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# Soil properties in reclaimed farmland by filling subsidence basin due to underground coal mining with mineral wastes in China

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**Abstract:** Reclaimed mining-induced subsidence area soils (RMSs) could restore soil quality and crop productivity in coal mining area. This study was conducted to evaluate the effects of mineral-processing wastes (fly ash vs coal gangue) as backfill substrates on soil chemical and microbial properties in mining-induced subsidence area. A general higher water holding capacity (WHC) and pH had been observed in fly ash than coal gangue reconstructed soil. Soil microbial biomass C (MBC) and N (MBN), MBC/TOC (total organic carbon) ratio ($q_{mic}$) were higher under the influence of the fly ash, while contents of As, Cr, C/$N_{bio}$, the basal respiration per unit of microbial biomass ($Q_{CO_2}$) were higher under the coal gangue reconstructed mode in 0−10, 10−20, 20−50 cm layers. The microbial basal respiration was higher in 0−10, 10−20, 0−50 cm layers, while was lower in 20−50 cm layer under fly ash than that of coal gangue reconstructed mode. The lower $Q_{CO_2}$ of fly ash mine soil suggested the lower maintenance energy requirement of the microbial community. Moreover, the contents of metals may possibly have negative implications for soil microbial and enzyme activities in reconstructed soil.

**Key words:** reconstructed mine soil; mineral-processing wastes; microbial biomass; enzyme activities

## 1 Introduction

Mineral resources are the most important resources on which human beings depend [1]. However, most of mineral resources stored underground and usually can not be got unless destroying the land and making a lot of mineral-processing wastes [2,3]. Mine soil had been completely submerged and backfilled by mineral-processing wastes causing soil structure and functions to be adversely affected in mining-induced subsidence area with high ground water level in China. This disturbance can have severe negative impacts on soil quality and crop productivity including organic matter and potential for impaired nutrient cycling in reclaimed mine soil [4].

Since crop productivity and agroecosystem function are dependent on the quality and fertility of soils, the most key challenge of mine soil reconstructed is to reestablish soils to a level of health similar to those originally present before mining. Thus, after completion of landscape reconstructed in land subsidence area, the most important process was agroecosystem development in mining-induced subsidence. There are significant differences in soil properties between reconstructed soils with mineral-processing wastes (fly ash or coal gangue) and undisturbed soils [5].

A variety of reports that the process of reconstruction leads to a great change in the soil physical and chemical parameters, showed the increased bulk density, pH and compaction of reconstructed soil [6]. Moreover, reclaimed soil is generally decreased in soil nutrients, such as organic matter, total nitrogen, rapidly available phosphorus, and rapidly available potassium [7]. However, physical and chemical properties of reconstructed soils would take decades or longer to reach equilibrium and be insensitive to environmental stress [8]. Recently, soil biochemical properties had been used as the indicators because of their great sensitivity to environment changes and feeding of nutrient cycling. Although there are some evidences show that soil quality is lower in reclaimed mine soil in those un-disturbance soil, there is a need for a systematic analysis of soil

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quality, and potential effect factors such as mineral-processing wastes, level of ground water, or the quantity of external nutrient inputs in mine soils with high ground-water level.

This study is aimed to assess the effects of different mineral-processing wastes (fly ash or coal gangue) on reconstructed mine soils with high ground-water level. We try to investigate that 1) the differences of the soil chemical, microbial and enzyme properties in the different reconstructed soils; 2) whether or not the microbial and enzyme properties are suitable as indicators to predict nutrient cycling in mine soil under higher groundwater environment; 3) whether or not the microbial and enzyme parameters are sensitive indicators under the soil metal stress in mine reconstructed soil. These data can be used to indicate which mine wastes is used as a better backfill matters in mine soils reclaimed high ground-water level.

## 2 Experimental

### 2.1 Site description

The experimental sites were in Liu-Xin National Reconstructed Demonstration Zones, Xuzhou, Jiangsu Province, China, as shown in Fig. 1 [9]. The soil was classified as brown soils. Climate in this region is temperate, characterized by hot, moist summers and cool winters. The annual average air temperature is 14.5 °C. The mean annual precipitation ranges between 800−930 mm.

