

Article

Physicochemical Properties and Planting Performance of Artificial Soil Developed from Multiple Coal-Based Solid Waste Materials

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Abstract: Using coal-based solid waste (CSWM) to develop artificial soil (AS) can solve the shortage of planting soil in mine ecological restoration and realize the resource utilization of solid waste, which is a very promising research direction. This study used three common CSWM, coal gangue (CG), fly ash (FA), and desulfurization gypsum (DG), to prepare AS. The physicochemical properties of AS, such as bulk density, specific gravity, porosity, field water capacity, available nutrient content, pH value and EC value, were studied. Simultaneously, *Elymus dahuricus* was utilized in pot experiments to explore the planting performance of AS. Results show that, as the CG content decreased, the specific gravity of AS decreased, and the porosity increased. Both field capacity and saturation capacity demonstrated a notable upward trend. The results of pot experiments showed that plant growth was best when the CG content in AS was 80% and the FA and DG content was 20%. In comparison to the control group consisting of pure CG, the plant biomass in the optimal experimental group exhibited a significant increase of 20.48%. This study verified the feasibility of making AS by combining various CSWM, and provides a new pathway for ecological restoration and resource utilization in mines.

Keywords: artificial soil; coal-based solid waste materials; physicochemical properties; planting performance



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1. Introduction

The total annual coal production in China is about 4 billion tons, resulting in a huge amount of CSWM generated in the process of coal development and utilization [1]. These materials include coal gangue (CG), fly ash (FA), desulfurization gypsum (DG), gasification slag, and bottom ash [2]. The issues associated with the disposal of these CSWM remain severe; the majority of the remaining CSWM is directly deposited and landfilled, resulting in serious environmental contamination [3,4]. Further improving the resource utilization efficiency of CSWM has become an urgent need for the development of a low-carbon society. Simultaneously, it is noteworthy that the middle and upper reaches of the Yellow River Basin serve as the primary coal reservoir [5,6], contributing to around 41.7% of China's overall coal production. However, the region mostly experiences a semi-arid and arid climate, leading to significant issues in land desertification and ecological degradation. The current ecological restoration of mines is encountering significant problems related to limited soil supplies. Therefore, the purpose of this study was to develop AS using CG, FA, and DG, so that it can be applied in mine ecological restoration. The high-value utilization of coal-based solid wastes has been studied not only on a laboratory scale, but also in pilot tests. The test results reached the laboratory level [7,8].

Currently, there is a wide range of research being conducted on the disposal and use of CSWM. The predominant research and application fields of CG are in engineering

fillers [9,10]. These fillers are typically employed in engineering applications such as mine backfill, subgrade fill, and foundation pit backfill. In addition, numerous researchers have conducted investigations into the viability of using CG to make construction products, including cement [11,12], ceramics, sintered bricks, and lightweight aggregates for concrete [13,14]. Additionally, numerous studies have demonstrated that the mineral composition of CG is similar to that of soil and that it also contains a significant amount of nutrients and trace elements [9]. Moreover, the organic matter content in CG is usually 2–10 times that of soil, which is very favorable for plant growth [15,16]. So, some scholars have conducted research on the production of soil amendments and fertilizers derived from CG [16]. FA is the primary solid waste generated by coal-fired power plants. It possesses favorable volcanic ash properties, making it predominantly utilized as an additive in cement and concrete production [17]. Numerous studies have demonstrated that FA serves as an effective soil conditioner, leading to notable enhancements in the physical structure, chemical properties, and microbial environment of soil. FA can also provide the macronutrients and micronutrients required for plant growth [18]. It was found that the application of modified FA had a positive effect on the remediation of heavy metals in sodium-containing soil. This application could improve soil pH value, enhance soil water retention capacity and promote the formation of soil aggregates [19]. DG is extensively utilized in the field of agriculture, proving its efficacy in enhancing the physical and chemical characteristics of soil. It has been observed to effectively regulate the loss of soil nutrients and replenish trace elements in the soil, thereby improving crop yields [20–22]. Moreover, DG has demonstrated significant potential in ameliorating saline-sodic soils, resulting in enhanced seedling emergence, reduced pH levels, and increased water retention capacity of the soil [22]. This study is also in line with the concept of the circular economy, as proposed by domestic and foreign scholars, with the goal of transforming waste into high-value materials and achieving resource sustainability [23,24].

In general, CG, FA, and DG exhibit favorable plant compatibility and can serve as effective soil amendments to enhance plant development. Consequently, these materials possess considerable potential for utilization in ecological contexts. However, previous studies mostly introduced these materials into the soil as external additives with the aim of enhancing soil characteristics. However, this approach does not adequately address the issue of insufficient soil resources for ecological restoration in mining areas. Indeed, it has been observed that CSWM, such as CG and FA [25–27], possess abundant mineral constituents such as aluminates, silicates, and oxides of iron and aluminum. These mineral components are close relatives to the natural soil. Hence, it is inferred that CSWM have the potential to be used as ecological soil, but there are few relevant studies. If these materials are suitable for direct use as planting soil in mining ecological restoration, it would enhance the efficiency of CSWM consumption and significantly conserve planting soil resources. In this study, three types of coal-based solid waste materials, CG, FA, and GG, were selected and mixed to prepare AS. The physicochemical properties of AS, including bulk density, specific gravity, porosity, field capacity, ammonium nitrogen (AN), effective phosphorus (AP), quick-acting potassium (AK), pH, and electrical conductivity (EC), were tested considering different raw material ratios. At the same time, Chinese *Leymus chinensis* was selected for planting experiment on AS to study the growth characteristics of this plant, including stem height, root length and biomass.

Coal gangue, fly ash and desulfurization gypsum are by-products of coal mines and coal-fired power plants and are often considered waste. By using these wastes for the preparation of artificial soil, the comprehensive utilization of resources is realized, the dependence on natural resources is reduced, and the problem of waste disposal is solved. It can reduce the exploitation of natural soil and help protect the natural environment. Some coal mine wastes have different physical and chemical properties, and by mixing and blending, the texture of artificial soil can be adjusted to make it more suitable for plant growth. This customized artificial soil can meet the specific needs of different plants for

soil and improve soil quality. Finally, the direction of this study was determined based on the lack of natural vegetation soil in the study area.

