Science of the Total Environment 951 (2024) 175656

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Simulation of red mud/phosphogypsum-based artificial *soil engineering applications* in vegetation restoration and ecological reconstruction

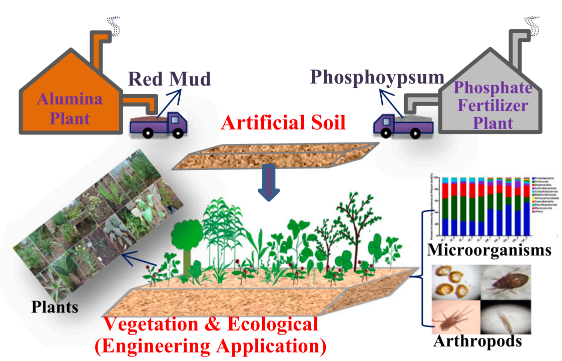
Yong Liu [a,*], Lishuai Zhang [a], Binbin Xue [a], Li Chen [a], Guocheng Wang [a], Jingfu Wang [b,*], Hefeng Wan [c], Xiaohong Lin [a], Guangxu Zhu [a]

[a] *College of Biological and Environmental Engineering, Guiyang University, Guiyang 550005, China*
[b] *State Key Laboratory of Environmental Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences (IGCAS), Guiyang 550081, China*
[c] *Guizhou Institute of Biology, Guiyang 550009, China*

HIGHLIGHTS

- The scheme of red mud/phosphogypsum-based artificial soil for ecological engineering was put forward.
- At least 18 kinds of suitable plants can be considered as priority for artificial soil vegetation restoration.
- The microbial and arthropod communities suggested the gradual construction of artificial soil micro-ecosystems.
- More assessment of nutrients, heavy metals and salinity is needed in ecological reconstruction of artificial soil.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Huu Hao Ngo

Keywords:
Industrial solid waste
Resource utilization
Ecological engineering
Red mud
Phosphogypsum

ABSTRACT

Red mud and phosphogypsum are two of the most typical bulk industrial solid wastes. How they can be efficiently recycled as resources on a large scale and at low costs has always been a global issue that urgently needs to be solved. By constructing a small-scale test site and preparing two types of artificial soils using red mud and phosphogypsum, this study simulated their engineering applications in vegetation restoration and ecological reconstruction. According to the results of this study, the artificial soils contained a series of major elements (e.g. O, Si, Al, Fe, Ca, Na, K, and Mg) similar to those in common natural soil, and preliminarily possessed basic physicochemical properties (pH, moisture, organic matter, and cation exchange capacity), main nutrient conditions (nitrogen, phosphorus and potassium), and biochemical characteristics that could meet the demands of plant growth. A total of 18 different types of adaptable plants (e.g. wood, herbs, flowers, succulents, etc) grew in the test sites, indicating that the artificial soils could be used for vegetation greening and landscaping. The preliminary formation of microbial (fungal and bacterial) community diversity and the gradually enriched arthropod community diversity reflected the constantly improving quality of the artificial soils, suggesting that they could be used for the gradual construction of artificial soil micro-ecosystems. Overall, the artificial soils provided a feasible solution for the large-scale, low-cost, and highly efficient synergistic disposal of red mud and phosphogypsum, with enormous potential for future engineering applications. They are expected to be used for

* Corresponding authors.
E-mail addresses: lyong821mmm@163.com (Y. Liu), wangjingfu@vip.skleg.cn (J. Wang).

https://doi.org/10.1016/j.scitotenv.2024.175656
Received 9 May 2024; Received in revised form 16 August 2024; Accepted 18 August 2024
Available online 20 August 2024
0048-9697/

vegetation greening, landscaping, and ecological environment improvement in tailings, collapse, and soil-deficient areas, as well as along municipal roads.