Coal mining induced the mined-out area in underground mines, and had formed land subsidence since 1980s. Mining-induced subsidence has changed waterlogged area for high ground water and had affected land use along with time. Soil reconstructed practice and plants restoration of study area had been conducted in 1996 (filling with coal gangue) and 1998 (filling with fly ash). The coal gangue was collected from the Chacheng Coal Mine and fly ash used in this project was obtained from Chacheng Power Plants. The depth of topsoil was 50 cm in reconstructed area. All plots were chisel plowed cultivated to break up compaction and incorporate fertilizer and compost before planting winter wheat. After wheat harvest, rice was planted with a no-tillage in the reconstructed soil.

### 2.2 Sampling design

Soil samples were collected in May 2008. The study sites utilized three experimental locations as follows: CTL, the undisturbed soil; RCG, reconstructed soils by coal gangue; RFA, reconstructed soils by fly ash.

At all sites, 20 m×100 m transects were randomly established and five sampling points were located along each of these transects. At each sampling point, soil

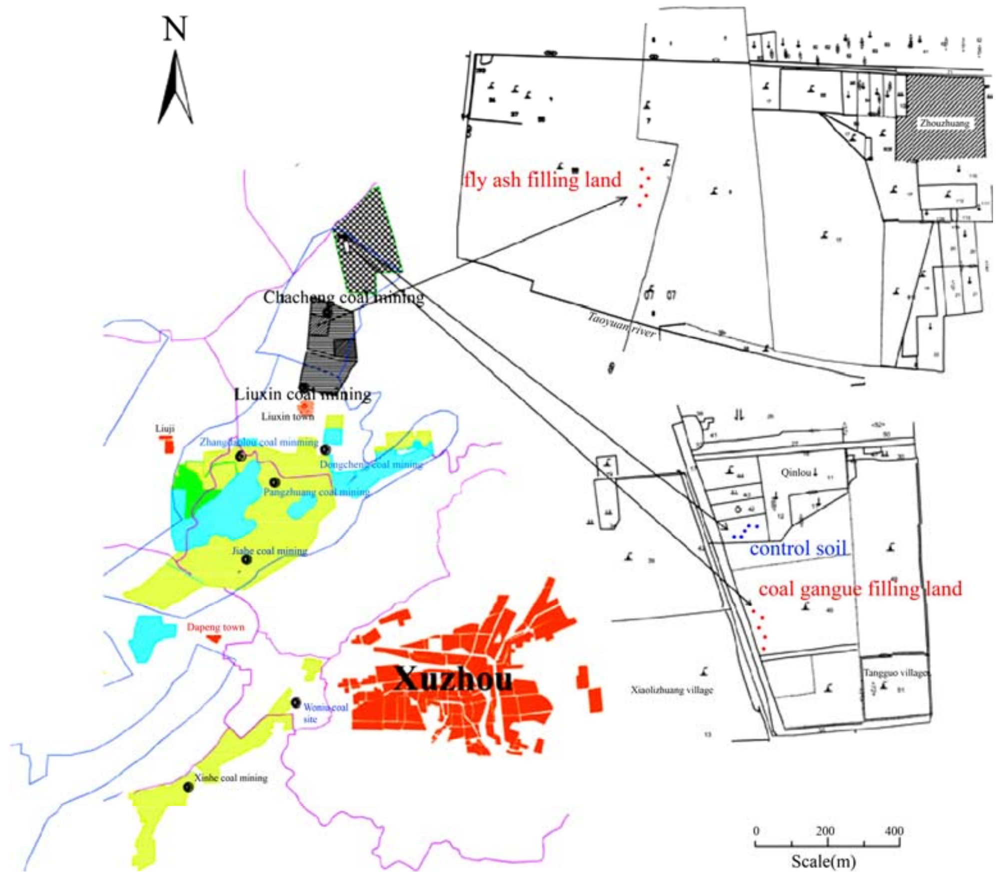


**Fig. 1** Map of study fields (cited by DONG [9], 2012)

samples were taken at depth increments of 0−10, 10−20, and 20−50 cm, resulting in a total 45 soil samples. Soil samples were transported in ice box to the laboratory, where they were sieved through a 2 mm mesh to remove plant debris and soil fauna. Each of the 45 samples was separated into two portions. The first portion was air dried for chemical analysis. The second portion was stored at 4 °C for microbial and enzyme activities analyses.

