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Optimizing Amendment Ratios for Sustainable Recovery of Aeolian Sandy Soils in Coal Mining Subsidence Areas: An Orthogonal Experiment on *Medicago sativa*

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Abstract

Coal mining in the aeolian sandy regions of western China has caused extensive land degradation. Traditional single-component soil amendments have proven inadequate for ecological restoration, underscoring the need for integrated and sustainable strategies to restore soil fertility and vegetation. A pot experiment using alfalfa (*Medicago sativa* L.) evaluated the effects of weathered coal, cow manure, and potassium polyacrylate combined in a three-factor three-level orthogonal design on plant growth, nutrient uptake, and soil properties. Results showed that compared with the control (C0O0P0), amendment treatments significantly increased alfalfa fresh weight (+47.57~107.38%), dry weight (+43.46~104.93%), plant height (+43.46~104.93%), and stem diameter (+12.62~31.52%), along with improved plant phosphorus and potassium concentrations (+15.41~46.65%). Soil fertility was also notably enhanced, with increases in soil organic matter, total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), available phosphorus (AP), and available potassium (AK) ranging from 4.25% to 777.78%. In contrast, soil pH and bulk density were significantly reduced. The optimal amendment combination was identified as 10 g·kg^{-1} weathered coal, 5 g·kg^{-1} cow manure, and 0.6 g·kg^{-1} potassium polyacrylate. Structural equation modeling revealed that the amendments promoted plant growth both directly by improving soil conditions and indirectly by enhancing nutrient uptake. However, high doses (30 g·kg^{-1}) of weathered coal may inhibit plant growth, and the co-application of high-dose weathered coal or manure with potassium polyacrylate may lead to antagonistic effects. This study provides fundamental insights into soil–plant interactions and proposes a sustainable amendment strategy for improving aeolian sandy soils, which could support future ecological reclamation efforts in coal mining area.

Keywords: coal mining subsidence area; aeolian sandy soil; weathered coal; organic fertilizer; potassium polyacrylate; sustainability; ecological restoration

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1. Introduction

Arid and semi-arid regions in China cover about 3.57 million km^2, accounting for 37% of the country's land area [1]. These regions are marked by low precipitation, high evaporation rates, and fragile ecosystems [2]. However, these regions of China are rich in

coal resources [3]. While open-pit mining dominates in the west, underground mining in deeper seams causes widespread surface subsidence and fissures, accelerating soil erosion and land degradation [4,5]. Aeolian sandy soils in these regions are typically dominated by sand particles, and are characterized by weak structure, low organic matter content, high alkalinity, and poor water retention. These conditions severely hinder natural vegetation recovery and ecosystem reconstruction [6,7].

To overcome these limitations, various studies have investigated soil amendments including organic fertilizers, mineral materials, and polymer water-retaining agents to enhance soil quality and support plant growth [8–12]. Organic fertilizers, notably cattle manure, are abundant in organic matter and nutrients like nitrogen, phosphorus, and potassium [13], which can enhance soil carbon sequestration and fertility, promoting plant growth [12,14]. Additionally, organic fertilizers can increase microbial activity and support sustainable soil productivity [14,15]. However, their large-scale application is often limited by cost and logistical constraints. Weathered coal, a common by-product in mining areas, is formed by the prolonged weathering of bituminous coal, anthracite, or lignite at or near the Earth's surface [16]. Owing to its high oxygen content and low calorific value, it is often discarded as waste, leading to resource waste and environmental pollution [17]. Nevertheless, weathered coal is typically rich in organic matter (approximately 40–80%) and contains abundant humic acid, thereby representing an economical and practical organic soil amendment [18,19]. A growing body of research has shown that the application of weathered coal or its humic derivatives can improve soil organic matter content and aggregate stability [19,20], optimize the soil microenvironment [21,22], increase the water-holding capacity of sandy soils, reduce alkalinity [23], and ultimately promote plant growth [24]. Potassium polyacrylate belongs to the class of polymeric superabsorbent materials [25]. Its hydrophilic functional groups enable rapid uptake of large volumes of water and swelling into a gel-like network, which slowly releases water into soil pores and root zones during dry periods, thereby improving instantaneous plant-available water [26,27]. Additionally, its swollen particles can improve soil pore structure, reduce surface runoff, increase water infiltration, and decrease evaporative loss, thereby significantly enhancing the soil's water retention capacity [28,29].

Although the individual effects of these amendments are well-documented, most existing studies are based on single-factor experimental designs, lacking systematic exploration of the combined effects and optimal ratios of multiple amendments. This limits their practical application in large-scale ecological restoration. Different types of amendments interact with soil through distinct mechanisms, and rational combinations can produce synergistic effects [12,30]. However, improper or excessive application may lead to negative outcomes [31], making it imperative to optimize amendment combinations and ratios.

Medicago sativa L. is a perennial leguminous forage crop rich in high-quality protein and represents an important source of dietary protein for livestock [32]. It develops a deep root system that enhances soil structure, exhibits strong drought tolerance [33,34], and fixes atmospheric nitrogen, thereby increasing soil nitrogen availability and promoting soil organic matter accumulation [35,36]. Consequently, alfalfa is widely employed in ecological restoration programs in arid and semi-arid regions [37], including reclamation projects in coal-mining landscapes [38]. In this study, three representative soil amendments, including weathered coal, cattle manure, and potassium polyacrylate, were selected to establish a factorial experiment with three variables at three levels. Plant growth parameters, nutrient uptake, and soil physicochemical properties were measured to evaluate the effects of different amendment combinations on alfalfa performance. The aims of this study were to (1) clarify the mechanisms through which soil amendments enhance plant growth, (2) evaluate the main and interactive effects of each amendment on alfalfa performance,

and (3) identify the optimal amendment combination as a theoretical foundation and preliminary screen for future field-based ecological restoration practices.

