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Effects of vegetation and fertilization on weathered particles of coal gob in Shanxi mining areas, China

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Abstract

Combined application of sewage sludge and chemical fertilizer in weathered particles of coal gob (WPCG) was studied by pot-scale trials. The accumulation of available nutrients and weathering process of coal gob piles were also investigated by field trial. It was showed that combined application of sewage sludge and chemical fertilizer increased yields of tall fescue, improved WPCG fertility especially its biological fertility. After application of sewage sludge, the microbial biomass carbon, urease activity and total microorganism population were, respectively, increased by 0.3–2.4, 1.8–2.8 and 34–150 times. Heavy metals did not accumulate in tall fescue after application of sewage sludge in WPCG. Available nutrients were accumulated in topsoil eight years after reclamation in the field trial. Moreover, the effects of biological weathering exceeded that of natural weathering in coal gob piles. The percentage of coal gob particle diameter smaller than 3 mm in the reclamation sites was increased by 85–203%, but 30% in the un-reclaimed sites. While that of greater than 10 mm in the un-reclaimed sites was decreased by 19%, however, 62–74% in the reclamation sites.

It was concluded that combined application of sewage sludge and chemical fertilizer could help quickly establishing a self-maintaining vegetation system in the primary process of reclamation.

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Keywords: Coal gob; Vegetation; Sewage sludge; Chemical fertilizer; Reclamation

1. Introduction

Coal gob, produced by coal-excavating and coal-processing, covers the largest proportion of industrial solid wastes in China. The component of coal gob differs with sorts of coal and coal-processing. Usually, coal gob was dumped in adjacent gullies and gradually accumulated to coal gob piles. At present, the total accumulative amount of coal gob is nearly 4 billion tonnes in China, which occupied 13340 ha land. Moreover, the amount of coal gob is still growing at a speed of 180 million tonnes per year and more than 400.2 ha land per year has being swallowed up by new produced coal gob with the increasing coal output, especially with the proportional increase of coal washing [1]. There were around 90 million tonnes of coal gob and more than 380 coal gob piles in Shanxi province, the largest coal mining industry base in China. Also, the annual production of coal gob in Shanxi is still growing at a speed of 25 million tonnes [2].

The accumulation of coal gob not only occupied precious land resources but also caused various environmental problems such as dump failures, gully erosion and underground water deterioration. Meanwhile, unreasonably piled coal gob easily causes spontaneous combustion and releases poisonous and deleterious wastes [3]. The mineral component of coal gob mostly consists of kaolinite, charcoal, quartz, illite and calcite. Besides carbon, hydrogen and oxygen, its chemical elements are mostly silicon, iron, aluminum and a few other heavy metals that can cause health risks [4]. In

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Abbreviation: WPCG, weathered particles of coal gob

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Shanxi province, coal gob easily undergoes weathering to shape loose porous materials (named as weathered particles of coal gob, WPCG), releases nutrition elements and gradually forms soil structure due to the semi-arid climate. Usually, the weathering crust of about 10 cm thickness in the surface of coal gob piles would be formed in a few months or several years as soon as the process of dumping coal gob ended [5]. Since the conventional utilization of coal gob, such as building bricks production, which can reduce the occupied land at very low ratio, and filling is a costly and challenging issue in the coal industry today, vegetation technique was proposed for the disposal of coal gob. The primary purpose of reclaiming mineral-related mining deposit sites is to prevent the hazard migration induced by the physical effects of wind and water erosion. Vegetative stabilization is one of the widely accepted techniques for controlling soil erosion and stabilization of dump slope [6–9]. Therefore, it is of great interest how to quickly establish a self-maintaining vegetation community in the primary period of reclamation.

WPCG is characterized chemically by low organic matter, lack of plant-essential nutrients, and low cation exchange capacity (CEC); physically by its low water-holding capacity and dark color, and biologically by lack of microorganisms. All above properties are required to support a quick establishment of a self-maintaining vegetation. So it is really important to improve the fertility of WPCG at the beginning of reclamation. Municipal sewage sludge usually contains high proportions of organic matter, plant nutrients of nitrogen and phosphorous, moreover, it is rich in microorganism which plays an important role in soil formation, plant establishment and transformation of soil organic matter. Soil microorganism has been treated as criteria for judging reclamation success, which is an essential aspect of soil health to reflect ecosystem viability and long-term stability [10]. Sewage sludge is widely used as organic fertilizer and soil conditioner and is an inexpensive source of nutrients within agriculture and in acidic coal refuse materials [11,12]. Many practices showed that it could accelerate nutrient accumulation and gradually improve the physical and chemical properties of soil by applying municipal sewage sludge or municipal solid waste compost [13–15]. However, few attempts have been made to reclaim coal gob piles with municipal sewage sludge in China. In this paper, combined application of sewage sludge and chemical fertilizer in WPCG was studied by pot trial. Meanwhile, the accumulation of nutrients in an available form and the weathering process of coal gob were also investigated by field trial eight years after reclamation was initiated.