2. Materials and Methods

2.1. Materials

The raw materials of AS include CG, FA, and DG. The CG was sourced from Huangbaici Coal Mine located in Wuhai City, Inner Mongolia Autonomous Region of China. The CG was crushed by a jaw crusher for use. FA and DG were manufactured by Inner Mongolia Energy Power Generation Jinshan Thermal Power Co., Ltd. in Hohhot, China. Inner Mongolia Mengcao Seed Industry Co., Ltd. in Hohhot, China. provided *Elymus dahuricus* seeds. Table 1 presents the fundamental physical and chemical characteristics of the three materials. It is evident that CG contains significant amounts of organic matter and humus, which are highly beneficial for plant growth. However, FA and GG contain high concentrations of soluble salts, primarily Ca^{2+} and SO_4^{2-} , which may potentially have adverse effects on plant growth. The grading curves of the three raw materials are depicted in Figure 1. The figure shows that the median particle sizes of CG, FA, and DG were 0.0540 mm, 0.011 mm, and 0.018 mm, respectively.

Table 1. Physical and chemical properties of CSWM.

Characteristics		Standard	Method	CG	FA	DG
Basic Properties	pH	ASTM D4972-19 [28]	Electrode method	3.81	10.83	7.18
	EC ($\mu\text{S}/\text{cm}$)	ISO 11265:1994/cor 1:1996 [29]	Electrode method	1045	1442	2423
	Specific gravity	ASTM D854-23 [30]	Pycnometer method	2.42	3.16	2.19
	Bulk density (g/cm^3)	ASTM D1556 [31]	Sand-cone method	1.35	0.84	0.83
	Organic matter (g/kg)	ASTM D2974-20e1 [32]	High-temperature heating method	65.097	-	-
	Salt ion (g/kg)	ASTM D4542-15 [33]	Refractometer method	1.193	2.976	10.511
Nutritive element content (mg/kg)	AP	NY/T 1121.7-2014 [34]	Sodium bicarbonate leaching-molybdenum antimony colorimetry method	5.82	60.599	0.618
	AN	ISO 14255-1998 [35]	Calcium chloride extraction method	10.11	142.86	10.85
	AK	NY/T 889-2004 [36]	Amine acetate leaching-flame photometric method	202.830	44.867	67.582
Salt ion content (mg/kg)	Ca^{2+}	ASTM D4373-21	Volumetric method	6.849	200.249	874.407
	K^+	LY/T 1251-1999 [37]	Optical spectrometer	3.032	5.96	1.787
	Mg^{2+}	ASTM D4542-15	Optical spectrometer	4.196	3.465	33.370
	Na^+	ASTM D4542-15	Optical spectrometer	10.076	13.29	12.233
	Cl^-	ASTM D4542-15	Mohr procedure method	9.752	12.215	596.393
	SO_4^{2-}	ASTM C1580-20 [38]	Gravimetric analysis method	767.463	1879.98	8792.762
	CO_3^{2-}	ASTM D4373-21 [39]	Volumetric method	0.000	585.807	0.000

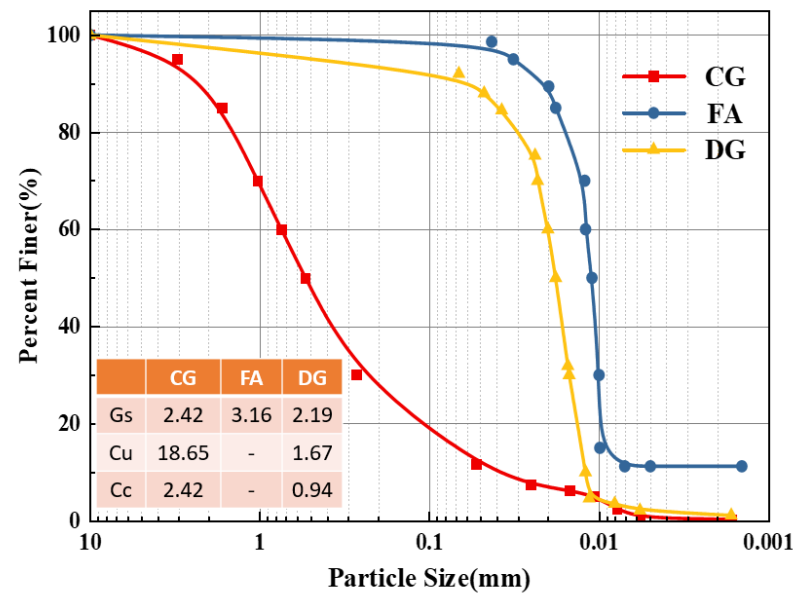


Figure 1. Grading curves of CSWM.

2.2. Test Methods

2.2.1. Pot Experiments

The three CSWM were initially air-dried to prepare the artificial soil (AS) according to the mixing ratios provided in Table 2. For each group of AS samples, 3 kg was taken and poured in layers into plastic tubs with the size depicted in Figure 2. The dry density of all potting soil was controlled at 1.65 g/cm³. The bottom of each pot was padded with rice husk to ensure proper soil aeration. Subsequently, we spread 5.0 g of *Elymus dahuricus* seeds evenly over the top surface of the potting soil. Then, we covered the seeds with a 0.5 cm layer of AS. All of the seeds were soaked in warm water at 40 °C for 12 h before sowing to enhance their germination rate. After sowing, we sprayed approximately 200 g of water into each pot to ensure that the potting soil was thoroughly dampened. Finally, the pots were placed in a room with an average temperature of 25 ± 5 °C, humidity of 55 ± 5%, and adequate lighting and ventilation for curing. During the curing process, the irrigation amount for each pot was controlled at 300 g of water per week.

Table 2. Experimental mixture proportions of AS.

Group	Test Number	Mass Proportion (%)		
		CG	FA	DG
1	C100	100	0	0
2	C80F10D10	80	10	10
3	C80F6.7D13.4		6.7	13.4
4	C80F13.4D6.7		13.4	6.7
5	C60F20D20	60	20	20
6	C60F13.3D26.6		13.3	26.6
7	C60F26.6D13.3		26.6	13.3
8	C40F30D30	40	30	30
9	C40F20D40		20	40
10	C40F40D20		40	20

Note: The code CxFyDz denotes that the AS contains x% CG, y% FA, and z% DG.