2. Materials and Methods

2.1. Experimental Materials

The test plant used in this study was alfalfa (*Medicago sativa* L.), with seeds obtained from Zhunge'er Banner, Ordos City, Inner Mongolia. The soil of this pot experiment was collected from a coal mining subsidence area in the same region (39°57′ N, 111°20′ E) at a depth of 0–20 cm. The soil amendments included weathered coal, cow manure, and potassium polyacrylate (an agricultural K salt-type superabsorbent polymer) as a water-retaining agent. Weathered coal was supplied by Yifan Trading Co., Ltd. (Xinyi, China), cow manure fertilizer by Xing'an Grassland Agricultural Supplies (Ordos, China), and potassium polyacrylate by Chang'an Holdings Group Co., Ltd., Shengli Oilfield (Dongying, China). Both the soil and cow manure were air-dried indoors, cleared of debris, and sieved through a 2 mm mesh prior to use. Their physicochemical properties are summarized in Table 1.

Table 1. Basic physicochemical properties of the soil and amendments used in the experiment.

Item	pH	OM/ $g \cdot kg^{-1}$	AN/ $mg \cdot kg^{-1}$	AP/ $mg \cdot kg^{-1}$	AK/ $mg \cdot kg^{-1}$	TN/ $g \cdot kg^{-1}$	TP/ $g \cdot kg^{-1}$	TK/ $g \cdot kg^{-1}$
Aeolian Sandy Soil	8.56	8.28	117.00	18.20	103.00	0.68	0.47	16.50
Weathered Coal	6.62	34.80	157.00	19.50	75.00	5.79	0.10	0.89
Cow Manure	7.29	319.00	329.00	271.10	11,368.00	19.49	6.94	19.40
Potassium Polyacrylate	7.80	157.00	-	-	-	70.34	0.12	116.00

Note: OM, organic matter; TN, total nitrogen; TP, total phosphorus; TK, total potassium; AN, available nitrogen; AP, available phosphorus; AK, available potassium. - indicates not determined. AN, AP, and AK were not measured for the potassium polyacrylate product because its strong super-absorbent behavior makes conventional extractant-based assays unreliable.

2.2. Experimental Design

The pot experiment was performed in the glass greenhouse at China University of Mining and Technology (Beijing) to evaluate the effects of soil amendments on alfalfa growth. A three-factor, three-level orthogonal design was implemented, including weathered coal (C: 10, 20, 30 $g \cdot kg^{-1}$), cow manure organic fertilizer (O: 3, 5, 7 $g \cdot kg^{-1}$), and potassium polyacrylate (P: 0.3, 0.6, 0.9 $g \cdot kg^{-1}$). In brief, soil was amended according to designated treatments, sown with pre-germinated alfalfa seeds, and maintained under controlled greenhouse conditions for 63 days, after which plant growth and soil properties were measured. The application rates of weathered coal and cow manure were selected based on evidence from published studies [15,19,21,39], while the rate of the water-retaining agent (potassium polyacrylate) was determined according to the manufacturer's guidelines (for details, see Appendix A) Nine amendment combinations and a control (C0O0P0) were established, totaling ten treatments: C0O0P0 (control), C10O3P0.3, C10O5P0.9, C10O7P0.6, C20O3P0.9, C20O5P0.6, C20O7P0.3, C30O3P0.9, C30O5P0.6, and C30O7P0.3, with four replicates per.

For each pot, the designated amendments were thoroughly homogeneously with approximately 4 kg of soil at the designated rates and placed in plastic pots (top diameter 20 cm, bottom 16 cm, and height 19 cm). Soil moisture was maintained at 70% field capacity for 5 d before sowing. The alfalfa (*Medicago sativa* L.) seeds were pre-germinated in water for 8 h. Twenty germinated seeds were sown per pot. After one week, the seedlings were adjusted to ten per pot. During the experiment, temperatures fluctuated between 20 °C and 35 °C in the day and 10–25 °C at night. The relative humidity was controlled within 20–70%. Soil moisture was regularly adjusted to 70% of field capacity.

2.3. Plant Sample Preparation and Analysis

After 63 days, the height of each plant was recorded with a standard ruler., and the stem diameter at the base was determined with a vernier caliper prior to harvesting. Shoots were cut at the stem base, thoroughly rinsed several times with distilled water, and surface moisture was gently blotted with paper towels before fresh weight measurement. Plant samples were oven-dried at 105 °C for 30 min, followed by drying at 75 °C until a constant weight was reached (approximately 48 h). Dry weight was subsequently recorded. High-purity nitric acid (HNO_3) was used to digest the ground, oven-dried samples and analyzed for phosphorus (plant P) and potassium (plant K) concentrations using inductively coupled plasma optical emission spectrometry (ICP-OES; Agilent Technologies 5110, Santa Clara, CA, USA) [40]. Aboveground nitrogen (plant N) concentrations were determined using an automatic Kjeldahl nitrogen analyzer (K1160, Haineng, Jinan, China) [41].

2.4. Soil Sample Preparation and Analysis

After harvesting the plant samples, intact soil cores were collected from the pots using a ring cutter to determine soil bulk density. Soil water content was determined by the gravimetric method (drying at 105 °C for 24 h). The residual soil was combined, air-dried, and sieved (<2 mm) prior to analysis. Soil pH was assessed in a 1:2.5 (*w/v*) soil-water suspension using a pH meter (PHS 3C, Leici, Shanghai, China) [42]. Soil organic matter content was quantified via dichromate-sulfuric acid digestion and measured using an automated soil organic matter analysis workstation (JX S7066, Jingxin, Shanghai, China). TN was quantified using an automatic Kjeldahl nitrogen analyzer (K1160, Haineng, Jinan, China) following digestion with concentrated sulfuric acid [43]. TP and TK in soil were determined by ICP-OES instrumentation (Agilent Technologies 5110, Santa Clara, CA, USA) after mixed acid digestion with hydrochloric, nitric, perchloric, and hydrofluoric acids [44]. AN in soil was quantified using the alkali diffusion method. AP was extracted from soil using $NaHCO_3$ (0.5 M) solution and quantified via the molybdenum-antimony anti-colorimetric method using a UV-Vis spectrophotometer (TU 1900, Purkinje General, Beijing, China) [45]. Available potassium (AK) was extracted with 1 mol·L^{-1} NH_4OAc and measured by ICP-OES [46].