### 2.3 Soil physico-chemical properties

Soil moisture was weighed after the soil was oven-dried at 105 °C for 24 h. Soil pH was measured in a 1:2.5 (w/v) aqueous solution using a pH meter. Total organic carbon was determined by oxidizing a soil solution with $K_2Cr_2O_7$ and concentrated $H_2SO_4$ at 170−185 °C, and then the solution was titrated with $FeSO_4$ [4]. Total soil N, available soil P and K concentrations were determined according to Ref. [10].

### 2.4 Soil microbial biomass

Soil microbial biomass was measured by the chloroform−fumigation extraction method. These analyses were completed within one week of sample collection [11−13]. Fumigated and un-fumigated samples were analyzed in triplicate. For the fumigated samples, 10 g of fresh soil was fumigated with alcohol-free chloroform for 24 h in a dark vacuum chamber. For un-fumigated samples, 10 g of fresh soil was also stored in the dark next to the vacuum chamber. Then, the fumigated and non-fumigated samples were extracted with 0.5 mol/L $K_2SO_4$. The extracts were filtered and frozen until analysis. The soil microbial biomass was measured with a TOC/TN analyzer. The conversion factors were 0.45 for biomass C and 0.54 for biomass N, respectively.

### 2.5 Soil enzyme activities

Phosphatase activity was measured using p-nitrophenyl phosphate (pNPP) as an orthophosphate monoester analogue substrate [14]. Briefly, 1 g of soil sample was placed in test-tube with buffer and substrate, then incubated at 37 °C. When reaction was terminated, the soil suspension was filtered and measured with a spectrophotometer at 405 nm against the reagent blank and p-nitrophenol content determined by reference to a calibration curve.

Measurements of catalase activity were determined by adding $H_2O_2$ to the soil. Briefly, 1g of sample was placed in test-tube with $H_2O_2$, then shaken. After 20 min, the reaction was stopped with $H_2SO_4$ and the degree of oxidation was evaluated with 0.1 mol/L $KMnO_4$. Protease activity was determined as follows: 1 g of soil was added to 0.5 mL of caseinate (0.2 g/L) solution and incubated at 30 °C. After 24 h, the reaction was stopped. The concentration of tyrosine equivalents in 1 mL aliquots of supernatant was determined colorimetrically (578 nm) using the Lowry method.

Urease activity was measured by determination of $NH_4$ released after the incubation of soil samples with a buffered urea solution at 37 °C for 2 h. Ammonium was determined with a spectrophotometer at 578 nm [15,16].

### 2.6 Contents of soil metal

The soil samples in air drying were homogenized in an agata mortar and subsequently around 0.5 g was weighed directly on polytetrafluorethylene (PTFE) flasks after adding $HNO_3$−$H_2O_2$ [17]. This digestion program was applied twice in order to guarantee the total decomposition. In addition, cooling steps were necessary to prevent leaking during the digestion process. After digestion, the solutions were diluted to 50 mL. Contents of soil metal were quantified with ICP−OES.

### 2.7 Statistical analyses

Analysis of variance (ANOVA) was performed using SPSS software package. The correlation matrix was performed using the average in three sampling sites of microbial and biochemical properties with chemical properties. Significance was accepted at $P<0.05$ in all cases. Principal components analysis (PCA) was applied using data for soil physical and chemical properties and soil enzyme activities.

## 3 Results

### 3.1 Soil physico-chemical properties

In study sites, most of physio-chemical parameters have significantly varied in different reconstructed modes at different depths in reconstructed soils. As shown in Table 1, the soil moisture increases from 20.17% in coal gangue reconstructed soils to 25.48% in fly ash reconstructed soils in 0−50 cm layer. In the 20−50 cm layer, the soil moisture in fly ash reconstructed soils has the highest value in all layers. On the contrary, the lowest soil moisture was found at 0−10 cm layer of coal gangue reconstructed soils. Soil pH showed higher values in fly ash reconstructed soils compared with coal gangue reconstructed soils in 0−50 cm layer. The highest value of pH of fly ash reconstructed soils was in 20−50 cm layers and the lowest value was in 0−10 cm layer in coal gangue reconstructed soils. The significantly highest values of SOC, TN, and the available P and K were observed in the 0−10 cm layers in all studied sites. Contents of SOC are higher in coal gangue reconstructed soils than fly ash reconstructed soils in 0−50, 0−10, 10−20 and 20−50 cm layers. Generally, values of soil total N are higher in fly ash reconstructed soils compared with coal gangue reconstructed soils in all layers. In comparison with the control soils, fly ash and coal gangue reconstructed soils have significantly lower contents of soil available P and K.