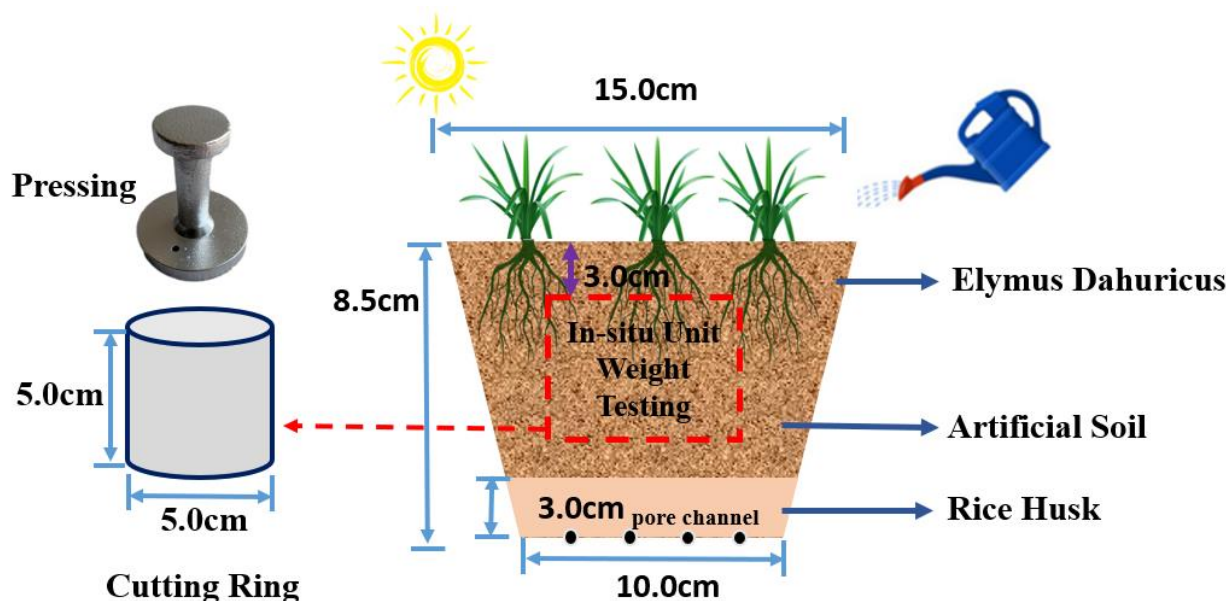


Figure 2. Pot design.

2.2.2. Planting and Maintenance

The quantity of water introduced corresponded to about 60–65% of the field capacity of AS, with a retention period of 12 h. We soaked all seeds in a 10% H_2O_2 solution for 10 min, then washed them with deionized water before sowing. All pots had drainage holes at the bottom and were sterilized with 75% ethanol and washed with deionized water before use. The seeds were delicately inserted into the AS using tweezers to a depth of 3–5 mm. Subsequently, the pots were enveloped in cling film to preserve moisture and warmth. The cling film was removed upon the observation of seed germination. In the first week, a daily application of 200 g of water was sprayed, while in subsequent stages, watering was reduced to once every 3 days. This experimental study lasted for 60 days.

2.2.3. Index Measurement

During the curing process, three representative plants were selected from each pot, and their stem height and root length were measured regularly with a ruler. The measurement times were set for the 10th, 20th, 30th, and 60th days, respectively. It is worth noting that plant extraction should be performed after watering to loosen the soil and ensure root integrity. After 60 days of planting, all of the plants in each pot were taken out, cleaned, and cut at the junction of the roots and stems, respectively. The roots and stems were then dried and weighed to determine the biomass of each. The prepared AS samples were sieved through a 2 mm screen, and then 10 g of each sample was taken out and mixed with deionized water at a solid–liquid ratio of 1:5. After shaking for 3 min and allowing the mixtures to stand still for 30 min, the pH and EC values were measured. The pH value was tested by the glass electrode method using a pH meter (PHS-3C, Leici-CN, Star A210, Thermo Fisher Scientific, Located in Waltham, MA, USA). All of the measurements were repeated three times for each group of samples. According to the ASTM D1556 standard, the bulk density of the AS in each pot after 2 months of planting was determined using the ring knife method. Before testing, the loose rhizosphere soil about 3 cm thick was removed from the top of the pot, and the lower soil was subsequently cut using a ring knife with a diameter of 61.8 mm and a height of 20 mm. During the extraction process, we ensured that the ring knife was completely filled with soil. The dry density of the cut soil was determined after drying it in an oven at 70 °C.

3. Results and Analysis

3.1. Analysis of Physicochemical Properties

3.1.1. Bulk Density, Specific Gravity, and Porosity

The changes in bulk density of the AS under different raw material ratios are shown in Figure 2. After 2 months of pot planting, the soil bulk density of the CK group (i.e., C100) was 1.44 g/cm³. The bulk density of AS was significantly influenced by the CG content. With the decrease in CG content, particularly when it was less than 60%, the soil bulk density of AS exhibited a significant decreasing trend. The ratio of FA to DG appeared to have little effect on the bulk density of AS. The bulk density of C40F30D30 was 1.15 g/cm³, which was the lowest.

Porosity is an indicator that characterizes the soil's capacity to store water and gas, providing an assessment of its permeability to air and water. The porosity of potting AS can be obtained by the following equation.

$$Pt(\%) = 100 \left(1 - \frac{rs}{ds} \right) \quad (1)$$

where: *Pt* denotes soil porosity; *rs* denotes bulk density; *ds* denotes specific gravity.

The calculation results for AS porosity in different pots are shown in Figure 3. It is clear that the porosity of potting AS increased significantly with the decrease in CG content. When the CG content was constant and less than 80%, decreasing the ratio of FA to DG was more beneficial for enhancing the porosity of AS. Compared to the CK group (i.e., C100), the porosity of AS increased by 10~12.3% when the CG content was 80%, and by 27.3~36.9% when the CG content was 40%. This suggests that as more FA and DG are added, the grain composition of AS will deteriorate, leading to a gradual increase in porosity. Based on particle analysis, it has been shown that CG is classified as coarse sand with a minimum porosity of 40.6%. This can be attributed to the tiny particle sizes of both FA and DG components.