2.5. Data Analysis

Data were analyzed in R (v4.4.3). Univariate analysis of variance (ANOVA) and Duncan's multiple range test ($p < 0.05$) were conducted on plant and soil physicochemical properties using the agricolae package. Visualizations, including bar plots, violin plots, and boxplots, were generated with ggplot2 and ggpubr. Pearson correlation analyses were carried out using the cor.test function, and correlation heatmaps were produced with ggplot2.

Soil water retention curves were estimated using the van Genuchten model. Soil bulk density and an assumed particle density of 2.65 g·cm^{-3} were used to calculate porosity as saturated water content (θ_s). Soil texture was determined from sand, silt, and clay contents following USDA classification, and typical van Genuchten parameters (θ_r, α, n) were assigned according to Carsel & Parrish [47]. Volumetric water contents were then calculated at common matric potentials (1–1500 kPa), averaged across four replicates per treatment, and plotted as mean water retention curves. Available water (AW) was defined as the difference between field capacity (θ at 33 kPa) and permanent wilting point (θ at 1500 kPa), i.e., $AW = \theta_{fc} - \theta_{pwp}$. Water use efficiency (WUE) was calculated as the ratio of mean plant dry weight (DW_{avg}) to available water (AW), i.e., $WUE = DW_{avg}/AW$.

To reduce dimensionality and construct composite variables, principal component analysis (PCA) was applied separately to soil properties (TP, AN, AK), plant nutrient

contents (plant N, P, K concentrations), and plant growth indices (fresh weight, dry weight, plant height, stem diameter). The first principal components (Soil PC1, Nutrition PC1, Biomass PC1) were extracted as comprehensive representations of soil characteristics, nutrient uptake, and plant growth, respectively. Subsequently, structural equation modeling (SEM) was performed using the lavaan and semPlot packages to investigate the direct and indirect effects of the three factors (C, O, P) on plant growth via soil and nutrient pathways. Using Biomass PC1 as an integrated growth index, main effect and two-factor interaction plots were generated with the dplyr and ggplot2 packages to visualize and interpret the main effects and two-way interaction effects of factors C, O, and P on plant growth. Moreover, an average ranking for each treatment was calculated based on four plant growth indicators to facilitate a comprehensive performance comparison. Finally, a three-factor interaction linear model was developed, and response surface plots were created using the persp function to visualize the effects of C, O, P, and their interactions on plant growth.

3. Results

3.1. Plant Growth and Nutrient Uptake

Different ratios of sandy soil amendments significantly influenced alfalfa biomass ($p < 0.05$) (Figure 1a–d). Compared with the control (C0O0P0), fresh weight increased by 47.57% to 107.38%, with treatments C10O7P0.6 and C20O3P0.3 producing the highest values ($p < 0.05$) (Figure 1a). Dry weight increased significantly by 43.46% to 104.93%, peaking under treatment C10O5P0.9 ($p < 0.05$) (Figure 1b). Plant height increased by 43.46% to 104.93%, reaching a maximum under C20O7P0.3 ($p < 0.05$) (Figure 1c). Stem diameter improved significantly by 12.62% to 31.52%, with the greatest thickness observed in C10O7P0.6 ($p < 0.05$) (Figure 1d).

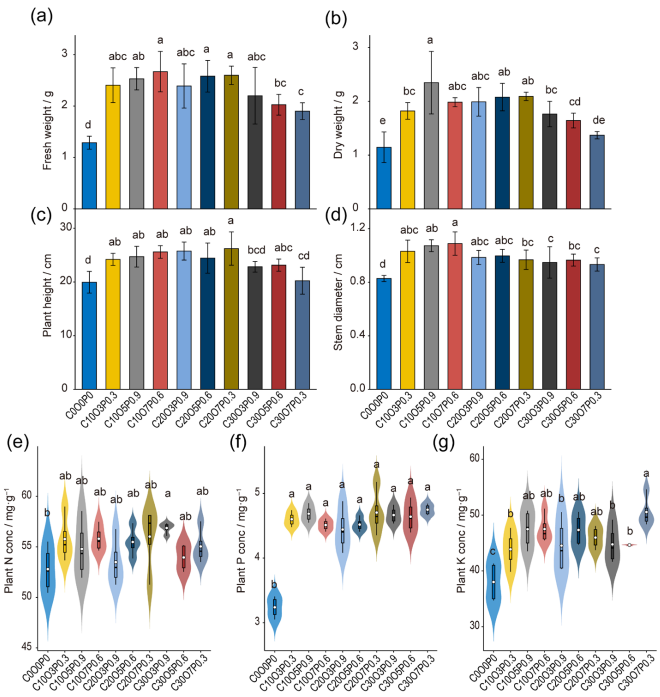

Figure 1. Fresh weight (**a**), dry weight (**b**), plant height (**c**), stem diameter (**d**), and N concentration (**e**), P concentration (**f**), and K concentration (**g**) in plants derived from different treatments. Each treatment represents a specific combination of weathered coal (C), cow manure organic fertilizer (O), and potassium polyacrylate (P) at designated application rates. For example, C10O5P0.9 indicates the application of 10 g·kg^{-1} weathered coal, 5 g·kg^{-1} cow manure, and 0.9 g·kg^{-1} potassium polyacrylate. Different lowercase letters indicate significant differences between treatments at $p < 0.05$ based on one-way ANOVA followed by Duncan's multiple range test.

