Journal of Waste Resources and Recycling
Volume 5 | Issue 1
ISSN: 2766-5887

Research Article Open Access

Soil Amendments in Open-Pit Coal Mine: Effects on Reconstituted Soil Nutrients and Enzyme Activities

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Citation: Zhuo Yang, Shibo Sheng, Peizhong Ma, Na Liu, Jianbao Xin (2023) Soil Amendments in Open-Pit Coal Mine: Effects on Reconstituted Soil Nutrients and Enzyme Activities. J Waste Resour Recycl 5(1): 101

Abstract

Reconstituted soil is mainly used to address the lack of soil in open-pit mines. To understand how soil amendments affect reconstituted soil nutrients and enzyme activities in open-pit coal mine, the investigation is carried on overburden material from an open-pit coal mine in Eastern Inner Mongolia, China. We tested the nutrients and enzyme activities of reconstituted soil under different conditioners of distiller's grains with corncobs or sodium humate. According to the stepwise regression analysis, "Distiller's grains + corncobs" was the best configuration of all. The application of distiller's grains enhanced the soil available nutrient content and enzyme activities. Its optimal application increased the content of AN (alkaline hydrolysis nitrogen), AP (available phosphorus), AK (available potassium) by 20.18%, 32.10% and 13.86%, and increased the enzyme activities of catalase, phosphatase, sucrase and urease, by -16.9% ~ 398.1%. It was soil enzyme activities mainly affected the AN, AP and AK content. For other amendments, when adding more sodium humate, AN increased at first and then lowered, and AP was increased. Supplying corncobs induced enzymes to change the content of AK. The greater influence on soil enzyme activities was observed when the dose of amendments was increasing. Therefore, our results consolidate the important position of soil enzyme activity in the nutrients transportation of mine reconstituted soil. The using of distiller's grains and corncobs should provide a scientific and technical support to improve mine soil reconstitution.

Keywords: Open-pit coal mine; Overburden material; Reconstituted soil; Distiller's grains; Soil enzyme

Introduction

Coal is an important energy source for human wellbeing. While mining continues to intensify year by year, the ecological disasters caused by the development of surface coal mines has become one of the major environmental concerns [1]. Open-pit coal mine has severely damaged the original landform, leading to the reconstitution of the stratum structure, and affected vegetation in the mining area [2]. Ecological restoration and reconstitution appear to be essential. However, the reconstituted soil lacks fertility and the stratum structure can hardly support the need for reclamation. Excavation and pile surface formed by mining are much larger than the original surface. This lack of surface soil for many mines hinders ecological restoration [3]. Relying on the topsoil overburden of the original topographic structure only is not enough to undertake reclamation in mines. Hence, soil reconstitution is the best way to solve the lack of topsoil [4].

Nutrients and enzyme activities reflect the quality of reconstituted soils [5,6]. Studies have shown that enzyme activities can indicate the performance of reconstituted soil. Soil enzymes and microorganisms catalyze the conversion of organic matter and the mineralization and homogenization of nutrients [7]. The contents of different forms of N, P, and K are strongly correlated with soil enzyme activities [8-11]. Thus, studying the effects of different amendments on soil nutrients and enzyme activities can characterize the most suitable amendment, especially catalase, phosphatase, sucrase and urease.

In China, mine soil reconstitution addresses the lack of soil for open-pit mine. The remaining mine overburden material actually constitutes both a waste and a resource. Using amendments to convert overburden material into a suitable reconstitution matrix has become a routine procedure for mine ecological restoration. Studies have shown that distiller's grains can increase soil microbial content [12] and control soil erosion [13], and therefore be a good soil amendment. However, the large amount of cellulose and hemicellulose in distiller's grains are difficult to degrade, considering the degradation cycle of the distiller's grains which is relatively long.