2. Materials and methods

2.1. Study site

This field trial was conducted at No. 9 coal gob piles in third mine, a very old underground coal mine in Yangquan (N37°46′13″–N37°58′30″, E113°19′45″–E113°34′47″), located in the east of Shanxi province, China (Fig. 1). The region enjoys a typical semi-arid continental monsoon climate with annual mean temperature of 10.9 °C, annual mean precipitation about 590 mm and more than 70% of annual precipitation occurs between July and September. The frost-free period varies from 114 to 180 days. Its dominant landform is loess-covered hills, which is sensitive to suffer soil erosion seriously. The coal gob in Yangquan belongs to the Carboniferous–Permian system, which is a representative coal gob in China [3]. All weathered particles used for pot trial were collected from No. 9 coal gob piles.

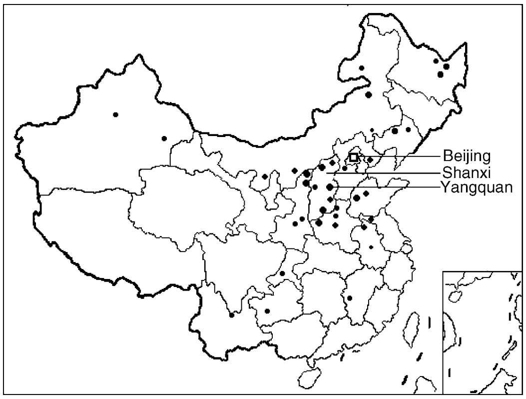

Fig. 1. Distribution of China main coal mines. Third mine was indicated in Yangquan, Shanxi province, China.

2.2. Experimental materials and methods

2.2.1. A pot trial

A pot trial was performed to evaluate the role of sewage sludge in the quick establishment of self-maintaining vegetation system. Dried sewage sludge (treated by aerobic digestion) was collected from Yangjiabao Municipal Sewage Treatment Plant in Taiyuan, Shanxi province, China. Total concentration of heavy metals in sewage sludge used in pot trial is within the limit of permitted values (GB 4284-84, Control Standards for Pollutants in Sludges from Agricultural Use, China) [16,17].

In order to simulate practical particle proportion of coal gob piles, the WPCG was mechanically sieved and obtained the following proportional particle diameter: 32% (>10 mm), 17% (10–7 mm), 8% (7–5 mm), 18% (5–3 mm) and 25% (<3 mm), respectively. Each pot was filled with 5 kg above proportional mixtures. Chemical properties of WPCG and sewage sludge were listed in Table 1.

The experiment was set up as a split-block design with 2 × 4 for nitrogen × sewage sludge, the factor of sewage sludge was placed in main plot, with four levels of application rate at 0%, 2%, 4% and 6% (respectively, equal to 0, 45, 90 and 135 tonnes/ha), and nitrogen in sub-plot, with two levels of chemical fertilizer application rate at 0 (N_0) and 0.06 g N/kg (N_1). Phosphorus and potassium was applied as basic fertilizers with application rate at P_2O_5 0.10 g/kg and K_2O 0.10 g/kg. Seeds of tall fescue (*Festuca*

Table 1
Chemical properties of WPCG and sewage sludge prior to application

Properties	WPCG	Sewage sludge
pH[a]	7.3	6.8
Total organic carbon (%)[b]	4.79	24.2
Total organic nitrogen (%)[c]	0.315	2.93
Carbon:nitrogen ratio	15.2	8.26
Total phosphorus[d]	0.066	0.186
Total potassium[e]	1.50	0.34
Conductivity (mS/cm)[a]	2.54	3.15
CEC (cmol(+)/kg)[f]	8.6	13.6
Extractable analysis (mg/kg)		
Nitrogen[g]	40.19	1811
Phosphorus[h]	1.60	340
Potassium[i]	81.0	495
Iron[j]	29.1	185.64
Manganese[j]	10.79	31.0
Copper[j]	0.58	6.39
Zinc[j]	6.16	90.86
Lead[j]	17.51	35.3
Chromium[j]	15.90	317
Cadmium[j]	<1	<1