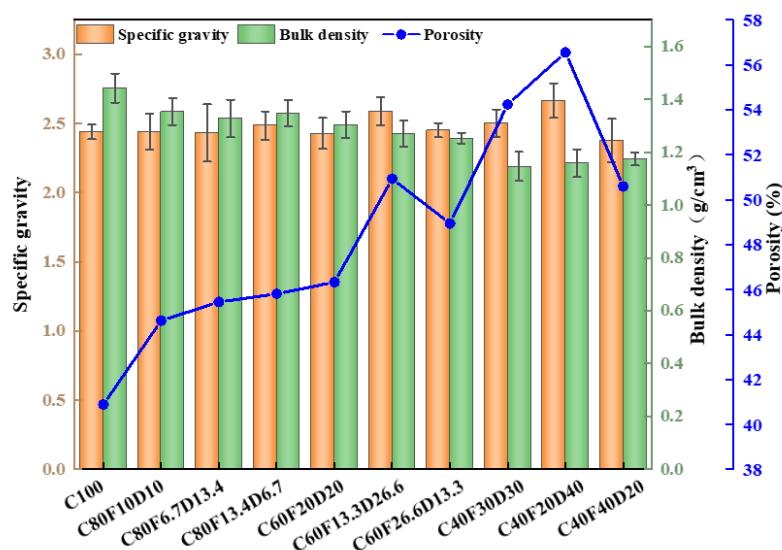


Figure 3. Bulk density, specific gravity and porosity under different ratios.

3.1.2. pH and EC Values

After 30 days of planting, the pH and AS EC of each sample were tested, and the results are shown in Figure 4. It can be found that the results for the plant length, biomass and potted plants comparison graph were roughly consistent. Therefore, it can be concluded that plant performance is best when the content of CG is 20–30%. The pH value of the CG was 3.56, which was comparatively lower than the pH values of the other test groups. This difference can be attributed to the sulfur content in coal, primarily in the form of sulfide. When exposed to air or subjected to wet oxidation, these sulfides undergo an

oxidation reaction, resulting in increased acidity of the CG. The specific reaction process can be represented by Equation (2).

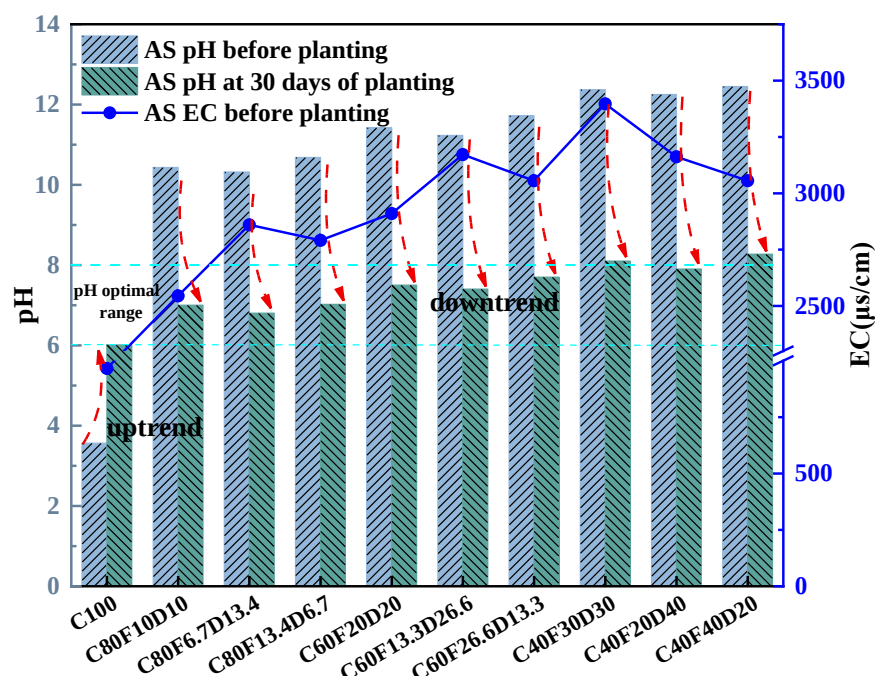
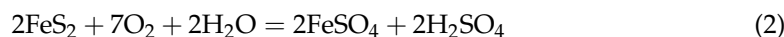


Figure 4. pH and EC values for AS under different ratios.

The pH value of the FA was 10.83. The primary constituents in FA are SiO_2 , Al_2O_3 , and Fe_2O_3 , and the Al_2O_3 and Fe_2O_3 contribute to its alkalinity. The specific reaction mechanism can be represented by Equation (3).



The inclusion of alkaline FA and nearly neutral DG results in a modification of the acidity and alkalinity of the AS. In general, when the amount of CG decreased, there was a corresponding increase in the pH value. When the amount of CG was fixed, altering the proportion of FA and DG led to a positive correlations between the pH value and the content of FA. Therefore, it is advisable to regulate the content of FA in order to control the acidity and alkalinity of AS. C40F40D20 exhibited a maximum pH value of 8.27, while C80F6.7D13.4 demonstrated a pH value close to neutrality, measuring at 7.02.

Elymus dahuricus exhibits adaptations that enable its survival in environments characterized by weakly alkaline and alkaline conditions. Deviations from this pH range, towards either acidity or alkalinity, result in diminished availability of essential nutrients in the soil, consequently impacting the growth of this plant species. Soil microbial activity is influenced by pH value, as certain microbes exhibit sensitivity to pH variations. When the pH value deviates from their optimal range, it has an impact on the activity of microorganisms [40,41], subsequently influencing the interactions between plants and soil. The soil pH has a significant impact on its structure and texture. When the soil becomes too acidic or alkaline, it can lead to the aggregation of soil particles, resulting in the formation of a compacted structure. This compacted structure hinders the penetration of water and air into the root zone, hence restricting the growth and development of plants. The root system also has an impact on the pH of AS. As shown in Figure 5, the absorption and release of substances in the rhizosphere will change the soil environment, and the respiration of plants will affect the metabolism of microorganisms.