Soil adding distiller’s grains will rise soil nutrient content and promote soil improvement effects [14-16]. Therefore, it is always to select distiller’s grains as an amendment mixed with other amendments to explore the mutual influence between amendments and optimize their effect. Corncobs can be easily decomposed and transformed by microorganisms. These bacteria process the enzymatic reaction and nutrient content and multiply during biomass cracking [17]. Corncobs mixed with fertilizer can strengthen microbial activities [18], but the mixed use with fermentation products such as distiller's grains is not well understood. Weathered coal humic acid contains a variety of active functional groups with acidity, hydrophilicity, and cation exchange capacity. These characteristics can improve the soil structure and the living environment of microorganisms [19,20], hence suitable as soil amendment. However, the effect of the coal humic acid mixed application with other amendments on the nutrients and enzyme activities is not well addressed. Research on the effect of single amendment on mine soil improvement is relatively rich. But the consequences of mixed application of amendments remain unclear, especially the mechanism and effect of mixed application of biological amendments with waste and inorganic amendments [21]. The evaluation for different soils is sparse and effects on soil enzyme activities display nuances even if the same kind of soil amendment is applied [22].

Organic matter - microorganism - humus - humic acid - microorganism is a whole system that runs through soil life. Humic acid leads the substance exchange and energy transformation of soil ecosystem during soil formation. So the sodium humate is always used in mining soil improvement as a necessary factor for sustainable soil life [19]. Against this background, soil amendment selection followed an extensive process to include diverse configurations. Both corncobs, distiller's grains and sodium humate are byproduct of coal mines easy to obtain. Two biological amendments of corncobs and distiller's grains and one inorganic amendment sodium humate are the approaches used to reconstitute the soil environment. So, we try to explore the optimal configuration of different amendments for the reconstituted soil in open-pit coal mines, and the resulting effect of nutrients and enzyme activities, and hope to provide scientific and technical support for the selection of soil amendments in local mine reclamation.

Materials and Methods

The reconstituted soil and experimental design

The reconstituted soil samples were collected from an open-pit coal mine in the Eastern Inner Mongolia, China, located at 119°08'–119°46' east longitude and 45°10'–45°40' north latitude. The soil freezes from early October to May. The multi-year average temperature is 0.1℃. The multi-year average precipitation is 358.98 mm. Precipitation mainly occurs from May to September, accounting for about 81.7% of the annual precipitation in the area. The multi-year average evaporation is 1556 mm. The samples (overburden material) were collected from the mine dump in September 2020, and then transported to the soil laboratory for testing. The soil contained TN (total nitrogen) 0.88 g kg^{-1}, TP (total phosphorus) 0.83 g kg^{-1}, and TK (total potassium) 16.33 g kg^{-1}.

The cultivation experiment was carried out in the laboratory. 5 kg mine overburden material mixed with soil amendments were placed in a 450mm190mm140mm long pot. The amendments were distiller's grains, corncobs and sodium humate. A total of 10 treatments and 5 replicates were set up in the experiment (Table 1). The temperature maintained at 27°C, soil moisture content 60%, illumination 12h/d and other management conditions kept constant. According to the pre-experiment and experience of reconstruction soil ameliorated by distiller's grains, corncobs and sodium humate [17–21], the numbers of 1, 2 and 3represented the application of different concentrations of amendments, and the letters of D, C and S represented the application of different amendments.

Table 1: Procedures of amendments with different treatments

Treatments	Amendments g kg^{-1}		
	Distiller's grains	Corncobs	Sodium humate
CK	0	0	0
D1	4	0	0
D1+C1	4	4	0
D1+S1	4	0	1.5
D2	8	0	0
D2+C2	8	8	0
D2+S2	8	0	3
D3	12	0	0
D3+C3	12	12	0
D3+S3	12	0	4.5

Soil enzymes determination and soil characteristics analysis

The indexes of enzyme activities and nutrient were measured after 5 months of cultivation. The measured indexes of soil enzyme were catalase, phosphatase, sucrase and urease. The catalase activity was determined by colorimetric method. Expressed by the number of milligrams of hydrogen peroxide, it decomposes 1-gram soil within 20 minutes. The phosphatase activity was determined by the colorimetric method of p-nitrophenol sodium phosphate. It is expressed by the milligrams of the mass of p-nitrophenol produced in 1-g soil after 1-h cultivation of constant temperature at 37°C. Sucrase activity was determined by sodium thiosulfate titration method and expressed by the deviation value of sodium thiosulfate consumed between blank control and different treatments in 1-g soil. The urease activity was determined by the sodium phenate-sodium hypochlorite colorimetric method and expressed by the milligrams of NH+ 4-N produced in 1-g soil after 24 h cultivation of constant temperature at 37°C.

