because the density of the fly ash is small. Therefore, the volume density of the functional soil was gradually decreasing with the proportional increase of fly ash.

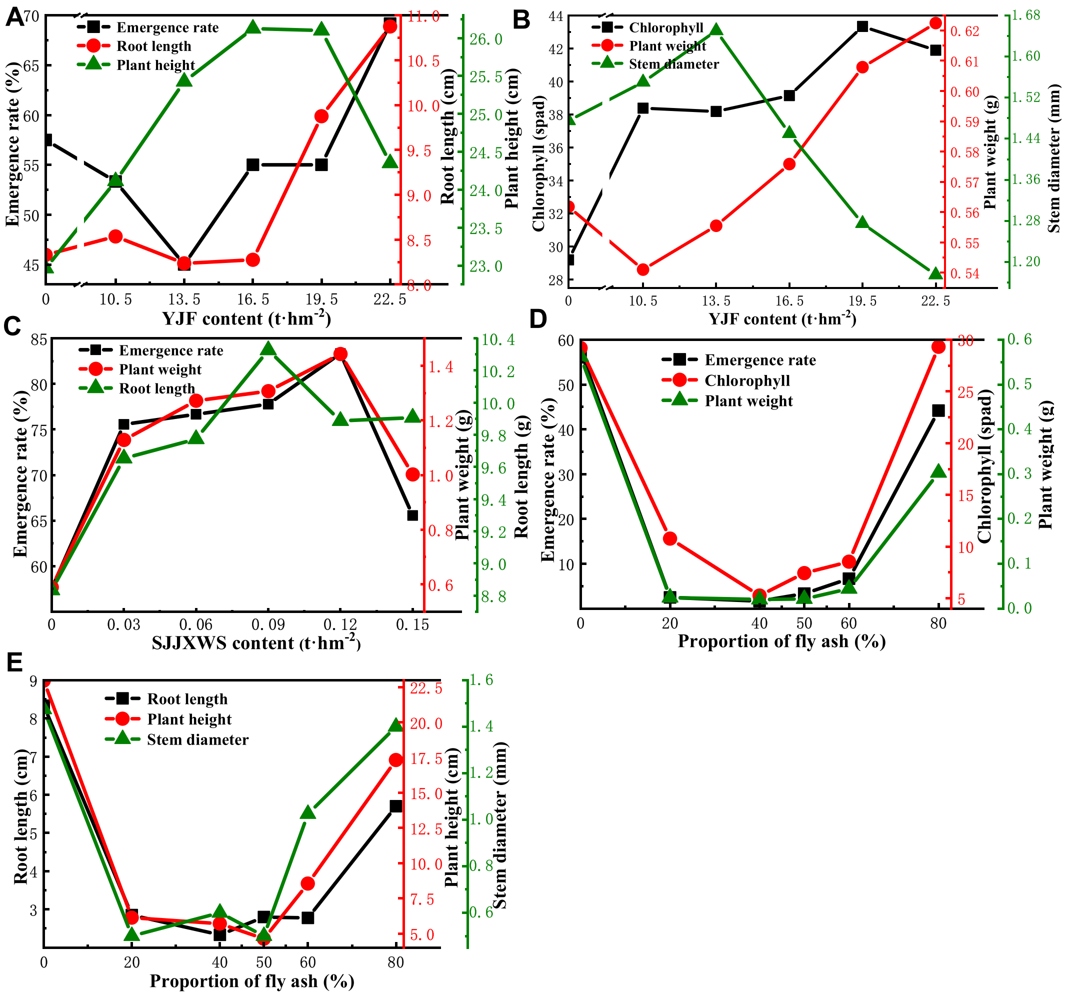

FIGURE 4
Agronomic characteristics of the plants in the functional soils used in this study.

Tables 4, 5 and Figure 2D show that the organic matter of the control functional soil was 37.99 g kg^{-1}. The organic matter content of Test 1 and 2 did not change significantly, and the organic matter of Test 3 showed a gradually increasing trend. The organic matter content of fly ash was higher than that of the gasifier slag-amended functional soil. Furthermore, the organic matter content of the functional soil gradually increased with the increase of the proportion of fly ash. The changes in the available phosphorus and potassium contents of Test 1 were insignificant, and the change in available potassium of Test 2 was also not significant. The contents of available phosphorus and potassium in the three functional soils varied from 40.71 to 89.38 mg kg^{-1} and 67.04–151.29 mg kg^{-1}, respectively, showing an increasing trend. This event could gradually reduce the available phosphorus content of the original functional soil. Furthermore, the content of available phosphorus and potassium in fly ash was higher than that of the gasification slag. Therefore, the content of available phosphorus and potassium gradually increased with the proportion of fly ash.

Agronomic characteristics of the plants in the functional soils

The seedling emergence rate reflects the soil quality to a certain extent (Editorial Board of the Agricultural Dictionary, 1998). Moreover, the chlorophyll content can characterize the nutritional status of plants. It is also an indicator of plants under stress and interference of external environmental factors, which can reflect the production capacity of the plants (Gong et al., 2014). Plant height, root length, stem diameter, and plant weight all reflect the growth status of plants to a certain extent and can also reflect the quality of functional soil. Figures 3A–C show pictures of the plants used in this study for Test 1, Test 2, and Test 3, respectively.