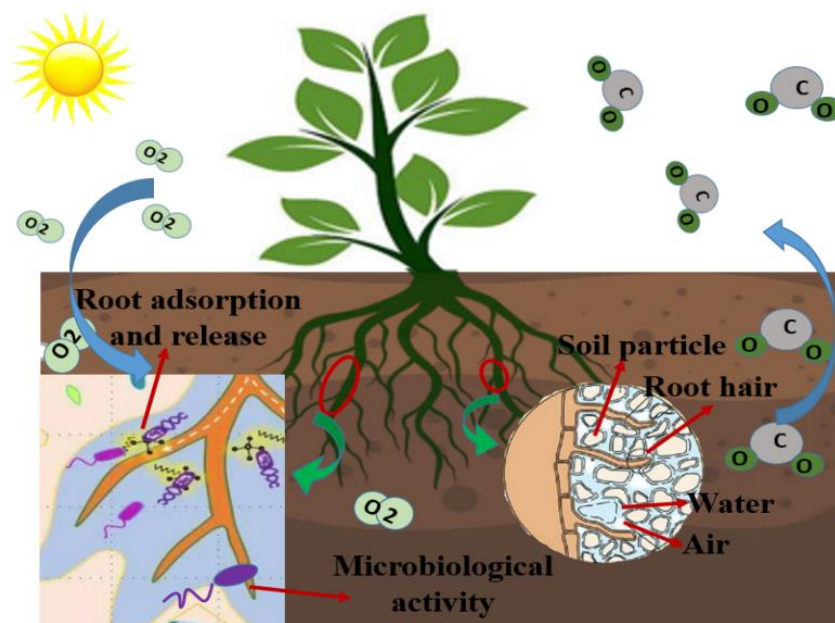


Figure 5. Schematic diagram of the effect of root on pH value of the AS.

3.1.3. Field Capacity and Saturation Capacity Analysis

Figure 6 illustrates the trend in field capacity of AS with varying ratios. The data show an upward trend, mostly influenced by the content of CG. The field capacity of C100 was 0.16, mostly attributed to the presence of a significant pore size in the CG, resulting in the formation of a greater number of interconnected pores. This is beneficial for internal water to be separated by gravity. Furthermore, it exhibits an angular surface morphology that is unfavorable for water retention, and the CG possesses a tiny specific surface area. The field capacity of C80 exhibited an increase of 10.6% (F10D10), 36.2% (F6.7D13.4), and 42.6% (F13.4D6.7) in comparison to C100. The field capacity of C60 exhibited an increase of 61.5% (F20D20), 66.2% (F13.3D26.6), and 80.1% (F26.6D13.3) in comparison to C100. The field capacity of C40 exhibited a significant increase of 118.6% (F30D30), 103.7% (F20D40), and 138.5% (F40D20) when compared to C100. The observation reveals that a decrease in CG, accompanied by an increase in FA and DG, leads to a significant increase in the field capacity of AS. The rationale behind this result can be attributed to two factors. Firstly, it is influenced by the mineral composition of the CSWM; the CG usually contains a large amount of clay minerals such as wollastonite and calcite [42,43], which are usually impermeable. The reduction of CG will reduce the proportion of these impermeable minerals; at the same time, the permeability and field capacity of AS will also be reduced. But the degree of influence of the reduction of CG on field capacity is much smaller than the influence of FA and DG on field capacity. Therefore, it appears that the field capacity of AS increases with the reduction in DG and increase in FA and DG. Secondly, FA is mainly composed of alumina, SiO_2 , Fe_2O_3 and other minerals. These minerals usually have a smaller particle size and a high number of microporous and mesoporous structures [44], which allows FA to adsorb and retain moisture. Therefore, the addition of FA will increase the water retention capacity of the soil.

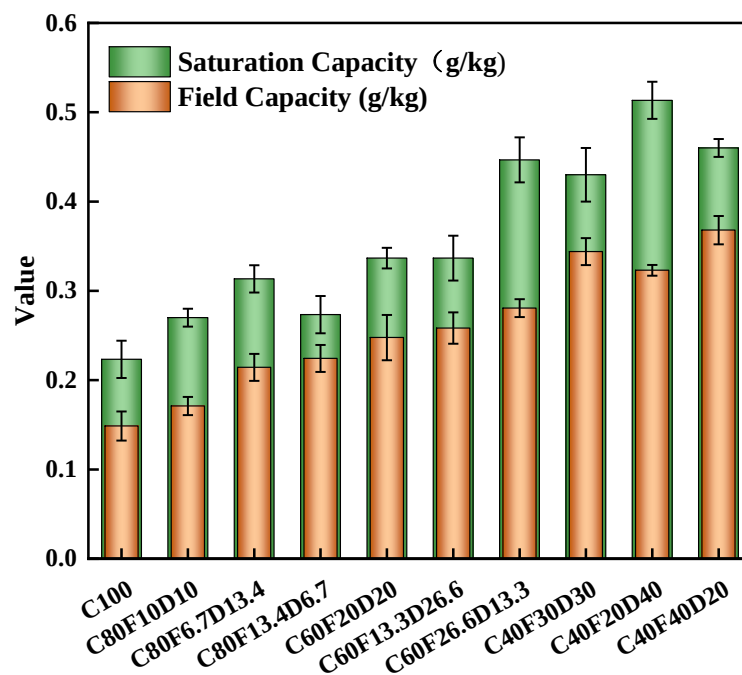


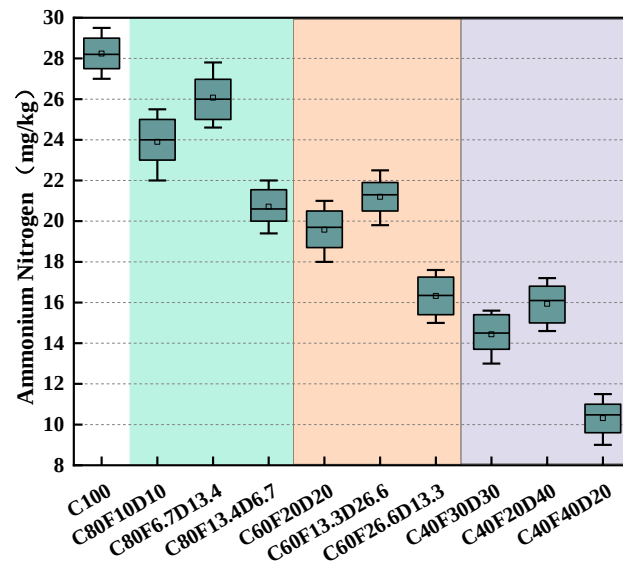
Figure 6. Field capacity and saturation capacity under different ratios.