[a] Soil/water ratio 1:1.
[b] $K_2Cr_2O_7$–H_2SO_4 method.
[c] Kjeldahl method.
[d] $HClO_4$–H_2SO_4 method.
[e] NaOH melting, analyzed AAS.
[f] 1 M NH_4OAc method.
[g] 1 M NaOH–H_3BO_3 method.
[h] Olsen (0.5 M $NaHCO_3$) extracts, analyzed colorimetrically.
[i] 1 M NH_4OAc (pH 7) extracts, analyzed AAS.
[j] 1 M HNO_3 extracts, analyzed AAS.

arnudinacea) were soaked in distilled water before sowing. All pots were kept in a glasshouse and watered when the soil surface showed evidence of drying out. Tall fescue was harvested after 150 days growth and its air-dried weight was recorded. Tall fescue was treated by dry-ash method and dissolved by diluted hydrochloric acid (HCL) or nitric acid (HNO_3), concentrations of heavy metals and trace elements were determined by an atomic absorption spectroscopy (AAS). Fresh WPCG per pot was collected for further analysis, such as urease activity analyzed by the indophenol blue colorimetric method; microbial biomass carbon by chloroform fumigation–incubation method [18,19], as well as total organic carbon, total nitrogen, total phosphorus and cation exchange capacity (CEC) measured by routine method (same as Table 1). Meanwhile, enumeration and characterization of standard spread plate methods for bacteria, actinomycetes and fungi were conducted in meat-peptone agar medium, starch casein medium and Martin's medium.

2.2.2. Field trials

Field trials have been continued for eight years at No. 9 coal gob piles. Chemical fertilizers were applied in the first year of reclamation, its application rate was 37.5 kg N/ha, 112.5 kg P_2O_5/ha and 15 kg K_2O/ha, respectively, and nitrogen fertilizer was applied one more time at 37.5 kg N/ha in the next year. Assigned fields were randomly assigned to 1 m × 1 m plots (separated by 1-m buffer zones) with six replicates. Plots were, respectively, covered with native species of black locust (*Robinia pseudoacacia*), desert wheatgrass (*Agropyron desertoum*) and milk vetch (*Astragalus adsurgens*), which could obviously stabilize the dump slope of coal gob piles in local areas.

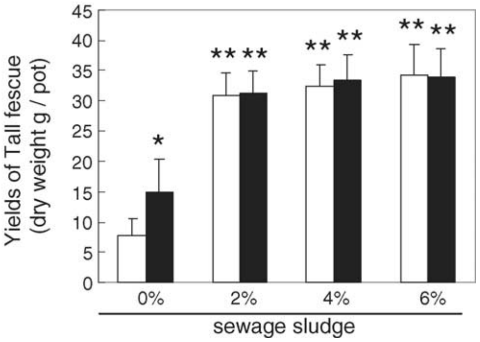

Fig. 2. Yields of tall fescue ($X \pm$ S.D., dry weight g/pot, $n = 5$). Blank bars represent for N_0 plot, and solid bars for N_1 plot. (*, **) Significant levels set at the 0.05 and 0.01 probability, compared to N_0 plot without sewage sludge, respectively.

In order to study whether the nutrient has been accumulated in the topsoil of coal gob piles eight years after reclamation was initiated, the weathered particles from coal gob piles were collected in each plot at 0–20 and 20–40 cm. Available nutrients at 0–20 and 20–40 cm were analyzed immediately by the same methods (Table 1). Meanwhile, the weathered particles from 0 to 20 cm will be used to study the biological weathering role. Bacteria, actinomycetes and fungi in reclaimed and un-reclaimed sites were numbered.

3. Results

3.1. Combined application of sewage sludge and chemical fertilizers in WPCG

3.1.1. Increasing yields of tall fescue in WPCG

After 150 days growth, in all sewage sludge treatment plots, yields of tall fescue were three times higher than in the control plot (N_0 plot without sewage sludge), and a statistically significant difference was observed ($p < 0.01$). There was also a significant difference between N_1 plot and N_0 plot without sewage sludge, $p < 0.05$). No significant differences were found among different levels of sewage sludge in the limited period of growth (tested by L.S.D.), and no significant differences were also found between two levels of nitrogen fertilizer in all sewage sludge treatment (Fig. 2).