Amendments also significantly affected alfalfa nutrient uptake ($p < 0.05$) (Figure 1e–g). N concentration in the plant increased by 7.70% under C30O3P0.9 relative to the control ($p < 0.05$) (Figure 1e). P concentration in the plant increased by 37.19% to 46.65% ($p < 0.05$) (Figure 1f), and K concentration in the plant increased by 15.41% to 32.99% ($p < 0.05$) (Figure 1g) compared to the control.

3.2. Sandy Soil Properties

Compared with the control (C0O0P0), soil water content in treatments C10O7P0.6, C20O5P0.6, C20O7P0.3, C30O3P0.9, C30O5P0.6, and C30O7P0.3 was significantly increased by 6.86%, 7.49%, 6.55%, 8.52%, 10.61%, and 10.19%, respectively ($p < 0.05$) (Figure 2a). Different combinations of soil amendments significantly enhanced soil water retention (Figure 2b). Meanwhile, water use efficiency of plant also increased under all amendment treatments, with the C10O5P0.9 treatment showing the highest water use efficiency (Figure 2c).

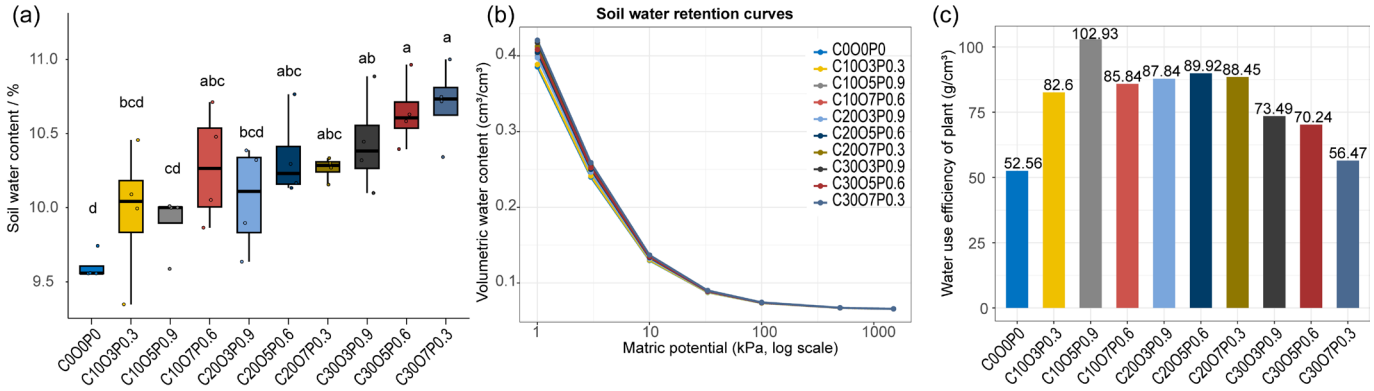

Figure 2. Soil water content (**a**), soil water retention curves (**b**), and water use efficiency of the plant (**c**) derived from different treatments. Each treatment represents a specific combination of weathered coal (C), cow manure organic fertilizer (O), and potassium polyacrylate (P) at designated application rates. For example, C10O5P0.9 indicates the application of 10 g·kg^{-1} weathered coal, 5 g·kg^{-1} cow manure, and 0.9 g·kg^{-1} potassium polyacrylate. Different lowercase letters indicate significant differences between treatments at $p < 0.05$ based on one-way ANOVA followed by Duncan's multiple range test. The values of plant available water are model estimates and are used for relative comparisons among treatments rather than as direct measurements. This approach helps interpret treatment trends, but its uncertainty should be noted.

Soil properties were significantly affected by different combinations of soil amendments ($p < 0.05$) (Figure 3a–i). Compared with the control (C0O0P0), all treatments showed a decreasing trend in soil pH, with the largest reduction (2.30%, $p < 0.05$) observed under the C30O5P0.6 treatment (Figure 3a). Soil organic matter content significantly increased by 70.30–213.10% ($p < 0.05$), with the highest value under the C30O7P0.3 treatment (Figure 3b). Bulk density was significantly reduced in most treatments ($p < 0.05$), with the greatest decrease (8.17%) observed under the C30O7P0.3 treatment (Figure 3c).

Compared with the control, the C20O7P0.3, C30O5P0.6, and C30O7P0.3 treatments significantly increased TN by 28.84%, 29.18%, and 31.17%, respectively ($p < 0.05$) (Figure 3d). TP was significantly increased in all treatments by 4.25–12.12% ($p < 0.05$), with the highest value in C20O7P0.3 (Figure 3e). No significant differences were detected in TK among treatments ($p > 0.05$) (Figure 3f).

AN, AP, and AK significantly increased by 18.06–777.78% ($p < 0.05$). C30O7P0.3 recorded the highest levels of AP and AK, with increases of 78.89% and 88.71%, respectively. The highest AP was observed under C20O7P0.3, representing a 777.78% increase compared to the control (Figure 3g–i).