The primary composition of DG consists of CaCO_3 , a mineral that is soluble in water. The addition of DG to the soil results in the hydrolysis of Ca^{2+} and SO_4^{2-} , leading to enhancements in soil structure and permeability [22,45]. The DG content results in a corresponding increase in these advantageous ions, hence augmenting the permeability of AS and perhaps boosting its capacity for water retention. Furthermore, the diminished influence of CSWM might be attributed to the limited specific surface area of FA and DG, as the gradual encapsulation of CG leads to a reduction in pore volume and pore blockage. When the content of the two reaches saturation, the water retention capacity comes from the pores produced by both FA-DG and the water-absorbing capacity of the surface of the AS itself, both of which have small particles and porous structure. The relationship between surface activity and specific surface area suggests that an increase in the latter results in a corresponding increase in the former. This is due to the larger specific surface area facilitating greater contact between particles and water molecules, hence leading to a substantial enhancement in water retention capacity. Furthermore, FA commonly incorporates other additions or modifications, including hydrophilic agents and cementing agents, among others. These modifiers have the potential to enhance the water-absorption capacity of FA, hence improving its ability to retain water. DG has hydrates, which have the capacity to undergo chemical reactions with water molecules, hence augmenting their water absorption characteristics. So the mineral composition of CSWM has a direct impact on the structure and water retention capacity of AS.

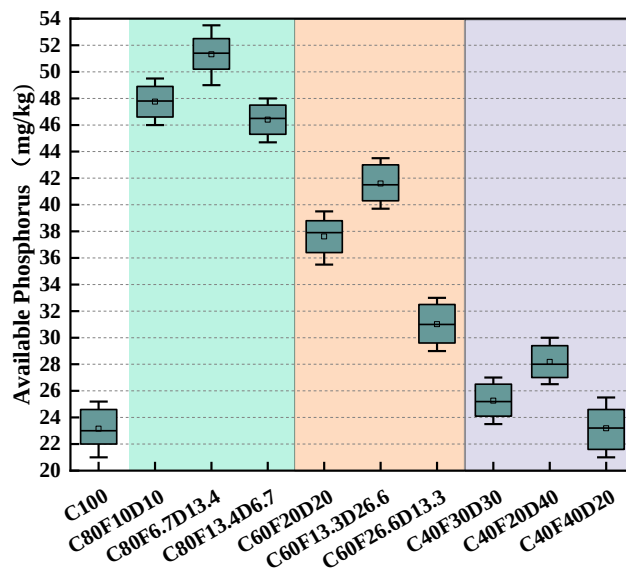
3.2. AS Nutrient Analysis

Figure 7 show the variation in the nutrient indicators for different ratios of the AS, CG, FA and DG additions. CG has many organic and inorganic substances [16]. It is worth noting that certain components within CG may consist of compounds containing nitrogen. Furthermore, the process of organic matter degradation in CG leads to the release of AN. The AN content observed in AS displays a consistent downward trend as the quantity of CG decrease. Ammonium salts present in FA [46] have the ability to be quickly released into AN within the AS, hence aiding in the stabilization of AN when exposed to alkaline environments. DG is characterized by a significant content of SO_4^{2-} . The presence of alkaline substances and SO_4^{2-} in DG contributes to the formation of $(\text{NH}_4)_2\text{SO}_4$, hence increasing the quantity of AN in the AS. Initially, due to the presence of P in CG, the AP

content in the AS may be higher. P can also manifest in the mineral form, such as apatite. Under acidic soil conditions, the dissolution of phosphorus minerals occurs, resulting in the release of P^{5+} , hence enhancing their availability for plant absorption. The addition of FA to the AS results in an elevation of soil alkalinity, hence inducing alterations in the form of P in the soil's adsorbed state. In alkaline environments, the solubility of P may decrease, resulting in a decrease in the concentration of AP.



(a)



(b)

Figure 7. Cont.

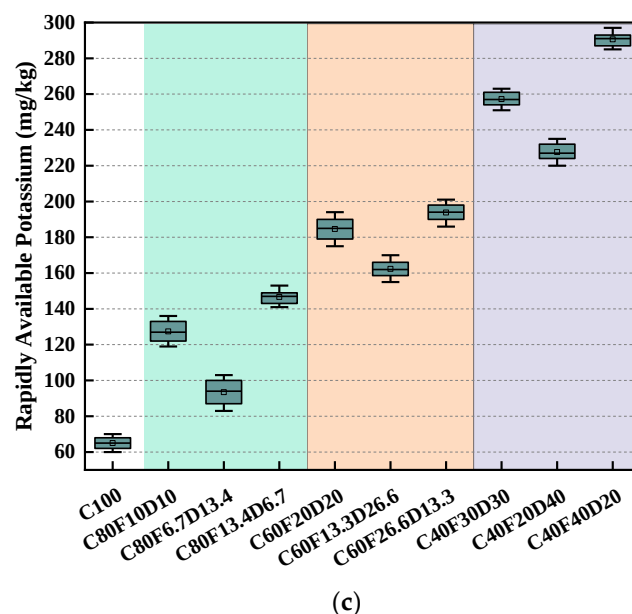


Figure 7. Variation in the nutrients of AS with CSWM content on (a) AN, (b) AP and (c) AK.

Potassium (K) predominantly occurs in the mineral form inside soil, namely as feldspar minerals (orthoclase, plagioclase), as well as potassium feldspar. These minerals break down K^+ that can be subsequently absorbed by plants [47]. The mineral composition of CG comprises potassium-rich minerals, namely mica and feldspar [48]. These minerals can be broken down into AK, and as CG decreases, AK content increases. This phenomenon can be attributed to the lower AK content typically found in acidic soils [49]; acidic environments can reduce the decomposition of AK in minerals. Soils with a neutral or alkaline pH typically exhibit higher content of available K^+ . The presence of acidic soils increases the affinity of AK to soil particles, resulting in a decrease in its solubility in the AS and impeding its uptake by plants. Furthermore, it is worth noting that the health and nutrient uptake efficiency of plant roots might be adversely affected in the acidic environments.