3.1.2. Improving the fertility of WPCG

It was showed that total organic carbon, total nitrogen and total phosphorus in WPCG were increased after application of sewage sludge. The magnitudes of increase in organic matter, total nitrogen, total phosphorus and CEC were found to be dependent on the sewage sludge application rates.

Table 2
Nutrients status in WPCG after application of sewage sludge

Items	Sewage sludge-0%		Sewage sludge-2%		Sewage sludge-4%		Sewage sludge-6%	
	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1
Total organic carbon (%)	4.66	4.67	5.59	5.05	5.72	5.12	5.85	5.25
Total nitrogen (%)	0.23	0.37	0.47	0.52	0.57	0.59	0.63	0.64
Total phosphorus (%)	0.085	0.082	0.165	0.151	0.180	0.181	0.220	0.202
C/N	20.7	12.8	12.0	9.7	10.0	8.7	9.3	8.2
CEC (cmol(+)/kg)	8.9	–	9.5	–	10.8	–	11.7	–

Compared with the control plot, total organic carbon, total nitrogen and total phosphorus in WPCG were, respectively, increased by 8.4–25.5%, 104–178% and 77.6–159%. CEC in WPCG was also increased by 6.7–31.5% as compared with the control plot, from 8.9 to 11.7 cmol(+)/kg 150 days after application of sewage sludge (Table 2).

3.1.3. *Changes of microorganism population in WPCG*

The total microorganism population in fresh coal gob is only 1.60×10^3 CFU/g, but 1.58×10^5 CFU/g in un-reclaimed sites. However, it reached to 2.03×10^6 CFU/g eight years after reclamation and 2.39×10^7 CFU/g 150 days after application of sewage sludge at rate of 6% in pot trial. Compared with un-reclaimed sites, the total microorganism population was increased by 12 times in reclaimed sites, 34–150 times after applying sewage sludge in WPCG, respectively (Table 3).

3.1.4. *Improving microbial biomass carbon and urease activity in WPCG*

There is a significant difference between with- and without-sewage sludge treatment, either for microbial biomass carbon or urease activity in WPCG ($p < 0.05$, 0.01). Either among different levels of sewage sludge or between different nitrogen fertilizers, there were no significant differences for microbial biomass carbon and urease activity. Microbial biomass carbon was increased when increasing sewage sludge rates are applied. Within the same level of sewage sludge treatment, microbial biomass carbon in N_1 plot (N_1) was increased more than in N_0 plot (N_0). Compared to the control plot, the microbial biomass carbon and urease activity were, respectively, increased by 0.3–2.4 and 1.8–2.8 times after application of sewage sludge in WPCG. In addition, the ratio of microbial biomass carbon to total organic carbon is dependent on the increasing sewage sludge rates (Table 4).

3.1.5. *Concentrations of heavy metals and trace elements in tall fescue after applying sewage sludge*

Concentrations of heavy metals (Ni, Cr, Pd, Cd) and trace elements (Fe, Mn, Cu, Zn) were measured in tall fescue 150 days after application of sewage sludge. The above heavy metals and trace elements did not occur any accumulation in tall fescue, but there was only slight change such as Fe, Zn, Cr in tall fescue with the increasing sewage sludge rates in WPCG (Table 5).

Table 3
Microorganism population after applying sewage sludge in WPCG (CFU/g)

Treatments[a]	Sewage sludge-0%	Sewage sludge-2%	Sewage sludge-4%	Sewage sludge-6%	Reclaimed sites	Un-reclaimed sites
Bacteria	9.50×10^5	3.31×10^6	7.64×10^6	2.15×10^7	1.95×10^6	8.20×10^4
Actinomycetes	1.49×10^4	1.95×10^6	2.21×10^6	1.77×10^6	3.90×10^4	1.60×10^4
Fungi	1.91×10^4	3.01×10^5	9.06×10^4	6.70×10^5	4.20×10^4	6.00×10^4
Total microorganism	9.84×10^5	5.56×10^6	9.94×10^6	2.39×10^7	2.03×10^6	1.58×10^5
Increased times[b]	5	34	62	150	12	

[a] N_0 was applied in WPCG.
[b] Compared with un-reclaimed sites.