The measuring nutrient indicators mainly include TN, TP, TK, AN (alkaline hydrolysis nitrogen), AP (available phosphorus) and AK (available potassium). TN was determined by sulfuric acid-mixed accelerator digestion kjeldahl method, and TP was determined by NaOH molten molybdenum-antimony ratio colorimetric determination (pH > 7). TK was determined by NaOH melting flame photometer colorimetric method. AN was determined by alkali hydrolysis diffusion method. AP was determined by sodium bicarbonate leaching molybdenum and antimony anti-colorimetric method. AK was determined by ammonium acetate extraction flame photometer colorimetric method.

Data processing method

Statistical analyses were performed using *IBM SPSS 22*. Analysis of variance (ANOVA) and LSD multiple comparisons were performed on the soil nutrients and soil enzyme activities for different treatments. Correlation between the treatments was evaluated, and Excel 2019 used for mapping.

Results

The effect of different amendments on soil nutrients

The soil nutrient changes that treated with different amendments are shown in Figure 1. Comparing treatments D1, D2, D3 and CK, the application of distiller's grains could promote the improvement effect of available nutrients, but cannot increase the total nutrients contents. The treatment of C concentration performed the best promotion effect.

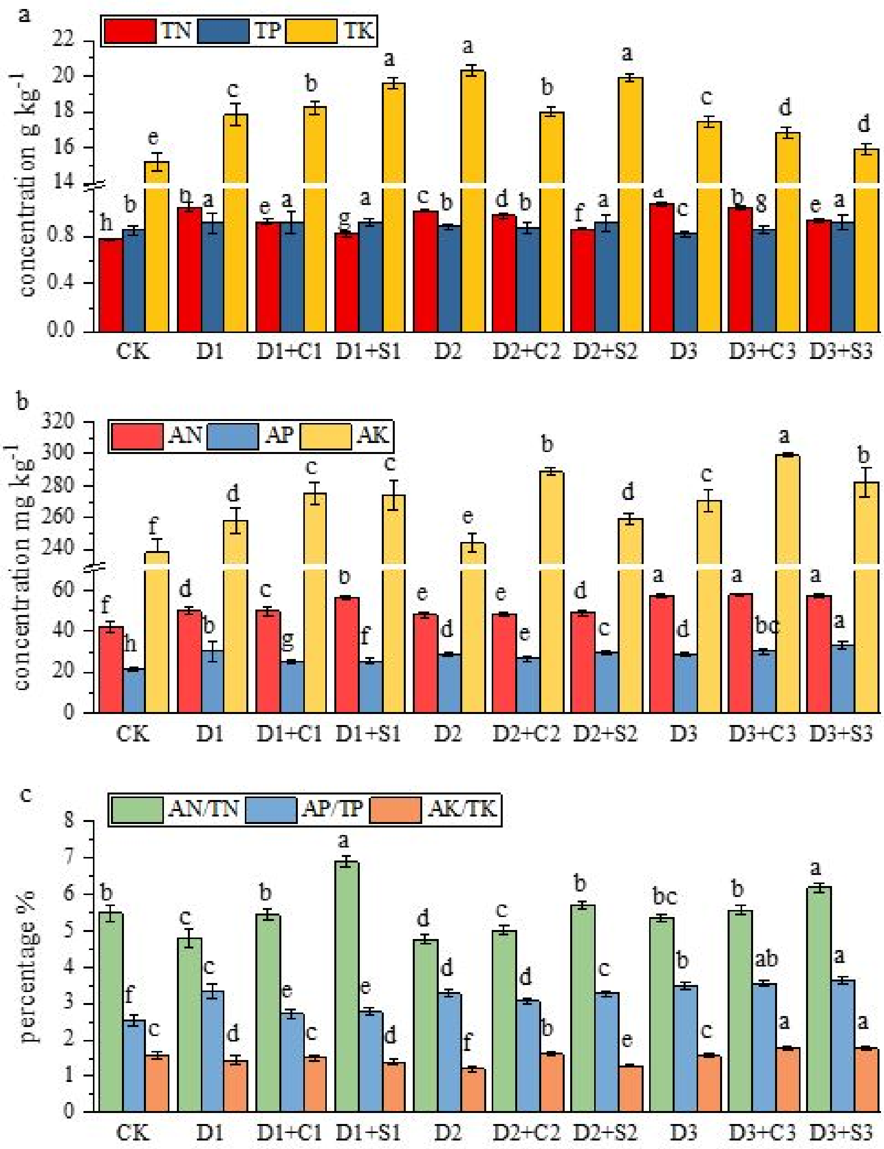

Figure 1: Changes of soil nutrients under different amendment conditions

Note: Different letters of the concentrations indicate the significant differences between treatments ($P<0.05$).

After application using different concentration of distiller’s grains, the conversion of available nutrients was increased (Figure 1c). The percentage of AN/TN, AP/TP and AK/TK under the distiller’s grains concentration of 8 g kg^{-1} and 12 g kg^{-1} treatments were higher than 8 g kg^{-1}. It showed a trend that corncobs and sodium humate adding could increase the effectiveness significantly. Furthermore, the treatments of A concentration shows a raise for the contents of AN, AP, and AK of -1.50%, 40.31%, and 8.80%. The treatments with 8 g kg^{-1} distiller’s grains show an increase of the contents of AN, AP and AK of 0.94%, 33.07%, and 2.40%. The treatments with 12 g kg^{-1} distiller’s grains show an increase of the contents of AN, AP, and AK of 20.18%, 32.10%, and 13.86%.