### 3.2 Soil microbial properties

Most soil microbial properties are significantly discriminated in different reconstructed mode and soil depths (Table 2). Compared with the control soil, the contents of soil microbial biomass C (MBC) and N (MBN) sharply decrease in all reconstructed soils under fly ash and coal gangue (Table 2). The microbial biomass C and N at the 0−10 and 10−20 cm depths are lower ($P<0.05$) in the coal gangue reconstructed soils than those in the fly ash reconstructed soils and control soils. For 20−50 cm layer, no significant difference is found when comparing contents of microbial biomass C and N between coal gangue reconstructed soils and fly ash reconstructed soils. $C/N_{bio}$ is greater in coal gangue reconstructed soils than in fly ash reconstructed soils. The $MR_{basal}$ is significantly lower in the both reconstructed soils than in control soil and no significant difference is found between fly ash reconstructed and coal gangue reconstructed soils in 0−10 and 10−20 cm layers. The $q_{mic}$ is significantly higher in fly ash soil than that in coal gangue reconstructed soil in 0−10, 10−20, and 20−50 cm layers. As shown in Table 2, the basal respiration per unit of microbial biomass ($Q_{CO_2}$) is significantly higher in coal gangue reconstructed soil than in fly ash reconstructed soil in 0−10, 10−20, and 20−50 cm layers.

### 3.3 Soil enzyme activities

Activities of soil urease and phosphatase have no significant difference between amendment type or soil depths (Table 3). Compared with fly ash reconstructed soil, no significant difference was found ($P>0.05$) for urease at coal gangue reconstructed 0−10 and 10−20 cm

**Table 1** Physico-chemical properties of reclaimed mine soils

| Soil | Layer depth/cm | Soil moister/% | pH | TOC/(mg·g$^{-1}$) | $N_T$/(mg·g$^{-1}$) | Available P/(μg·g$^{-1}$) | Available K/(μg·g$^{-1}$) | C/N ratio |
|---|---|---|---|---|---|---|---|---|
| CTL | 0−10 | 20.99 | 8.17 | 26.92 | 3.28 | 56.56 | 547.93 | 10.27 |
| | 10−20 | 21.71 | 8.55 | 15.81 | 2.31 | 27.28 | 530.33 | 7.73 |
| | 20−50 | 21.91 | 8.57 | 15.53 | 2.35 | 25.95 | 385.56 | 6.92 |
| | 0−50 | 21.65 | 8.54 | 17.87 | 2.44 | 32.59 | 476.92 | 7.32 |
| RCG | 0−10 | 16.12 | 7.97 | 25.98 | 4.07 | 27.39 | 936.92 | 7.31 |
| | 10−20 | 20.80 | 8.38 | 11.54 | 2.30 | 7.15 | 160.48 | 5.70 |
| | 20−50 | 23.54 | 8.43 | 9.96 | 1.52 | 9.27 | 48.44 | 12.86 |
| | 0−50 | 21.51 | 8.33 | 13.48 | 2.19 | 12.47 | 248.54 | 6.55 |
| RFA | 0−10 | 22.27 | 8.38 | 5.09 | 1.46 | 28.99 | 147.02 | 3.43 |
| | 10−20 | 22.30 | 8.61 | 4.61 | 1.17 | 10.89 | 64.22 | 3.50 |
| | 20−50 | 29.73 | 8.55 | 4.28 | 1.38 | 7.03 | 56.93 | 3.20 |
| | 0−50 | 26.48 | 8.59 | 4.51 | 1.34 | 12.63 | 76.35 | 3.37 |