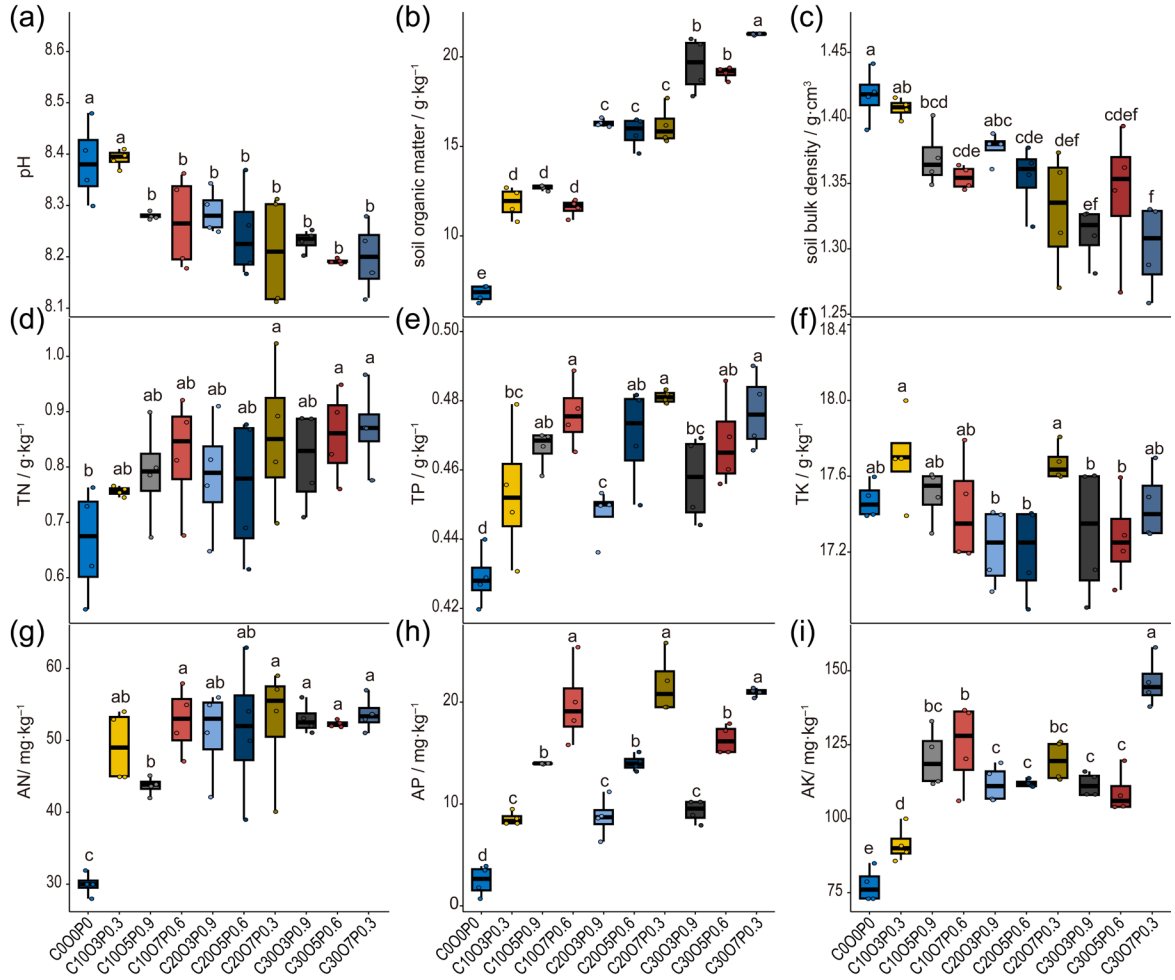

Figure 3. Soil pH (**a**), organic matter (**b**), bulk density (**c**), TN (**d**), TP (**e**), TK (**f**), AN (**g**), AP (**h**), and AK (**i**) derived from different treatments. Each treatment represents a specific combination of weathered coal (C), cow manure organic fertilizer (O), and potassium polyacrylate (P) at designated application rates. For example, C10O5P0.9 indicates the application of 10 g·kg^{-1} weathered coal, 5 g·kg^{-1} cow manure, and 0.9 g·kg^{-1} potassium polyacrylate. Different lowercase letters indicate significant differences between treatments at $p < 0.05$ based on one-way ANOVA followed by Duncan's multiple range test.

3.3. Correlation Analysis and Structural Equation Modeling (SEM)

Correlation heatmap analysis revealed significant positive correlations between TP and AN and plant biomass indices ($p < 0.05$), with the exception of plant height. Soil AP and AK showed significant positive correlations with plant fresh weight and stem diameter ($p < 0.05$). Plant height was positively correlated with soil water content ($p < 0.05$) (Figure 4a). Positive correlations were also observed between plant growth indices and nutrient uptake (plant N, P, K concentrations), particularly plant P concentration, which showed significant positive correlations with all biomass indices ($p < 0.01$) (Figure 4b). Furthermore, plant fresh weight displayed a strong, significant association with plant K concentration ($p < 0.001$). In addition, plant nutrient concentrations (N, P, K) showed significant correlations with soil physicochemical properties. Soil organic matter, TP, AP, AK, and AN were positively correlated with plant nutrient uptake (plant K and P) ($p < 0.01$), whereas soil pH and bulk density demonstrated an inverse relationship with plant P and K uptake ($p < 0.05$) (Figure 4c).

SEM indicated the links among amendments, soil physicochemical properties, plant nutrient uptake, and plant biomass. The model demonstrated good fit ($\chi^2 = 2.53$, df = 2,

p = 0.282; CFI = 0.995; RMSEA = 0.081; SRMR = 0.035), confirming the validity of the path structure. The three factors C, O, and P exerted significant positive effects on the soil properties, with O having the strongest influence (standardized coefficient = 0.68, $p < 0.001$). Soil properties had a marginally notable positive effect on the nutrient uptake (standardized coefficient = 0.448, p = 0.067). Both nutrient uptake and soil properties positively and significantly influenced plant growth, with standardized coefficients of 0.444 (p = 0.008) and 0.585 (p = 0.030), respectively. Furthermore, weathered coal exhibited a significant negative direct effect on plant growth (standardized coefficient = −0.495, p = 0.001) (Figure 4d).