The mixed application of distiller’s grains and corncobs had much more effect on the content of TK and AK. The TK content after the application of corncobs was less than that of distiller's grains alone, and the content of AK was higher than that of distiller's grains alone. This indicated that the mixed application of distiller's grains and corncobs can augment the conversion capacity of potassium. The application of corncobs provided a suitable living environment for the microorganisms in the distiller's grains and improved the microbial activities.

There were significant differences in the content of AN between the treatment of distiller's grains mixed with sodium humate and distiller's grains alone in the three concentrations. The content of AN improved significantly by applying sodium humate of 1.5 g kg^{-1} and 3 g kg^{-1} concentration. The concentration of 1.5 g kg^{-1} had increased by 20.61% and B by 22.81%. Humic acid can stimulate the transformation of nitrogen in mine overburden material and the release of AN. These finding are consistent with the conclusions reached for the study of the influence of humic acid on coal gangue [23]. Application of sodium humate at 4.5 g kg^{-1} concentration reduced the content of AN by 23.07%.

There are some difference between applying corncobs and sodium humate in distiller's grains. The improvement effect of 1.5 g kg^{-1} sodium humate treatment was similar to that of corncobs. The effect of 8 g kg^{-1} corncobs treatment was better than that of sodium humate in improving the content of AK, and other nutrient indexes were not as good as that of sodium humate. The improvement effect of corncobs was further promoted. Among them, there were significant differences in the concentrations of AN. This indicates that the application of sodium humate and distiller's grains will cause differences in AN. The ability of corncobs applied at concentration 4 g kg^{-1} and 8 g kg^{-1} to improve alkaline nitrogen hydrolysis was worse than that of sodium humate. The opposite was true for concentration 12 g kg^{-1}. There was no significant difference for the concentration of AK in 4 g kg^{-1}, but significant one for the concentration of 8 g kg^{-1} and 12 g kg^{-1}. This indicates that the application of corncobs and sodium humate with the concentration of No.1. Affected by sodium humate, D2+C2 > D2+S2, D3+C 3> D3+S3. This phenomenon suggests that the application of corncobs at the concentration of 8 g kg^{-1} and 12 g kg^{-1} was better than that of sodium humate in increasing AK.