3.3. Plant Performance Analysis

Figure 8 shows the trend of stem height and root length and biomass data of *Elymus dahuricus* after treatment with different proportions of combined CSWM, focusing on aboveground and underground biomass. The plant growth comparison chart for *Elymus dahuricus* maintenance periods of 10, 20, and 30 days is shown in Figure 9. According to the observation, different ratios resulted in different rates of potted plant germination, and the grass grew significantly better in C80 and C60 than in C100 and C40. It can be seen from Figures 9 and 10 that the height of grass increased almost linearly during the first 10 days of planting. Grass grew the fastest in C80, followed by C60 and C100, and the slowest in C40.

The stem height showed an initial surge during the maintenance phase, followed by a gradual plateauing. This phenomenon can be attributed to various factors, including soil fertility, physical characteristics, chemical environment, and inherent biological properties. In comparison to C100, C80 yielded the greatest stem height and root length, while C60 and C40 resulted in comparatively shorter plant heights, potentially attributable to the low porosity of C100. During the initial 20 days, the plants underwent a period of accelerated growth characterized by increased stem height and root length. This can be attributed to the expeditious release of efficacious nutrients and ions from CSWM into the AS, thereby supplying the plant seedlings with these substances. After 20 days, the stem heights exhibited a decelerated growth phase. As the plant develops, it influences the physicochemical properties and microbial community of the AS. This may lead to a

hindered nutrient release from the AS, thus impeding plant growth. Alternatively, the plant's growth may be attributed to the elevated concentration of soluble salt ions in the FA and DG, which impede respiration and nutrient extraction [50]. The EC of AS is shown in Figure 4, which can reflect the ion content, water status, and soil salt concentration in the soil. A greater EC value indicates a greater abundance of salts or ions in the soil. Specifically, the EC values for C80, C60, and C40 were 216%–251%, 201%, and 228% higher than that for C100, respectively. After 30 days, the plants had progressively adjusted to their surroundings, resulting in a tendency for the degree of inhibition to stabilize.

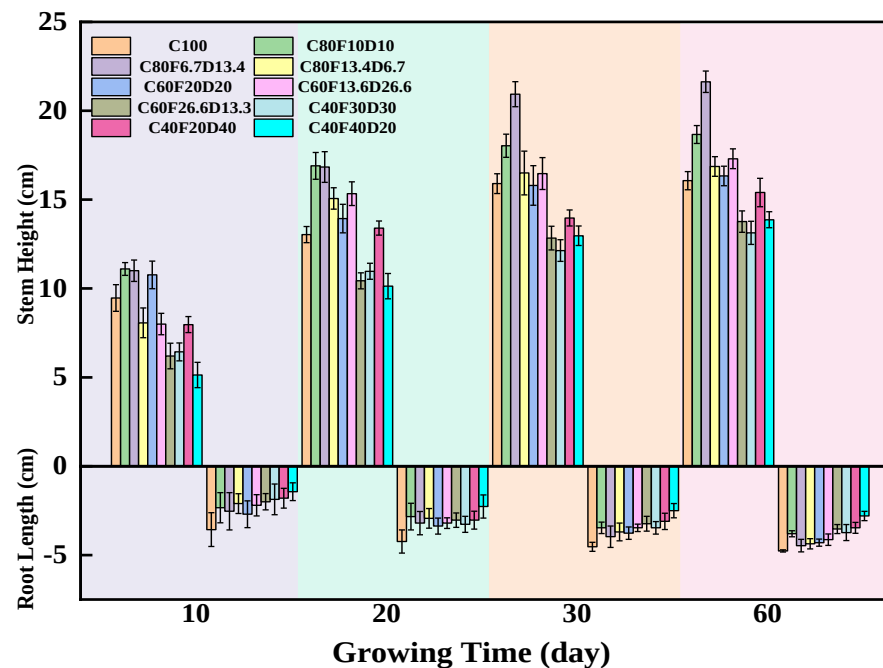


Figure 8. Height of *Elymus dahuricus* during planting.

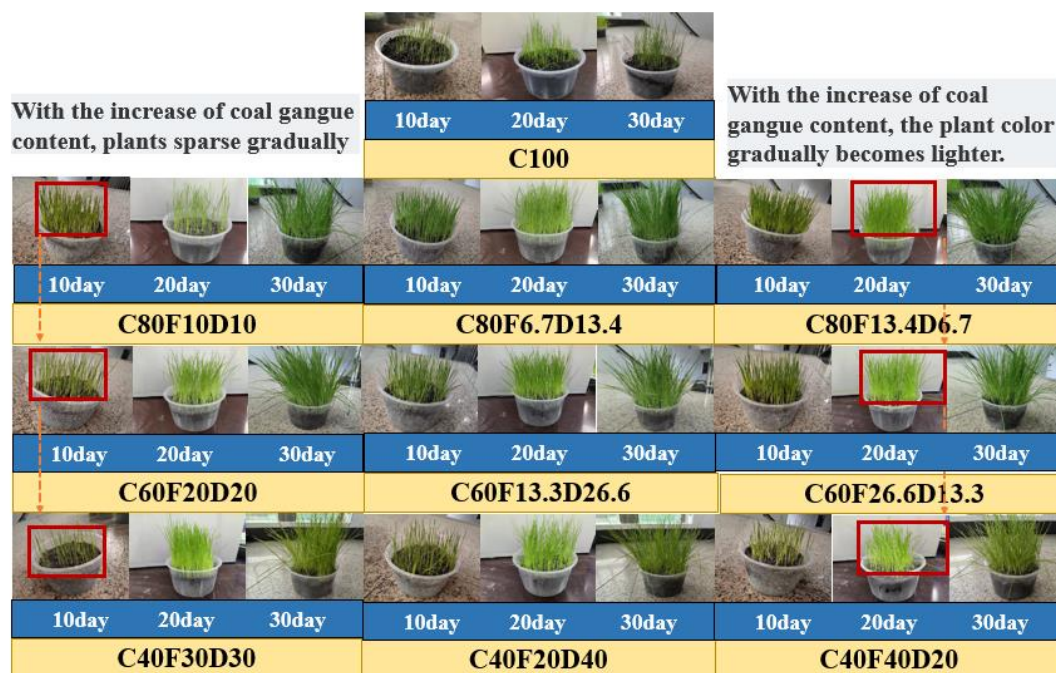


Figure 9. Comparison of potted plant growth.