**Table 2** Biochemical properties of reclaimed mine soils

| Soil | Layer depth/cm | MBC/(μg·g$^{-1}$) | MBN/(μg·g$^{-1}$) | $C/N_{bio}$ | $MR_{basal}$ | $q_{mic}$ | $Q_{CO_2}$ |
|---|---|---|---|---|---|---|---|
| CTL | 0−10 | 198.83 | 18.67 | 10.65 | 83.05 | 0.74 | 0.42 |
| | 10−20 | 82.93 | 14.08 | 5.89 | 58.18 | 0.52 | 0.70 |
| | 20−50 | 3.19 | 1.86 | 1.71 | 29.40 | 0.02 | 9.2 |
| | 0−50 | 58.27 | 7.67 | 7.60 | 45.89 | 0.33 | 0.79 |
| RCG | 0−10 | 103.37 | 14.33 | 7.21 | 83.59 | 0.40 | 0.81 |
| | 10−20 | 32.51 | 10.87 | 2.99 | 41.36 | 0.28 | 1.27 |
| | 20−50 | 30.33 | 4.19 | 7.23 | 16.28 | 0.30 | 0.54 |
| | 0−50 | 45.37 | 7.55 | 6.01 | 34.75 | 0.34 | 0.77 |
| RFA | 0−10 | 121.58 | 16.55 | 7.34 | 61.53 | 2.39 | 0.51 |
| | 10−20 | 79.72 | 13.27 | 6.01 | 40.55 | 1.73 | 0.51 |
| | 20−50 | 41.84 | 5.04 | 8.30 | 14.48 | 0.98 | 0.35 |
| | 0−50 | 65.36 | 8.99 | 7.27 | 29.10 | 1.45 | 0.45 |

**Table 3** Enzyme activities of reclaimed mine soils

| Soil | Layer depth/ cm | Urease/ (μg $NH_4$–N $g^{-1}\cdot dw\cdot h^{-1}$) | Phosphatase/ (μg PNP $g^{-1}\cdot dw\cdot h^{-1}$) | Catalase/ (mg $CO_2$ $g^{-1}\cdot dw\cdot s^{-1}$) | Protease/ (mg Glycine$\cdot g^{-1}\cdot h^{-1}$) |
|---|---|---|---|---|---|
| CTL | 0−10 | 0.23 | 151.19 | 6.15 | 1.83 |
| | 10−20 | 0.22 | 61.78 | 6.07 | 1.48 |
| | 20−50 | 0.24 | 73.16 | 5.89 | 1.11 |
| | 0−50 | 0.23 | 86.49 | 5.98 | 1.33 |
| RCG | 0−10 | 0.25 | 172.32 | 5.99 | 2.46 |
| | 10−20 | 0.23 | 95.92 | 6.10 | 2.57 |
| | 20−50 | 0.15 | 16.26 | 6.15 | 1.87 |
| | 0−50 | 0.19 | 63.40 | 6.11 | 2.13 |
| RFA | 0−10 | 0.18 | 69.92 | 4.75 | 1.39 |
| | 10−20 | 0.35 | 56.90 | 4.29 | 0.81 |
| | 20−50 | 0.20 | 27.64 | 4.05 | 0.42 |
| | 0−50 | 0.23 | 41.95 | 4.24 | 0.69 |

layers. The mean values of phosphatase activities in the fly ash reconstructed soil are higher than those in coal gangue reconstructed soil in 0−10 and 10−20 cm layers. The catalase activity is the lowest in fly ash reconstructed soils in 20−50 cm layer and highest in control soils in 0−10 cm layer. The activities of protease show a decreasing trend in control soil, fly ash reconstructed soil, and coal gangue reconstructed soil in all layers. Overall, protease activities are the highest in the soil surface layer (0−10 cm), and decrease significantly with soil depth in all study sites.

### 3.4 Content of metal in soil

Layers of fly ash or coal gangue are significantly affected by trace metals (e.g. Pb, Cr, As, Hg) in reconstructed soils. The contents of arsenic and chromium in coal gangue reconstructed soil are significantly higher than those in fly ash reconstructed and control soils in 0−50, 0−10, 10−20, and 20−50 cm layers (Table 4). The contents of mercury in control soils are the highest among three type soils in 0−10, 10−20, and 0−50 cm layers. The lead in fly reconstructed soils is higher than that in coal gangue reconstructed soil in 20−50 cm and lower than that in 0−50, 0−10, or 10−20 cm layer.