Effects of different amendments on soil enzyme activities

The catalase activity for different concentrations follows this pattern: No.3 concentration> No.2 concentration> No.1 concentration, with the catalase activity of CK treatment being the lowest (Figure 2a). The significant difference between No. 1 treatment and CK treatment after applying distiller's grains, reveals that adding distiller's grains can strengthen catalase activity. The treatment of "distiller's grains + corncobs" produced the highest catalase activity. This implies that the mixed amendment of distiller's grains and corncobs was the most effective form of improving soil catalase activity, with the No.3 concentration the optimal one. After the application of sodium humate, the catalase activity of the D1+S1 and D3+S3 decreased slightly, and the catalase activity of the D2+S2 treatment increased slightly. But the catalase activity for each treatment was much smaller than that of the "distiller's grains + corncobs" treatment. Therefore, the application of sodium humate was not very helpful in improving soil catalase.

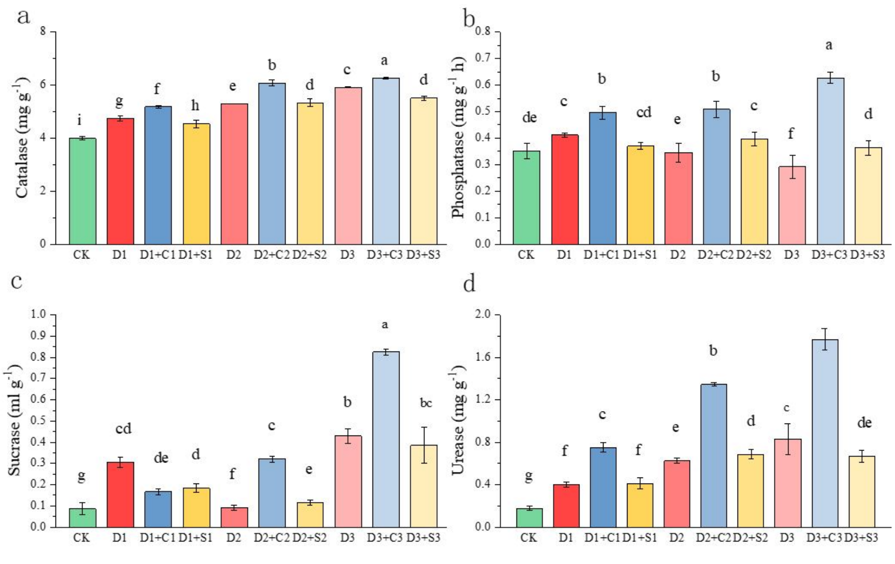

Figure 2: The activities of Catalase, Phosphatase, Sucrase and Urease

Note: Different letters of the concentrations indicate the significant differences between treatments (P<0.05).

As the concentration of distiller's grains increased, the phosphatase activity gradually decreased, and the phosphatase activity for distiller's grains 8 g kg^{-1} and 12 g kg^{-1} was lower than that of the blank treatment (Figure 2b). This denotes that too much distiller's grains will inhibit the soil phosphatase activity. The phosphatase activity of corncobs significantly increased between "distiller's grains" and "distiller's grains + corncobs" treatment. As the distiller's grains concentration raised, phosphatase activity did likewise. The mixed effect was much better than that of the distiller's grains alone. The application of sodium humate treatment had no effect on the phosphatase activity at the three concentrations. The mixed application of sodium humate and distiller's grains can reduce the negative effects of distiller's grains on the phosphatase activity, but could not improve the phosphatase activity.