1. Introduction

Red mud is a byproduct of the alumina production from bauxite ore. It has a strong alkaline nature (pH > 10) and is named for its red coloration due to the presence of a large amount of iron oxide. It also contains elements such as aluminum (Al), calcium (Ca), silicon (Si), sodium (Na), potassium (K), various heavy metals and rare earth elements. For every ton of alumina produced, 1 to 2 tons of red mud is generated. Currently, the global production of red mud is as high as 4 billion tons, with an annual increase of 120 million tons (Liu et al., 2023; Anagnostopoulos et al., 2021). The phosphogypsum is a byproduct produced during the production of phosphoric acid from phosphate rock. It is highly acidic (pH < 5), usually in the form of grayish-white powder, with its main component being $CaSO_4 \bullet 2H_2O$ (usually exceeds 70 %). It also contains phosphorus (P), fluorine (F), heavy metals, rare earth elements, etc. The amount of phosphogypsum generated is enormous, with 4 to 5 tons of phosphogypsum produced for every ton of phosphoric acid. The global production of phosphogypsum reaches up to 7 billion tons, increasing annually by 250 million tons (Lv and Xiang, 2023). For a long time, due to the lack of effective disposal techniques, both red mud and phosphogypsum have been mainly disposed of through stacking, forming numerous yards. This not only severely occupies a large amount of land resources but also poses a significant threat to the surrounding environment and human health. In particular, with the continuous increase of storage stock, there are many uncertainties in the subsequent maintenance and management of storage yards, as well as their environmental health risks, which also makes the production, industry development and government management of relevant enterprises face great challenges and pressures (Tayibi et al., 2009; Chernysh et al., 2021; Liu et al., 2023).

As two typical bulk industrial solid wastes, red mud and phosphogypsum will have a series of negative effects on atmosphere, water, soil and biodiversity if they are not properly disposed of. For example, the leachate from red mud and phosphogypsum has strong alkaline and acidic properties, respectively, which are not only highly corrosive but also, when discharged into water bodies, lead to significant changes in water pH, posing a serious threat to aquatic life and their metabolic processes (Liu et al., 2023; Wang et al., 2024b). The leachate from red mud entering the soil causes soil alkalinization and hardening, causing poor growth or death of crops, while the leachate from phosphogypsum may lead to soil acidification, increasing the risk of heavy metals and other harmful substances being released again from soil particles (Wang et al., 2023b; Remisha et al., 2024). Phosphogypsum contains a large amount of soluble phosphorus, which, when washed by rainwater, enters rivers and lakes through surface runoff, causing phosphorus pollution and eutrophication of water bodies (Hu et al., 2023). The soluble fluoride in phosphogypsum entering water bodies leads to fluoride pollution, causing fluoride poisoning when consumed by humans, resulting in diseases such as bone fluorosis and dental fluorosis (Xie et al., 2022). Various harmful elements, such as heavy metals in red mud and phosphogypsum, may also enter the environment, causing a series of biological poisoning and human health hazards. Additionally, the dust particles from dried red mud and phosphogypsum are also highly corrosive and carry harmful substances like heavy metals, dispersing in the air and causing particulate pollution. This mey directly damage the respiratory tract, skin of surrounding residents, leading to health issues such as heavy metal poisoning from long-term exposure to the population (Wagh and Thompson, 1988).

Many studies have shown that red mud and phosphogypsum can be effectively utilized as valuable resources (Liu and Wu, 2012; Akfas et al., 2024). For instance, red mud possesses excellent adsorption properties and, with appropriate modifications, can be utilized as an effective adsorbent for the removal of pollutant (Luu et al., 2022). Red mud can also be utilized for brick making or as a material for road construction (Wang et al., 2023a). The high content of metals such as iron, aluminum, and titanium in red mud enables their recovery for various valuable metal resources (Liu and Wu, 2012). Phosphogypsum can be utilized in the production of gypsum and cement for building materials and can be combined with other materials to form adsorbent materials (Rashad, 2017; Syczewski et al., 2020). Calcium and oxygen in phosphogypsum can be recycled as resources through low-temperature decomposition (Yang et al., 2024), while the associated soluble phosphorus, fluoride, and rare earth elements can be leached and recovered as resources (Rychkov et al., 2018). Additionally, both red mud and phosphogypsum can be utilized as soil conditioners, offering advantages in immobilizing heavy metals, ameliorating soil salinity, and optimizing soil physicochemical properties (Outbakat et al., 2022). Many of the mentioned resource recovery technologies are still in the research stage and are not extensively employed in practical production. Currently, the utilization of red mud and phosphogypsum resources remains very low, with utilization rates of approximately 4 % and 15 %, respectively (Wang and Liu, 2021; Yang et al., 2024). It is evident that, compared to the annual increases and historical stockpiles, existing technologies for reducing red mud and phosphogypsum stockpiles are still quite limited. Therefore, the efficient resource utilization of red mud and phosphogypsum, especially through large-scale, cost-effective technologies, remains urgently needed and is an international focus.