Figure 4 shows that the emergence rate of the corresponding plants in the control was 57.50%. Experiment 1 shows that the emergence rate of the corresponding plants in the functional soil varied from 45% to 69.17%, and showed a decreasing trend and then an increase. Experiment 2 showed that the range of plant emergence rate was 57.50%–83.33%, and the trend was the opposite of Experiment 1. In Experiment 3, the corresponding plant emergence rate range was 1.67%–57.50%, showing the same trend as Experiment 1. On the other hand, YJF, as an organic nutrient regulator, did not change significantly at the beginning due to its low dose. However, the nutrient content of functional soil increased with the dose. The seedling emergence rate was higher. The plant weight, root length, and chlorophyll also increased (Figure 4). Conversely, the amount of potting soil will limit the growth of plants (Shi et al., 2010). The stem diameter decreased due to the limited nutrients available in the pot, even though the seedling emergence rate of plants in the early stage was high. In the case of the SJJXWS-treated soil, the water was retained in the gasification furnace slag-amended functional soil, resulting in a good living environment for the functional soil. The growth of plants and the seedling emergence rate were improved. However, the seedling emergence rate decreased at high SJJXWS contents. The excess of this water-retaining agent could cause the saturation of the functional soil, which could hinder plant respiration, reducing the seedling emergence rate. Also, the plant weight and root length increased first and then decreased. Since the density of fly ash is far less than that of the gasification furnace slag and the particle size ratio of the fly ash and gasification furnace slag was different, the soil evenness index (Huang et al., 2014) changed after the two components were mixed. In general, when the proportion of fly ash was 0%, the evenness index of functional soil was 1. Also, the average evenness index of soil particles was the smallest, the soil texture was optimal and conducive for plant growth. Conversely, when the proportion of fly ash was 50%, the soil evenness index was the largest. The texture was also the worst, which is the most unfavorable condition for plant growth at this time (Chen et al., 2012). Then, the soil evenness index also was small with the continuous increase of the fly ash.

Discussion

YJF is an organic nutrient regulator rich in nitrogen, organic matter, phosphorus, potassium, and other nutrients (Zhao et al., 2022). This component can improve the salt content and pH of functional soil and provide nutrient conditions for the functional soil. This effect was corroborated because the electrical conductivity and pH value increased with the increase of the YJF content. The plant height, chlorophyll, and weight increased with the increase of YJF content, which implied that YJF could effectively promote the growth of plants on functional soils.

Regarding SJJXWS, as a water-retaining agent, it could not provide a considerable amount of nutrients for plants. Nevertheless, it compensated for the large water loss caused by the high porosity of the gasification furnace slag (Zhao et al., 2016). Test 2 showed that SJJXWS could effectively reduce the water evaporation capacity of functional soil. However, excessive water retaining agents can also fill all the pores of functional soil, affecting plant growth. This study evidenced that the emergence rate, plant weight, and root length of the corresponding plants in Test 2 increased first and then decreased with the increase of SJJXWS content. It shows that SJJXWS can effectively promote the growth of plants on functional soil in the range of 0–0.12 t hm^{-2} within the test range.

Test 3 showed that the particle size of fly ash was smaller compared with that of the gasification slag, and it had a high specific surface area. Consequently, the water evaporation capacity of the functional soil will be reduced. This event was verified from the water evaporation experiment in Test 3, so the water evaporation capacity decreased with the increased proportion of fly ash. On the other hand, fly ash also has some nutrients, such as phosphorus, potassium, and organic matter, which can provide nutrients for functional soil. The phosphorus, potassium, and organic matter contents of the three functional soils proportionally increased with the fly ash content. However, in the last pot experiment (Experiment 3), the growth trend of plant characteristics such as seedling emergence rate, plant weight, chlorophyll, plant height, root length, and stem diameter decreased first and then increased with the increase of the proportion of fly ash. The proportion of fly ash and gasification furnace slag changed the texture of the functional soil from optimal to non-optimal and *vice versa*. The influence of the texture of functional soils on plant growth is far greater than the advantages of the influence of nutrients and bulk density of functional soil *per se*.

Conclusion

1) The addition of YJF to the gasification furnace slag as a substrate benefits plant growth.
2) It is beneficial for plant growth to add SJJXWS into the functional soil with gasification furnace slag as substrate.
3) Adding SJJXWS into functional soil with gasification furnace slag as a substrate can reduce water evaporation.
4) In Test 3, it was found that the texture of functional soil was crucial for plant growth, which was far greater than the effect of functional soil nutrients.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

TL: writing-original draft, investigation, formal analysis, visualization; FH: writing-review and editing, supervision, project administration, funding acquisition; BY: investigation, formal analysis; ZX: investigation, formal analysis; JW: investigation, formal analysis; XD: writing-review; CA: investigation, supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1053760/full#supplementary-material

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