The sucrase activity – between CK and distiller's grains treatment – showed a decrease and then an increase as the amount of distiller's grains increased after applying distiller's grains to the reconstituted soil (Figure 2c). The 12 g kg^{-1} distiller's grain relatively stimulated more the soil sucrase activity. The mixed application of distiller's grains and corncobs imposed sucrase activity significantly. The D3+C3 treatment obtained the highest sucrase activity. This suggests that the configuration mode of "distiller's grains + corncobs" at 12 g kg^{-1} was the best way to improve sucrase activity. The mixed application of distiller's grains and sodium humate does not enhance the sucrase activity as much as adding distiller's grains alone, but it is still much better than that of CK. To sum up, the "distiller's' grains + corncobs" configuration mode was the best way to improve soil sucrase activity, and the combination "distiller's' grains + sodium humate" was slightly worse than that of adding distiller's grains alone. Both of them had intensified much more the sucrase activity at 12 g kg^{-1} concentration, resulting in the improvement effect.

The urease activity amplified with the increase of the amount of distiller's grains after applying distiller's grains to the reconstituted soil (Figure 2d). The urease activity of the soil after applying distiller's grains was much greater than that of CK treatment. This reveals that distiller's grains could strengthen soil urease activity. The mixed application of "distiller's grains + corncobs" improved urease activity significantly. The D3+C3 treatment displayed the highest sucrase activity. This suggests that the configuration mode of "distiller's grains + corncobs" at 12 g kg^{-1} concentration was the best improved way to improve urease activity. The mixed application of distiller's grains and sodium humate stimulated as much sucrase activity as adding distiller's grains alone, indicating that the application of sodium humate had no influence on soil urease activity.

The effects of different amendments on soil enzyme activities are summarized in Table 2. The corncobs intensified soil enzyme activities the most, and followed by distiller's grains. Corncobs are good amendments of mine overburden material as they stimulate the four kinds of enzyme activities. The mixing of corncobs and distiller's grains can effectively improve the activity of the four soil enzymes. Sodium humate mainly supplements the carbon content in soil and improves the cation exchange capacity as a high molecular compound, but has little influence on the enzyme activities.

Table 2: The Pearson Correlation of different amendments on soil enzyme activities

	Catalase	Phosphatase	Sucrase	Urease
Distiller's grains	0.877**	0.145	0.667*	0.659*
Corncobs	0.639*	0.930**	0.709*	0.913**
Sodium humate	0.005	-0.253	-0.081	-0.180

Note: "**" Correlation is significant at the 0.01 level (2-tailed).

"*" Correlation is significant at the 0.05 level (2-tailed).

Effects of different amendment conditions on the relationship between soil nutrients and soil enzyme activities

The relationship between soil nutrient indexes and soil enzyme indexes under different amendment conditions was analyzed. The catalase, phosphatase, sucrase, and urease were used as dependent variables. The TN, TP, TK, AN, AP, and AK were considered independent variables. The linear stepwise regression analysis for different treatments was performed and reported as Table 3.

Table 3: Stepwise regression analysis results between soil nutrients and enzyme activities

Amendment	Parameter								
	y0	a	b	c	d	e	f	R^2	P
Catalase=y0+a TN+ b TP +c TK+ d AN+ e AP+ f AK									
D	2.16	-1.58	-	-	0.09	-	-	0.92	<0.01
D + C	0.50	-	-	-	-	-	0.02	0.55	<0.01
D + S	2.53	-	-	-	-	0.09	-	0.40	<0.05
CK	2.36	-	-	-	0.04	-	-	0.77	<0.01
Phosphatase=y0+a TN+ b TP +c TK+ d AN+ e AP+ f AK									
D + C	968.59	-	-	-	-25.24	-	-	0.46	<0.05
Sucrase=y0+a TN+ b TP +c TK+ d AN+ e AP+ f AK									
D	0.48	-	0.35	-0.07	0.01	-	-	0.87	<0.05
D + C	-2.94	-	-	-	-	-	0.01	0.71	<0.01
CK	-0.37	-	0.31	-	0.00	-	-	0.86	<0.01
Urease=y0+a TN+ b TP +c TK+ d AN+ e AP+ f AK									
D	-0.94	-1.01	-	-	0.03	-	0.01	0.87	<0.01
D + C	-4.75	-	-	-	-	-	0.02	0.66	<0.01
D + S	-0.06	-0.69	-	-	-	0.04	-	0.66	<0.05

Note: D: Distiller's grains; C: Corncob; S: Sodium humate; y0 (intercept), a, b, c and d: parameter of the multiple linear regression; R^2: coefficient of determination; p: probability of significance. "–" means nutrient factor not included in given equation, or no equation with significance.