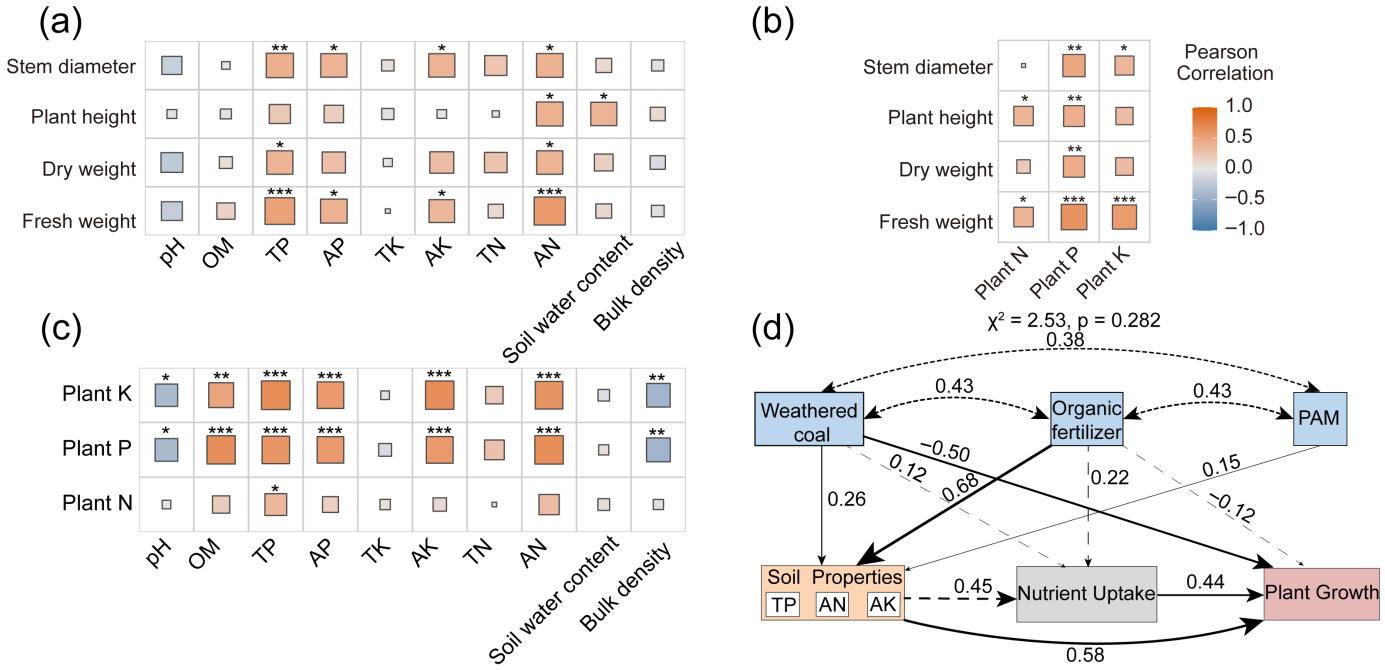

Figure 4. Correlation heatmaps between plant growth indices and soil properties (**a**), plant growth indices and nutrient uptake (**b**), nutrient uptake and soil properties (**c**), along with a structural equation model (SEM) (**d**). Asterisks indicate statistically significant correlations in the heatmaps (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). In the SEM, arrows represent hypothesized causal relationships, with numbers indicating standardized path coefficients. Solid arrows indicate significant paths ($p < 0.05$), while dashed or absent arrows indicate non-significant paths. Arrow thickness is proportional to the magnitude of the coefficient, reflecting the strength of the influence. weathered coal (C), organic fertilizer (O), and PAM (potassium polyacrylate, P).

3.4. Main Effects, Interactions, and Integrated Responses of Soil Amendments on Plant Growth

The main effect analysis based on the first principal component of plant growth indices (Biomass PC1) demonstrated that weathered coal (C), cattle manure (O), and potassium polyacrylate (P) significantly influenced alfalfa growth (Figure 5a–c). As the application rates of C, O, and P increased, Biomass PC1 values first rose and then declined, indicating the existence of optimal dosage levels. The optimal rates were 10 g·kg^{-1} for C, 5 g·kg^{-1} for O, and 0.6 g·kg^{-1} for P.

Interaction effect analysis of C × O interaction (Figure 5d) showed that under low C conditions (10 g·kg^{-1}), increasing O levels significantly enhanced Biomass PC1. For the C × P interaction (Figure 5e), treatments with P = 0.6 or 0.9 g·kg^{-1} yielded higher biomass at C = 10 or 20 g·kg^{-1}, but a notable decline occurred at C = 30 g·kg^{-1} with P = 0.9 g·kg^{-1}. Regarding the O × P interaction (Figure 5f), the highest biomass was observed at O = 3 or 5 g·kg^{-1} with P = 0.9 g·kg^{-1}, whereas biomass significantly declined at O = 7 g·kg^{-1} under the same P level.