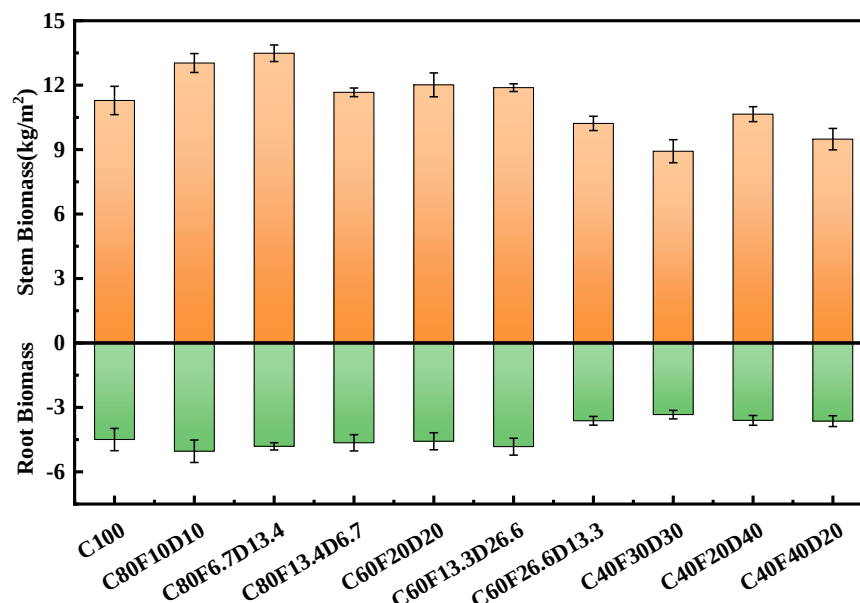


Figure 10. Biomass of *Elymus dahuricus* under different ratios.

4. Discussion

CG is a prevalent CSWM that generally comprises soil-like constituents, including silicates, oxides, and carbonates [51,52], in addition to substantial quantities of organic matter, N, P, and K. CG is an acidic mineral, and as the amount of CH increases, the EC and pH values decrease. The particle size of coal gangue is relatively large, so the field capacity and porosity of the AS exhibit a decline as the CG content increases. FA has a large specific surface area; approximately 980 m²/kg of FA was utilized in this study. Therefore, through field water capacity experiments and soil property measurements, it could be confirmed that the porosity and water retention capacity of AS increased. Moreover, FA is rich in nutrients and can supply the AS with nutrients. The alkaline FA chosen for this study was capable of controlling the acidic environment of the AS. The addition of DG and FA altered the structure of the AS, increased its permeability and water retention capacity, and transformed its texture from suboptimal to optimal. Based on the comparison graphs of plant height and growth, it can be observed that as FA and DG content increased and CG gradually decreased, plant growth initially improved and then declined. Therefore, regulating FA and DG content within the range of 20%–30% can effectively stimulate plant growth in the AS prepared by CSWM.

From the perspective of resource utilization, artificial soil solves the problem of large accumulations of coal-based solid waste in coal mine areas, and the raw material is accumulated waste, avoiding pollution to the environment and groundwater and other natural resources. In addition, water resources are scarce in the study area, and normal soil ecological slope protection will increase the cost. Compared with normal soil, artificial soil is easy to obtain, lower in cost, has better nutrient content and water retention performance, will reduce the risk of pests and diseases, and improve the health of the vegetation growth environment. The raw material of the artificial soil is prepared from coal-based solid waste material, which not only solves the problem of waste accumulation but also beautifies the environment. This idea is conducive to environmentally friendly and sustainable development and the goal of ecological restoration of mines. Coal-based solid waste materials support plant growth conditions and can provide sufficient nutrients, water retention and ventilation. The preparation process for artificial soil is simple, easy to manage, and can be easily realized in practical implementations. The concept of preparing artificial soil conforms to the reality of local shortages of water and soil. The use of artificial soil for slope ecological restoration is beneficial to society and the environment and can reduce soil erosion and improve water quality.

5. Conclusions

(1) The physical properties of artificial soil prepared with coal gangue, fly ash and desulfurization gypsum are different. The porosity increases with the decrease in coal gangue content. The porosity of C100 is 0.48 and that of C40F20D40 is 3.1. The bulk density decreases with the decrease in coal gangue content. The water retention capacity increased with the increase in fly ash and desulfurization gypsum content. From C100 to C40F40D20, the field water retention capacity increased from 0.148 to 0.368, and the saturated water content increased from 0.223 to 0.46, respectively.

(2) With different proportions of the three coal-based solid waste materials, the chemical properties of artificial soil also differed. Under the condition of no vegetation growth, the pH of C100 was 3.56 at a minimum, and that of C40F40D20 was 12.45 at a maximum. However, under the influence of plant growth for 30 days, the pH of each experimental group was close to neutral. This result is attributed to two factors: plant respiration and microbial metabolism. The additions of CG, FA, and DG can all alter the physical structure and chemical properties of AS, but their modification mechanisms are different. FA facilitates the generation of an alkaline environment and the release of ammonium nitrogen (AN). DG contributes sulphate ionic compounds.

(3) The preparation of artificial soil (AS) for plant growth can be achieved through the composite formulation of three commonly used materials: coal gangue (CG), fly ash (FA), and desulfurization gypsum (DG). Specifically, the incorporation of FA and DG at a ratio of 20%–30% enhances the AS texture and water retention capacity, promoting plant growth. Based on the growing situation of plants and the physicochemical characteristics of the AS, the following order can be established to indicate the advantages and disadvantages of each ratio: C80 > C60 > C100 > C40.

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