### 3.5 Principal components analysis

Principal component analysis was applied to the whole set of data. The first two principal components were selected and the components were rotated using varimax rotation. Ordination biplots for principal component analysis of soil phsico-chemical, microbial property, and enzyme activity data are shown in Table 5. Eigenvalues from the PCA analysis indicate that the first three principal components (PCA) accounted for 90.3% of variance of data (PC1: 46.76%, PC2: 18.53%, PC3: 15%). Soil organic carbon, total N, available P and K, urease, phosphatases, catalase, protease, MBC, MBN, and $MR_{basal}$ are significantly correlated with PC1 scores. Soil pH, WHC, As, Pb, and Cr were significantly correlated with PC2 scores (Table 6).

## 4 Discussion

As a typical reclamation mode, the feature of reclamation soil is different from cultivated land. The physico-chemical, microbial and enzymatic properties in mine reconstructed soils are resulted from the reconstructed mode, filling material properties, and tillage mode. Previous study showed that some factors are important, including thickness, physical properties of the topsoil, and underlying rooting zones. After the changes of macroporosity and hydraulic conductivity in reclaimed topsoil, the physical properties were probably the most significant and widespread factors limiting crop yields in mine reclamation zones [18,19]. In the present study, we found that soil properties are significantly different in soil amendment types and depths in land subsidence. Soil reconstructed practices change the soil properties, such as soil texture, soil infiltration capacity, soil water holding capacity. Soil fly ash or coal gangue addition to soil changes the void ratio of reconstructed. The small silt particles of fly ash make it possible to accumulate in voids, then modify the soil texture and pore structure of the soil. For example, the fly ash has been reported to reduce clay characteristics and improve texture that makes the soil more malleable. When fly ash was applied at a high rate, a notable improvement in water holding capacity was reported, while coal gangue coarse-textured had increased soil infiltration capacity

**Table 4** Metal content of reclaimed mine soils

| Soil | Layer/cm | Content/(ng·g$^{-1}$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | As | Hg | Pb | Cu | Cd | Cr | Zn |
| CTL | 0−10 | 14.99 | 47.13 | 58.86 | 81.08 | 5.087 | 104.02 | 138.89 |
| | 10−20 | 16.40 | 50.38 | 46.83 | 80.49 | 4.12 | 98.51 | 132.43 |
| | 20−50 | 16.55 | 37.17 | 56.27 | 61.81 | 2.98 | 119.88 | 102.74 |
| | 0−50 | 16.21 | 41.78 | 54.90 | 69.40 | 3.63 | 112.43 | 115.91 |
| RCG | 0−10 | 14.58 | 42.568 | 59.32 | 82.072 | 3.692 | 99.72 | 178.58 |
| | 10−20 | 17.89 | 22.12 | 53.79 | 76.11 | 3.91 | 93.10 | 235.12 |
| | 20−50 | 17.62 | 22.42 | 56.24 | 84.94 | 5.02 | 102.31 | 190.97 |
| | 0−50 | 17.07 | 26.39 | 56.36 | 82.60 | 4.53 | 99.95 | 197.32 |
| RFA | 0−10 | 6962.61 | 35.40 | 34.72 | 41.72 | 2.41 | 62.55 | 66.93 |
| | 10−20 | 7535.85 | 28.30 | 32.79 | 69.67 | 2.35 | 83.07 | 90.35 |
| | 20−50 | 8196.97 | 46.74 | 35.53 | 51.13 | 2.21 | 62.03 | 43.87 |
| | 0−50 | 7817.87 | 40.79 | 34.82 | 52.96 | 2.28 | 66.34 | 57.78 |

**Table 5** Results of total variance explained of statistically significant soil indicators

| Component | Initial eigenvalue/% | | | Extraction sum of squared loading/% | | |
|---|---|---|---|---|---|---|
| | Total | Variance | Cumulative | Total | Variance | Cumulative |
| 1 | 11.221 | 46.754 | 46.754 | 11.221 | 46.754 | 46.754 |
| 2 | 4.449 | 18.536 | 65.290 | 4.449 | 18.536 | 65.290 |
| 3 | 3.606 | 15.024 | 80.314 | 3.606 | 15.024 | 80.314 |