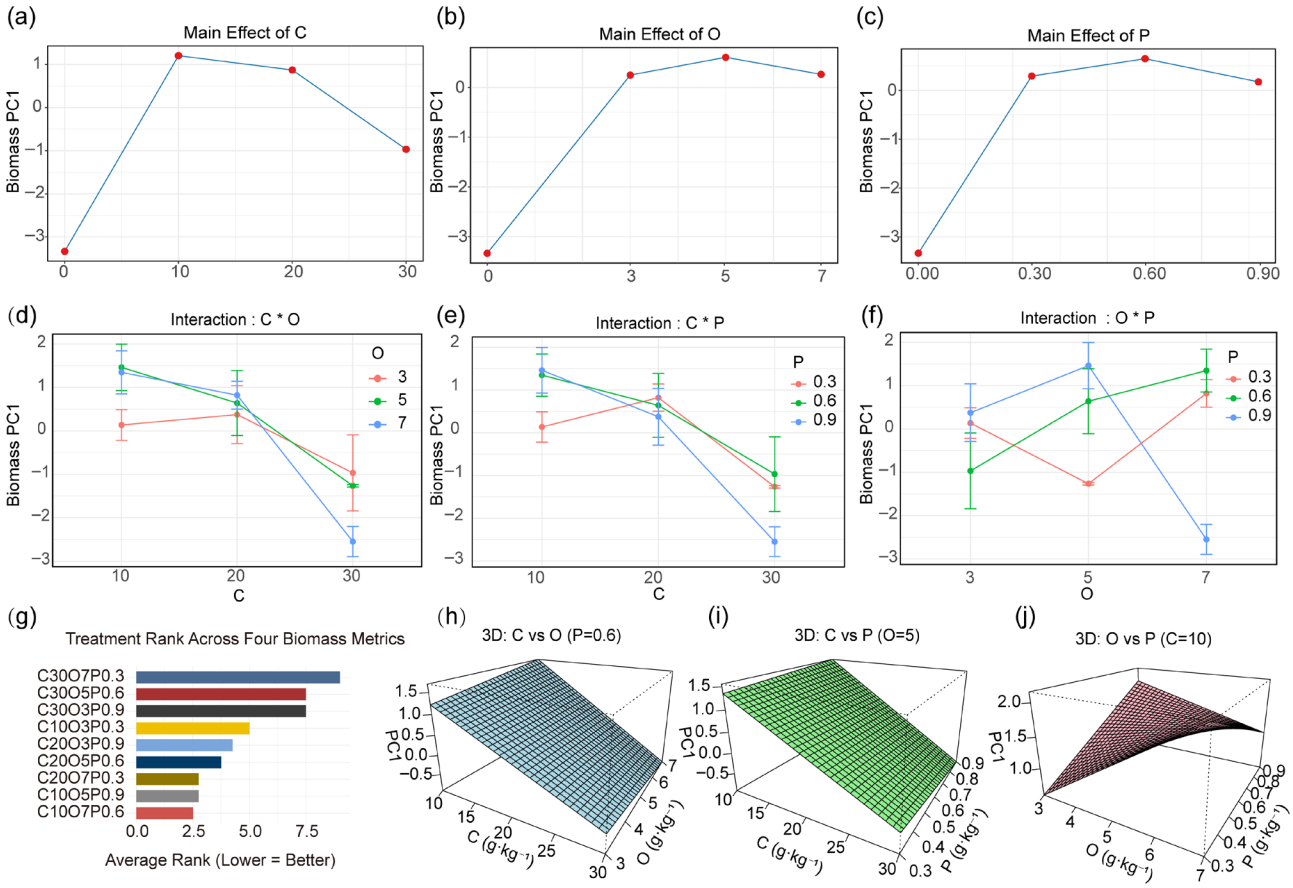

Figure 5. Main effect plots of weathered coal (**a**), cattle manure (**b**), and potassium polyacrylate (**c**), along with interaction plots of weathered coal and cattle manure (**d**), weathered coal and potassium polyacrylate (**e**), and cattle manure and potassium polyacrylate (**f**), overall rankings of nine treatments (**g**) and response surface analyses (**h**–**j**) are also presented. The main effect plots are based on the first principal component (PC1) of plant growth indices, including fresh weight, dry weight, plant height, and stem diameter. * indicates the interaction between two amendments (e.g., C*O = C × O interaction).

The overall ranking of four biomass indicators across treatments (Figure 5g) indicated that the C10O7P0.6 treatment performed best, suggesting it as the optimal combination for promoting alfalfa growth. Response surface modeling showed good model fit (adjusted $R^2 = 0.5488$, $F = 8.094$, $p < 0.001$), explaining 54.9% of the variability in plant growth. Three-dimensional response surface analyses (Figure 5h–j) further clarified the interaction effects among C, O, and P. Specifically, under moderate P levels, a balanced combination of C and O significantly improved biomass accumulation, while excessive C reduced growth. When O was at a moderate level, the combination of high C and high P suppressed growth. The O × P interaction appeared more complex; notably, high doses of O should not be combined with excessive P, as this may adversely affect plant performance.

4. Discussion

4.1. Optimal Ratios and Mechanisms of Soil Amendment–Induced Plant Growth Promotion

This research showed that the combined use of weathered coal, cattle manure organic fertilizer, and potassium polyacrylate at various ratios significantly enhanced the growth of *Medicago sativa* L. These amendments substantially improved plant uptake of P and K (Figure 1f–g), thereby enhancing the overall nutrient status. Notably, P concentration in the plant showed the strongest correlation with growth parameters (Figure 4b), indicating

that P was the primary limiting factor in alfalfa development. This finding aligns with the well-documented sensitivity of perennial legumes to P availability in arid and semi-arid regions [48,49].

Among all treatments, C10O7P0.6, C10O5P0.9, and C20O7P0.3 exhibited the most pronounced effects. The superiority of these ratios can be attributed to a synergistic balance among structural improvement, nutrient supply, and rhizosphere water buffering. Specifically, applying 10–20 $g \cdot kg^{-1}$ weathered coal effectively increased soil organic matter content (Figure 3b), enhanced aggregate stability, slightly reduced soil pH, and decreased bulk density (Figure 3a,c), thereby improving soil structure and nutrient retention [20,50]. Application of 5–7 $g \cdot kg^{-1}$ cattle manure provided adequate yet moderate nutrient input, significantly increasing AP and AK (Figure 3h,i), which were strongly positively correlated with plant P and K concentrations and biomass (Figure 4a–c). These changes fostered a favorable soil environment for root development and microbial activity [9,51]. Potassium polyacrylate created a transient rhizosphere moisture buffer, alleviating short-term drought stress and potentially enhancing the water use efficiency of the plant (Figure 2b,c), without causing excessive water retention or impeding nutrient diffusion [27,52]. Our findings are consistent with the reported benefits of combining a carbon/structural component, an organic nutrient source, and a water-retention agent. For example, Tiwari et al. [53] reported that co-application of coal char and manure at a 10% (v/v) ratio increased aboveground the biomass of five perennial herbaceous species in semiarid rangelands of the western USA by approximately 40–100% across different years. Roy et al. [11] found that, under an 80% field moisture regime, the combined application of 2% (w/w) cattle manure and 2% (w/w) biochar significantly increased *Onobrychis viciifolia* biomass by 162.5% after two months compared with the control. Moreover, combined applications of manure/compost, carbonaceous amendments, and water-retaining agents have been shown to increase soil-available N, P, and K, as well as plant N/P/K concentrations [10], while also improving soil water content, porosity, and long-term crop productivity [10,54], which were consistent with our results (Figure 2a).