Table 4
Microbial biomass carbon and urease activity after application of sewage sludge in WPCG

Items	Sewage sludge-0%		Sewage sludge-2%		Sewage sludge-4%		Sewage sludge-6%	
	N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1
Urease activity[a]	3.76	4.17	12.34*	10.53*	14.10*	13.58*	13.97*	13.92*
Biomass carbon (μg/g)	234	255	306*	387*	393*	472*	504**	792**
Biomass carbon/organic carbon (%)	0.502	0.547	0.547	0.766	0.687	0.922	0.864	1.509

[a] $mgNH_3–N/100$ g soil, 37° C, 24 h.
* Significant levels set at the 0.05 probability, compared to N_0 plot without sewage sludge.
** Significant levels set at the 0.01 probability, compared to N_0 plot without sewage sludge.

Table 5
Concentrations of heavy metals and trace elements in tall fescue after reclamation (mg/kg)

Items		Sewage sludge-0%		Sewage sludge-2%		Sewage sludge-4%		Sewage sludge-6%	
		N_0	N_1	N_0	N_1	N_0	N_1	N_0	N_1
Trace elements	Fe	330	194	321	308	263	357	399	405
	Mn	45.1	27.3	7.0	17.3	6.3	10.9	14.2	21.5
	Cu	34.2	39.1	35.8	14.1	1.8	2.0	1.9	14.7
	Zn	46.6	81.2	73.9	74.1	70.5	95.4	98.8	91.1
Heavy metals	Ni	1.5	3.9	3.5	2.2	0.6	2.2	3.2	1.2
	Cr	2.5	0.6	2.3	5.4	3.5	4.6	9.0	5.2
	Pb	11.6	6.4	16.0	7.8	12.3	16.3	8.6	6.3
	Cd	Undetected (detected limit is 0.02 mg/kg)							

3.2. Accumulation of available nutrients in surface layers and biological weathering role of the coal gob after reclamation and revegetation

3.2.1. The accumulation of available nutrients in surface layers after reclamation

The WPCG was collected at 0–20 and 20–40 cm in the areas covered with black locust, desert wheatgrass and milk vetch in coal gob piles, as well as in un-reclaimed sites. Available nitrogen, available phosphorus as well as available potassium were measured. The results showed that all items were accumulated in surface layers, respectively, eight years after reclamation was initiated. Accumulated amount of available nitrogen was less than that of available phosphorus or available potassium in surface layers in reclaimed sites. There was no accumulation of available nutrients in the surface layer of un-reclaimed sites (Table 6).

3.2.2. Effects of biological weathering exceeded that of natural weathering in coal gob piles

The WPCG were sampled at 0–20 cm in the un-reclaimed sites and in the areas covered with black locust, desert wheatgrass and milk vetch in coal gob piles. The percentage of particle diameter in WPCG was analyzed. Compared with that of eight years ago, the percentage of particle diameter greater than 10mm in the un-reclaimed sites was decreased by 19%, while in the areas covered with black locust, desert wheatgrass and milk vetch decreased by 74%, 62% and 65%, respectively. However, the percentage of small particles smaller than 3 mm in the areas covered with black locust, desert wheatgrass and milk vetch was, respectively, increased by 203%, 85% and 160%, while it was just increased by 30% in the un-reclaimed sites. The percentage of other particles was increased or decreased to a certain extent (Table 7).

4. Discussion

In general, coal mine waste is seriously deficient in nitrogen [20–24]. According to the estimation of Dancer and Robert, a self-sustaining and independent ecosystem could not be established until 700 kg N/ha was accumulated in coal mine waste [20,23]. Nevertheless it is very slow to form the organic nitrogen pool in coal gob piles by planting legumes or applying nitrogen fertilizers. In the process of slowly establishing organic nitrogen pool, the physical effects of wind and soil erosion may be followed. Thus, it is very important to quickly establish the organic nitrogen pool from the outset of

Table 6
Available nutrients in reclaimed and un-reclaimed sites at 0–20 and 20–40 cm (mean ± S.D., $n = 6$)