In recent years, the ecological management of red mud and phosphogypsum yards, as a new idea with low input cost, relatively simple technology and large-scale management, has been widely concerned (Xue et al., 2016; Kong et al., 2017; Tian et al., 2020). However, it is also faced with problems such as how to remove the acid and base of red mud and phosphogypsum, the difficulty of finding pioneer plants suitable for growth, and the unclear effect of ecological management and environmental risks. Red mud shares some characteristics of clay minerals, and red mud and phosphogypsum both contain some major elements commonly seen in common natural soil, such as Fe, Al, O, Si, Na, K, and Mg in the case of red mud, and Ca, O, S, and P in the case of phosphogypsum (Tayibi et al., 2009; Liu and Wu, 2012). The artificial soil preparation for vegetation restoration based on acid-alkali neutralization reaction of red mud and phosphogypsum has great potential (Liu et al., 2024). This study constructed a small-scale test site where two types of artificial soils were prepared. Red mud and phosphogypsum occupied absolute proportions in both types of artificial soils and were amended with slight amounts of other auxiliary materials. By simulating the engineering applications in vegetation restoration and ecological reconstruction of the two types of artificial soils prepared on the test site, this study systematically analyzed their basic physicochemical parameters, major nutrients, different enzymes, typical heavy metal content, and plant growth and physiological and biochemical indicators, as well as microbial (fungal and bacterial) and arthropod community diversity. In this way, it provides an important reference for the practical engineering applications of artificial soils in vegetation restoration and ecological reconstruction, offering a potential scientific solution for the large-scale, low-cost, and efficient synergistic recycling of red mud and phosphogypsum as resources.

2. Materials and methods

2.1. Preparation of the two types of artificial soils

Both types of artificial soils were mainly prepared from red mud and phosphogypsum, with the addition of other auxiliary materials. Specifically, one of them, denoted as DK, was amended with other auxiliary materials mainly composed of rice husks; the other, denoted as JZ, was amended with other auxiliary materials based on distiller's grains (Table 1). Red mud was sourced from an alumina plant in Guizhou, China, with a moisture content (W_{H2O}) of 15.2 % and a pH of 11.7; phosphogypsum was sourced from a yard of a phosphorus chemical plant in Guizhou, China, with a W_{H2O} of 16.3 % and a pH of 2.4 (Fig. S1). Distiller's grains were mainly composed of fermented sorghum and rice, with a W_{H2O} of 74.4 %, sourced from a brewage workshop in Guizhou, China; common dry rice husks with a W_{H2O} of 7.7 %, bentonite, and polyacrylamide (PAM). The JZ and DK were prepared by evenly mixing the above materials and then adding small amounts of distiller's yeast and yeast powder and a certain volume of microbial suspension diluent (e.g. *Bacillus amyloliquefaciens*, *Bacillus licheniformis*, *Bacillus subtilis*, effective viable bacteria count >200 million/mL), followed by water injection to near saturation. After that, they were sealed with a membrane and balanced for 10 d. In addition, 100 larvae of *Eisenia foetida* (5–7 cm) were added to each soil.

2.2. Construction of the test site and different plant cultivation

An open space of about 30 m^2 was selected and divided into two equal parts for the placement of the two types of artificial soils (JZ and DK). Rainproof and anti-seepage treatments were installed at the test site to prevent uncontrollable factors from affecting test results. A total of 38 different types of plant seedlings and seeds (including wood, herbs, flowers, succulents, etc) were directly transplanted or sprinkled into two types of artificial soil for plant seedling growth and seed germination. During the test of about one year, artificially watering regularly to maintain soil moisture content of about 30 %, the ambient climate was generally moist, and the temperature varied generally between 5–30 °C.