The main influencing factor of catalase activity was AN through the blank treatment fitting equation. Combined with the treatment of distiller's grains and the blank treatment, catalase had an effect on nitrogen before and after distiller's grains were applied. Combined with the treatment of "distiller's grains + corncobs" and distiller's grains, the influencing factor of catalase activity changed from nitrogen element to AK after the corncobs were put. Combining the fitting results of the "distiller's grains + sodium humate" treatment and the distiller's grains treatment, the catalase was greatly affected by the AP after sodium humate was applied.

There was no linear correlation between the phosphatase activity and nutrients in the treatment of the distiller's grains, "distiller's grains + sodium humate" and the blank. The addition of distiller's grains has a positive effect on the relationship of nutrients and phosphatase activity. The potassium has an influence on the phosphatase activity after adding corncobs.

The nutrient indexes affecting the sucrase activity without the addition of amendments were AN and TP. The TP and AN stimulate much more the sucrase activity after the application of distiller's grains, while the inhibitory effect of TK on sucrase activity increased. Adding corncobs enhances the sucrase to convert TK, TP and AN into AK.

AN and AK had a positive effect on urease activity after distiller's grains were applied, while TN had an increased inhibition on urease activity. The addition of corncob weakened the effect of nitrogen on urease activity. However, potassium still had a positive effect on urease activity. Before and after the application of sodium humate, the TN remained unchanged: the improvement effect on the AN and AK was transformed into that on AP.

In summary, the imitative effect of catalase was the best, and there was a linear relationship between nutrients and enzyme activities in the four treatments. This reveals that the application of amendments had the greatest impact on the internal connection between nutrients and catalase activity. And the imitative effect of phosphatase was the worst. Only the distiller's grains + corncobs treatment showed a linear relationship between nutrients and enzyme activities. This suggests that the amendments had little effect on the internal relationship between nutrients and phosphatase.

Discussion

In this study, the application of distiller's grains in reconstituted soil heightened the content of soil available nutrient. The application amount of distiller's grains with C concentration was the optimal application amount [24]. The contents of AN, AP and AK would be increased by 20.18%, 13.86% and 32.10%, respectively. After the mixed application of "distiller's grains + corncobs", other nutrients except potassium had little change. The application of corncobs converted TK into AK. The AK content multiplied with more corncobs. The application of sodium humate in distiller's grains had a greater impact on the content of AN. As the amount of sodium humate grew, the AN tended to increase first and then decrease. The available nutrients and soil enzyme activities were significantly improved with the application of distiller's grains. When distiller's grains and corncobs were applied together, the soil enzyme activities increased significantly compared to the application of distiller's grains alone. The lack of nutrients and microorganisms in the reconstituted soil might be the reason [2]. The application of distiller's grains in the soil changed the balance of soil microorganisms and improved the conversion efficiency of available nutrients [25]. The limited amount of aggregates in reconstituted soil and the poor microbial living conditions hindered the microorganisms' development [26]. These could only attach themselves to the distiller's' grains and inhibited the improvement effect. In addition, the decomposition ability of microorganisms would be weakened if the ratio of carbon to nitrogen is too large [27]. Therefore, applying the 12 g kg^{-1} distiller's grains concentration of sodium humate would cause a too high soil carbon content. The amount of sodium humate should be limited within the concentration of 1.5 g kg^{-1} and 3 g kg^{-1}.

Corncobs were the raw material for the production of potash fertilizer, and potassium was one of the main components. The AK content heightened through the decomposition and transformation of the microorganisms and corncobs. Corncobs serve as good carriers for microorganisms in the distiller's grains, providing a suitable habitat for the microorganisms and increasing the soil enzyme activities [28]. The study also found that the TK content for the treatment "distiller's grains + corncobs" was reduced compared to the treatment with distiller's grains alone. In result, the AK content was increased. The addition of corncobs caused a significant increase in soil enzyme activities. The increase in soil enzyme activities promotes the conversion of TK into AK. And the main components of corncobs are cellulose, hemicellulose, lignin, etc. [29]. With the biomass pyrolysis pushed by enzyme, potassium ion conversion was intensified, making corncobs an important amendment to enhance the contents of AK [30,31].