Items (mg/kg)	Black locust		Desert wheatgrass		Milk vetch		Un-reclaimed sites	
	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm	0–20 cm	20–40 cm
Available nitrogen	46.8 ± 3.7	42.3 ± 9.2	42.6 ± 5.4	37.8 ± 5.0	55.2 ± 8.3	46.8 ± 8.2	40.6 ± 2.7	56.3 ± 3.2
Available phosphorus	1.3 ± 0.1	1.0 ± 0.1	1.1 ± 0.1	0.8 ± 0.2	1.6 ± 0.3	0.8 ± 0.2	0.7 ± 0.2	0.9 ± 0.5
Available potassium	72.5 ± 11.3	44.3 ± 11.2	78.2 ± 12.1	63.0 ± 18.0	189.7 ± 69.6	127.0 ± 45.4	28.0 ± 9.4	54 ± 17.0

Table 7
Percentage of particle diameter of WPCG in reclaimed sites and un-reclaimed sites (%)

Items	Un-reclaimed sites	Black locust	Desert wheatgrass	Milk vetch	Before reclamation
>10 mm[a]	32.4 (−19%)	10.4 (−74%)	15.3 (−62%)	14.0 (−65%)	40
10–7 mm	13.9	5.6	9.2	4.6	
7–5 mm	9.7	5.3	9.2	6.0	38
5–3 mm	13.9	12.2	25.5	18.3	
<3 mm[b]	28.7 (+30%)	66.7 (+203%)	40.8 (+85%)	57.1 (+160%)	22

[a] Values in parenthesis are decreased percentage compared to before reclamation.

[b] Values in parenthesis are increased percentage compared to before reclamation.

reclamation. According to Guo's research in Taiyuan, organic matter, nitrogen and phosphorus contents in sewage sludge are five, three and three times those in manure (a typical traditional organic waste used for agricultural land in China), respectively [16]. The total nitrogen in sewage sludge is primary in organic fraction, which is easy to mineralize for nutrient uptake by plants. Many research projects showed that soil amended with sewage sludge produced similar a yield of rice to that applied with chemical fertilizers, but kept organic matter and plant nutrient contents higher for the next crop [25,26]. Moreover, organic matter and plant nutrient contents of soil were increased by application of sewage sludge more than by livestock manure [14,27]. So sewage sludge could contribute to the establishment of organic nitrogen pool in WPCG. Our research showed that application of sewage sludge to WPCG has increased biomass production and improved soil fertility such as organic matter, total nitrogen and total phosphorus. After application of sewage sludge, no significant differences were found among different levels of sewage sludge due to the limited growth period in pot trial, but it was confirmed that sewage sludge contributed to the improvement of fertility in WPCG.

The immediate goal of reclamation is to establish a vigorous vegetative cover that can prevent soil erosion and pollution; the long-term goal is soil development and stability, which were needed to support the plant growth and quickly set up a self-maintaining vegetation in the end. Besides lacking of organic matter and plant-essential nutrients in WPCG, it lacks soil microorganism. Microorganism is essential for the development and conservation of soil fertility and quality in WPCG, which is very important for the establishment of healthy ecosystem in coal gob piles. Sewage sludge could provide large amounts of organic matter and plant available nutrients that benefit for the activity of original microorganisms in WPCG. On the other hand, it itself is activated sewage sludge that could increase microorganism population in WPCG. According to our study, the total microorganism population in fresh coal gob was very low. It had reached to 2.03×10^6 CFU/g eight years after reclamation only by applying chemical fertilizers in the first year. However, it had reached to 2.39×10^7 CFU/g 150 days after application of sewage sludge. Compared with un-reclaimed sites, it was increased by 34–150 times after application of sewage sludge in WPCG. Sopper's study showed that bacteria and fungi of soil after application of sewage sludge were 5–10 and 3–4 times higher than those in without-sewage sludge spot [28]. Moreover, it was reported that earthworm community and activity were also improved in mine soils by the application of sewage sludge while earthworms are important for the development and conservation of soil fertility and quality [29].

The increase of microorganism population indicates biological fertility has been improved significantly in WPCG. As it is known, microorganisms decompose organic matter, form humus and release nutrients in soil, simultaneously, microorganism biomass is produced through transforming soil carbon and fixing inorganic nutrient elements. Moreover, microbial biomass is not only the drive of transformation of organic matter and residua of plants and animals but also the capital of plant nutrients. Usually, soil quality will be significantly improved with the increasing carbon level of microbial biomass. Our research showed that the microbial biomass carbon and urease activity were, respectively, increased by 0.3–2.4 and 1.8–2.8 times in WPCG applied with sewage sludge. Microbial biomass carbon as an indicator of soil fertility was measured to determine the most suitable type of sewage sludge as organic-mineral fertilizer by Selivanovskaya. They found that application of composted municipal sewage sludge to soils could make microbial biomass carbon increase about 1.9- to 4.4-fold [30]. Our results suggest that changes in microorganism population, microbial biomass carbon and urease activity in WPCG reflect changes in biological fertility in WPCG.