Extraction method: Principal component analysis

**Table 6** Results of principal component analysis of statistically significant soil indicators

| Indicator | Component | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Soil moister | −0.691 | −0.505 | −0.325 |
| pH | −0.397 | 0.153 | −0.723 |
| TOC | 0.885 | 0.313 | −0.250 |
| TN | 0.848 | 0.371 | −0.195 |
| AVP | 0.196 | 0.803 | −0.232 |
| AVK | 0.580 | 0.654 | −0.337 |
| C/N ratio | 0.741 | −0.350 | − |
| As | −0.993 | − | − |
| Hg | −0.338 | 0.431 | −0.537 |
| Pb | 0.969 | −0.155 | − |
| Cu | 0.765 | −0.245 | 0.215 |
| Cd | 0.847 | −0.263 | 0.325 |
| Cr | 0.897 | − | −0.318 |
| Zn | 0.818 | −0.246 | 0.458 |
| MBC | −0.539 | 0.582 | 0.526 |
| MBN | −0.331 | 0.639 | 0.642 |
| $CN_{bio}$ | −0.551 | −0.152 | 0.263 |
| $MR_{basal}$ | − | 0.912 | 0.389 |
| $q_{mic}$ | −0.852 | 0.280 | 0.360 |
| $Q_{CO_2}$ | 0.364 | 0.103 | −0.693 |
| Urease | −0.242 | 0.354 | −0.237 |
| Phosphatase | 0.414 | 0.715 | − |
| Catalase | 0.982 | − | 0.107 |
| Protease | 0.765 | − | 0.597 |

and decreased water holding capacity in reconstructed soils.

Soil pH is important parameter of soil acidity and usually is used as a quality indicator of mine soil. The pH of mine reconstructed soils can change slowly as filling material for weathering and oxidization. Alkaline fly ash, with high content carbonate (Ca/$MgCO_3$), can significantly reduce soil acidity to a level suitable for arable land. In addition, SEOANE and LEIRÓS [20] found that the addition of fly ash to soil can gradually increase the pH of mine spoil due to slow weathering of the aluminum silicates. On the contrary, pyritic minerals ($FeS_2$) in coal gangue will be oxidized to sulfuric acid and tend to decrease the soil pH. In our study sites, coal gangue layers containing a lot of $FeS_2$ would drop the pH of reconstructed soils if exposing to groundwater and oxygen. Others studies also reported that the critical role of soil pH is to determine the bioavailability of chemical constituents. The soil pH ranging from 6.0 to 7.5 is ideal for agronomic or horticultural use, and thus extreme (higher or lower) pH can increase biological toxicities, such as, the reduced population of microbial and elements fixation. Moreover, metals of filling material are more soluble in acidic solution compared with alkaline condition. Moreover, the growth of plant will be inhibited due to the impairment of metabolic processes by high concentrations of toxic metal ions. In our study, the various ions in the filling layer (fly ash and coal gangue) are gradually released by the effects of groundwater and oxygen, which changes soil components in a long term.

Many studies have shown that nutrient substance of topsoil in reconstructed area will sharply decline during the transportation and stockpile, such as soil organic, total N, available P and K. According to other research, nutrients were generally found to be deficient in topsoil of reconstructed soils. Typically, fly ash, the residue derived from the burning of coal, does not contain organic carbon (C). Although deficiency of organic carbon, coal gangue may contain various amounts of fossil C compared with fly ash, it is difficult to assess the function of soil fossil C in study sites because the importance is mostly unknown to contribution of fossil C to organic carbon. The fertility of reconstructed soil largely depends upon the properties of the development of vegetation and the tillage mode in mine reconstructed soils. The decomposition of crop residues will enrich the substrates with carbon and nitrogen. The transformation of crop residues to complex litter layer and C/N ratio are lower in reconstructed soils. The study showed that there was a rapid accumulation of C and N in the soil profile during early stage after being reconstructed [21]. Compared with other studies, there are higher SOC and total N in both reconstructed soils in our study, and we found that no tillage can promote soil carbon storage in reconstructed mine soils. In addition, coal gangue reconstructed soils contain a much greater proportion of carbon than fly ash reconstructed soils and have a higher C/N ratio. According to microbial and enzymatic parameters, we could conjecture that soil organic matter has a slower decomposition velocity under the coal gangue reconstructed mode.