The application of amendments would result in interaction changes between nutrients and enzyme activities. In this experiment, the enzyme activities mainly affected the content of AN without adding amendments. After applying distiller's grains, the enzyme activities still affected the AN. The effect of corncobs enzyme activities on potassium element was changed by adding sodium humate into distillers' grains. The effect of enzyme activities on AP was changed by adding sodium humate into distillers' grains, probably due to the main catalytic of soil enzymes. With the addition of amendments, the chemical reaction process changed, likely related to the type of amendments. The addition of corncobs accelerated the conversion process of soil enzymes to AK. In one hand, sodium humate has strong adsorption and potentially remediate heavy metals contaminated soils and increase the amount of aerobic bacteria, actinomycetes and fiber decomposing bacteria [32,33]. In another hand, it could also accelerate the mineralization of organic matter and promote the release of nutrient elements [34]. Studies such as Andrade have found that humic acid can regulate the content of phosphorus in the soil [35]. Therefore, the application of sodium humate amplified the release of soil phosphorus and AP by soil enzyme activities.

The enzyme activities are related to nutrient conversion. It is recommended that the substrate, various amendments and the relationship between soil microbial activities and enzyme activities should be combined with actual conditions in the subsequent research of soil reconstitution. Different types of amendments can cause diverse effects in soil nutrients and enzyme activities [23]. In general, the types of amendments are important indexes affecting enzyme activities. Soil enzymes need a suitable environment to survive. The addition of corncobs improves soil porosity and soil aggregate structure. It provides a comfortable living environment for various soil enzymes and strengthens their activity. The complex biological flora could help the soil microbial system to rebuild better after the fermentation. As the soil quality of mine overburden material got degraded overtime, the microorganism living environment was threatened [36]. A better carrier with mixed use is needed to achieve optimal results. Distiller's grains – fermented residues of rice, wheat, sorghum etc., and sugars – produce lactic acid after fermentation, which had a certain impact on soil alkaline phosphatase. The mixed application of distiller's' grains and corncobs could amplify the soil phosphatase activity, and the optimal concentration was 12 g kg^{-1}. The types of mixed amendments should be developed to form a perfect amendment system of reconstituted soil in mine.

Conclusion

This work analyzed nutrient characteristics and enzyme activities, and their relationship for reconstituted soil in open-pit coal mine with different amendments. The application of distiller's grains would augment the soil available nutrient content. The concentration of 12 g kg^{-1} distiller's grains was the optimal application amount. After mixing corncobs and distiller's grains, the TK decreased, the AK increased, with the releasing concentration rising. The mixed application of distiller's grains and sodium humate had a greater influence on the content of AN. The AN augmented first and then lowered with the increasing of sodium humate contents.

The reconstituted soil enzyme activities increased after the application of distiller's grains. The contents of nutrients and enzyme activities were similar to those of distiller's grains after the mixed application of distiller's grains and sodium humate. The "distiller's grains + corncobs" was the best form of amendment ratio. In terms of the relationship between soil nutrients and enzyme activities for different amendment conditions, the enzyme activities without amendments mainly affected the AN content. After adding corncobs to the distiller's grains, the enzyme activities affected the content of K. After adding sodium humate to the distiller's grains, the enzyme activities affected the content of AP.

Author Contributions

Z.Y and P.M conceived and designed the methodology; S.S, N.L and J.X , performed the numerical simulations and data analyses; Z.Y, S.S and N.L wrote, edited and reviewed the manuscript. Z.Y and P.M handled project administration and secured funding. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the Science and Technology Innovation Venture Fund of China Coal Science and Industry Corporation (2018-2-ZD005) and Natural Science Foundation of Liaoning Province (2023-MS-342).

Conflicts of Interest

The authors declare no conflict of interest.

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