Plant-available nitrogen, phosphorous and potassium are generally low in WPCG because coal gob is mainly composed of weathered rock and coal fragments. It was showed that available nutrients were, respectively, accumulated in topsoil eight years after reclamation, and no accumulation in un-reclaimed sites. In the process of such soil development, the plants have an important role in protecting the soil surface from erosion and allowing the accumulation of fine particles, but they also cause the accumulation of nutrients in an available form. If grass and shrub are to grow, the available nitrogen has to be accumulated in the mined lands [21]. It was observed that available nitrogen was not obviously accumulated due to the slowly establishing of organic nitrogen pool in coal gob piles merely by planting legumes or applying nitrogen fertilizers. Meanwhile, both nitrogen uptakes by plants and soil microorganism, and nitrogen loss by leaching and volatilization result in little inorganic nitrogen accumulation in the surface layer of coal gob piles. It could accelerate establishment of organic nitrogen pool in WPCG by applying different organic waste materials such as municipal sewage sludge. There was no significant difference between N_1 plot and N_0 plot with sewage sludge for yields of tall fescue in pot trial. It indicates that sewage sludge could provide a short-term input of plant available nutrients and stimulation of microbial activity, and contributes to long-term maintenance of nutrient and organic matter pools [31]. Meanwhile, the percentage of particle diameter less than 3 mm in the reclamation sites was increased more than that of in the un-reclaimed sites, while the lager particles greater than 10 mm in the reclamation sites was decreased more than that of in the un-reclaimed sites. It means that the effects of biological weathering exceeded that of natural weathering.

Heavy metals are one of the important factors that affect the agricultural use of sewage sludge. After application of sewage sludge, no accumulations of heavy metals and trace elements were found in tall fescue 150 days. Although sewage sludge used in our pot trial didn't exceed the maximum permitted content of GB 4284-84 [32], we still need more detailed work to be done before the correct answer can be finally obtained in order to accurately assess accumulation of heavy metals. In the primary stage of reclamation, we focus on how to control soil erosion and restore the ecological landscape in mining area. Theodoratos reported that the treatment of soil contaminated by mining activities with 10% (w/w) of municipal sewage sludge was sufficient to stabilize Pb, Zn and Cd. They found that sewage sludge addition had a positive effect on plant growth. Furthermore, the Pb and Zn uptake of plant leaves and roots was reduced, while Cd uptake was unaffected by the sewage sludge treatment. It was suggested that municipal sewage sludge is a potential effective stabilizing agent for mine soil [33].

5. Conclusion

Reasonable fertilization strategy can not only increase the biomass productivity but also improve the fertility of WPCG. We advanced a fertilization strategy of combining sewage sludge and chemical fertilizers, a good strategy to improve the biological fertility of WPCG from the outset of reclamation. It was showed that applying sewage sludge with chemical fertilizers together to WPCG could significantly increase yields of tall fescue and improve the fertility of WPCG. According to the results presented, sewage sludge is favorable for improving the soil fertility, such as organic matter and plant-available nutrients, microorganism population, and microbial biomass carbon in WPCG. It means that vegetation could be recovered efficiently and rapidly in WPCG and the fertility of WPCG was gradually improved by applying sewage sludge. Heavy metals (Ni, Cr, Pd, Cd) did not accumulate in tall fescue 150 days after application of sludge at rates of 2–6% in WPCG. Meanwhile, it was showed that available nutrients were accumulated in topsoil eight years after reclamation was initiated in the field trial. Moreover, the effects of biological weathering exceeded that of natural weathering in coal gob piles.

Application of sewage sludge in WPCG improved the fertility of these soils and alleviated waste disposal problem. The results suggest a new strategy for how to quickly establish a self-maintaining vegetation system in reclaiming coal gob piles, because vegetation plays an important role in soil development such as accelerating the weathering process of coal gob and accumulation of nutrients in an available form, meanwhile, vegetation also plays an important role in water and soil conservation in coal gob piles. It had been confirmed in the field trial. Future land resources may be acquired by the reclamation of coal gob piles.

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