In addition, our results revealed significant positive correlations between plant growth indices and soil TP, AP, AK, and AN, as well as internal concentrations of N, P, and K (Figure 4a,b). Moreover, plant nutrient concentrations were positively correlated with soil physicochemical properties (Figure 4c), suggesting that the amendments not only improved soil nutrient supply but also enhanced P and K uptake efficiency. The structural equation modeling (Figure 4d) confirmed that the amendments facilitated biomass accumulation both indirectly by improving nutrient uptake and directly by enhancing soil properties. These findings support a causal sequence in which soil improvement enhances nutrient availability, thereby promoting biomass accumulation and highlighting the pivotal role of soil quality in regulating plant growth.

4.2. Interaction Effects of Soil Amendments

Although alfalfa biomass under high-dose weathered coal treatment remained significantly higher than the control, response surface modeling and growth trends indicated a potential risk of growth inhibition at excessive levels (Figures 4 and 5). This finding aligns with [24], who reported growth suppression in *Pinus sylvestris* var. *mongolica* seedlings treated with high proportions (>8%) of weathered coal. The inhibitory effect may result from acidic components in weathered coal (Table 1, low pH), which can suppress soil urease activity and microbial function, thereby reducing nitrogen utilization efficiency [55]. However, our multifactorial design showed no significant reduction in plant nitrogen uptake under high weathered coal levels (Figure 1e). Additionally, abundant humic acids in weathered coal may reduce uptake and accumulation of essential trace metals (Zn, Cu,

Mn) without affecting overall plant growth [56]. Interaction analyses further revealed that excessive potassium polyacrylate should be avoided when applied with high weathered coal levels (Figure 5e). Similarly, high levels of organic fertilizer combined with polyacrylate showed antagonistic effects (Figure 5f). This may be attributed to polyacrylate-induced soil pore blockage, leading to excessive soil K^+ accumulation, which inhibits root growth and uptake of Ca^{2+} and Mg^{2+} [8,57]. In summary, the optimized ratio of weathered coal, organic fertilizer, and water-retaining agent is critical for maximizing alfalfa biomass. Future research should focus on elucidating the specific effects of composite amendments on soil enzyme activities and the structure and function of microbial communities, and should optimize amendment ratios according to the physicochemical properties of the materials to enhance nutrient use efficiency and ecological safety. For leguminous crops, concurrent measurements of root nodules and nitrogenase activity would help further clarify symbiotic nitrogen fixation and growth-promotion mechanisms. In addition, long-term field monitoring with multi-temporal sampling is recommended to validate model predictions, refine restoration parameters, and provide empirical support for the practical application of these amendments. Systematic measurements of soil micro- and macronutrient composition in future studies would further clarify the effects of amendments on soil nutrient dynamics and plant nutrient uptake efficiency, providing a more comprehensive theoretical basis for optimizing composite amendment ratios.

5. Conclusions

This study demonstrated that all nine combinations of weathered coal, cattle manure organic fertilizer, and potassium polyacrylate significantly enhanced the growth of *Medicago sativa* L. (alfalfa). Among them, the optimal amendment combination was 10 $g \cdot kg^{-1}$ weathered coal, 5 $g \cdot kg^{-1}$ organic fertilizer, and 0.6 $g \cdot kg^{-1}$ potassium polyacrylate. The soil amendments promoted plant growth by improving soil nutrient availability and structure, thereby enhancing the efficiency of nutrient uptake and utilization by plants. However, excessive application of weathered coal may inhibit plant growth. Furthermore, high levels of potassium polyacrylate should be avoided, particularly when combined with high doses of weathered coal or organic fertilizer, to prevent antagonistic effects. Therefore, precise regulation of amendment ratios is essential to achieve synergistic effects and minimize resource waste during soil improvement efforts.

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Abbreviations

The following abbreviations are used in this manuscript:

OM	Organic Matter
TN	Total Nitrogen
TP	Total Phosphorus
TK	Total Potassium
AN	Available Nitrogen
AP	Available Phosphorus
AK	Available Potassium
AW	Available Water
WUE	Water Use Efficiency
C	weathered coal
O	cow manure organic fertilizer
P	potassium polyacrylate

Appendix A. Dosage Selection and Rationale for Soil Amendments

This greenhouse pot experiment employed three-level (low–medium–high) application rates for each soil amendment to evaluate dose–response relationships and interaction effects. The treatment levels were selected based on published literature and manufacturer recommendations. Specifically, weathered coal (C) was applied at 10, 20, and 30 $g \cdot kg^{-1}$ (≈1%, 2%, and 3% w/w, dry-weight basis), following recent studies on its use for soil improvement [19,21] to represent low–medium–high intensities. Cattle manure (O) was applied at 3, 5, and 7 $g \cdot kg^{-1}$, a range that falls within the commonly used pot and incubation study rates (1–10 $g \cdot kg^{-1}$), with 5 $g \cdot kg^{-1}$ often adopted as a medium reference [15,39], thereby establishing a gradient for dose–response analysis. Potassium polyacrylate (P) was applied at 0.3, 0.6, and 0.9 $g \cdot kg^{-1}$ (≈0.03%, 0.06%, and 0.09% w/w, dry-weight basis), informed by the product datasheet recommendation for sandy soils (recommended rate ≈ 60–80 $g \cdot m^{-2}$).

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