Topsoil in reconstructed sites can provide substrates for crop growth and reduce the effects of filling materials. The developments of MBC and MBN are important components of reconstructed soil ecosystem. The growth and death of crops provided important inputs of C, N, and others elements. The values of soil microbial biomass can reflect the long-term trend of SOC and is more sensitive than SOC as an indicator of soil quality. The amount of microbial community is sharply decreased during the period of transporting and stockpiling. Earlier studies indicated that the diversity of microbial community generally increases as filling material weathers and nutrients accumulates. While some factors such as water moisture, pH, toxicity of metal elements, deficiency of soil organic carbon, and total N can limit the colonization of microbial community. The metabolic quotient can also be as an indicator to elevate the quality of microbial community and as a response of microflora to environmental stress or disturbance. The difference in soil management can result in a change of metabolic quotient. The lower metabolic quotient suggests a decrease of the energy requirement of the microbial community maintenance. In our study, the high value of soil microbial biomass in fly ash reconstructed soils may be due to a relatively high available C and N, while low value of metabolic quotient in fly ash reconstructed soil suggests that the microorganisms are more efficient in fly ash reconstructed soil compared with the coal gangue reconstructed soil. Moreover, our research also confirmed that the generally accepted fact that soil microbial activity is greater at the surface layer than at deeper layers.

The soil microbial indices are also confirmed to be useful indicators of the changes in nutrient cycling and soil pollution. Among microbial and enzymatic parameters, MBC, MBN and enzyme activities usually are used as indicators to evaluate soils C and N accumulation under different management types in other reports. The result of the correlation matrix and principal components analysis confirmed that microbial indices are useful indicators in nutrient cycling and efficient microbial community in reconstructed mine soils. Previous evidences also supported that the $Q_{CO_2}$ and $q_{mic}$ are valuable indices to access soil quality. In our study, $Q_{CO_2}$ and $q_{mic}$ are indeed suitable in predicting stress conditions and chemical properties in mine reconstructed soils. The analysis shows that soil microbe and enzyme are also suitable in predicting soil conditions [22,23].

In many researches, the MBC, MBN, and enzymatic activities were used to study the toxic effects of metals on soil microbial activities. Like enzymatic activities, the values of MBC, MBN in the heavy metal-amended samples were significantly decreased with increasing metal concentrations. They also highly varied during different incubation periods. The study shows that soil microbial properties were decreased with increasing Cd concentration in soil. Our research also suggested that the values of MBC and MBN have a significantly negative correlation with the metal concentrations. These results are in agreement with previous studies [24].

## 5 Conclusions

1) The lower microbial and enzymatic activities measured in reconstructed soils than in control soils

indicate a lower microbial activity and decomposition of the crop residues, whichs limit the release of nutrients from the litter in these reconstructed soils.

2) The higher content of WHC, pH, TN, available P, MBC, MBN, $MR_{basal}$, $q_{mic}$, and lower respiratory quotient in fly ash showed larger and more efficient microbial and enzymatic activities under fly ash but coal gangue reconstructed soils after 10 years crop rotation.

3) The results of correlation matrix and principal components analysis showed that the soil microbe and enzyme are most suitable indicators to predict soil quality changes in reconstructed mine soils. Moreover, the results also indicate that microbial parameters and enzymatic activities could be two more effective and consistent indicators for soil quality than physic-chemical parameters in response to environmental stress, which also highlights the need to consider a wide variety of both microbial and biochemical analyses when comparing the impacts of fly ash with coal gangue on soil quality.

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# 中国高潜水位沉陷区采煤废弃物复垦农田的土壤特征

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**摘 要**：为了研究充填介质对中国东部高潜水位采煤塌陷区复垦土壤特征的影响，对采用煤矸石或粉煤灰作为充填介质形成的复垦土壤化学和微生物指标进行分析。结果表明，充填介质粉煤灰的存在能显著提高复垦土壤中 pH 值和含水率；在 0~10 cm、10~20 cm、20~50 cm 土壤层，采用粉煤灰形成的复垦土壤 MBC、MBN、MBC/ TOC 的比率高于采用煤矸石形成的复垦土壤；采用煤矸石作为充填介质形成的复垦土壤中，重金属 As 和 Cr 含量、土壤微生物碳氮比、呼吸熵等高于对照土壤和粉煤灰充填形成的复垦土壤；主成分分析表明，充填土壤中重金属含量、土壤微生物量和土壤酶活性能代表大部分复垦土壤特征。

**关键词**：复垦土壤；矿山废弃物；微生物量；土壤酶活性

**(Edited by Hua YANG)**