2.3. Sample collection

After the construction of the test site, the two types of artificial soils samples were collected at 30 d, 90 d and 150 d respectively by the diagonal distribution method. A total of 3 points were set on the diagonal line of each artificial soil plot as three parallel groups. At each point, samples were collected 3 times within a diameter of 30 cm and mixed as the final sample at the point. The depth of soil sample collection was 8–15 cm. After freeze-drying, crushing, removal of foreign bodies (e.g. plant residues, sand, etc), using the quartering method to reduce the sample, the soil samples were stored in cold storage and used for analysis the various artificial soils indicators as soon as possible, including of the basic physicochemical indicators (pH, W_{H2O}, organic matter (OM), and cation exchange capacity (CEC)), different nutrients (total nitrogen (TN), total phosphorus (TP), total potassium (TK), alkaline nitrogen (AN), available phosphorus (AP), and available potassium (AK)), enzymes (catalase (S-CAT), sucrase (S-SC), urease (S-UE), alkaline phosphatase (S-AKP), and acid phosphatase (S-AP)), chemical forms of typical heavy metals. Similarly, the two artificial soil samples were collected at 180 d and 360 d respectively, and the natural soil (NS) without human interference near the test site was collected simultaneously as a control group, to analyze soil arthropod community. Significantly, on the 30th day after the test site was constructed, a total of 5 points were set on the diagonal line of each artificial soil plot as five parallel groups to analyze the microbial (fungal/bacterial) community diversity. After five months of continuous growth, some adaptable plants with good growth on the test site were collected for determination of the activity of different enzymes (catalase (CAT), peroxidase (POD), superoxide dismutase (SOD), ascorbate peroxidase (APX)) and typical stress resistance indicators (malondialdehyde (MDA), soluble sugar (SS), soluble protein (SP), and proline (PRO)).

2.4. Determination methods

The pH value was measured by a Mettler acidity meter with a soil-water mass ratio of 1:2.5. The W_{H2O} was measured by weighing. OM, CEC, and main nutrients referred to China's national, local, and agricultural and forestry industry standards: OM (GB 9834–88), CEC (HJ 889–2017), TN (LY/T 1228–2015), AN (DB51/T-1875-2014), TP (GB 9837–88), AP (NY/T 1848–2010), TK (LY/T 1234–2015), and AK (NY/T 889–2004). The determination of different enzyme activities in artificial soil mainly refered to the book (Guan, 1986): S-SC, 3,5-dinitrosalicylic acid colorimetric method; S-CAT, potassium permanganate titration; S-AP and S-AKP, disodium phenyl phosphate colorimetric method; S-UE, sodium phenol-sodium hypochlorite colorimetric method. The different chemical forms of heavy metals were extracted using the Tessier method (Tessier et al., 1979), which classifies heavy metals into five distinct chemical forms: water-soluble (F_{H2O}), exchangeable (F_{EXC}), carbonate-bound (F_{CA}), iron-manganese oxide-bound ($F_{Fe/Mn}$), organic-bound (F_{OM}), and residual (F_{RES}), and determined using inductively coupled plasma mass spectrometry (ICP-MS).

The microorganism (fungi and bacteria) communities in the two artificial soils were analyzed using high-throughput sequencing by Shanghai Majorbio Bio-pharm Technology Co., Ltd. (https://www.majorbio.com), as follows approximately: DNA concentrations were measured using the Nanodrop-2000 instrument, DNA integrity was detected by agarose gel electrophoresis, and PCR amplification experiment (PCR-primer design: 338F—ACTCCTACGGGAGGCAGCAG; 806R—GGACTACHVGGGTWTCTAAT; ITS1F—CTTGGTCATTTAGAGGAAGTAA; ITS2R—GCTGCGTTCTTCATCGATGC). The arthropod community diversity was determined using the Tullgren dry funnel method (Yang et al., 2023). The different enzyme activities and stress resistance indicators of plants were determined using common methods as follows: POD, guaiacol method (Wang et al., 2010); CAT and APX, UV spectrophotometry (Li et al., 2007; Sun et al., 2008); SOD, riboflavin-nitro blue tetrazolium photoreduction method (Zhu, 2018); SP, coomassie brilliant blue method (Cai, 2013); SS, anthrone method (Li, 2000); PRO, acid ninhydrin method (Yang, 2022); MDA, thiobarbituric acid method (Yi et al., 2013).

2.5. Data statistics

Excel 2010, SPSS 22, and Sigmaplot 10.0 were used for data collation, analysis, and mapping, respectively. The data were presented using the mean and standard deviation of parallel samples. The significant differences of data in graphs and tables were analyzed by single factor ANOVA, LSD or paired sample *t*-test.

3. Results and analysis

3.1. Artificial soil evaluation

(1) Micro-morphology and basic physicochemical characteristics

Table 1
Material mass ratio of two types of artificial soils at the test site.

Name	Red mud	Phosphogypsum	Distillers' grains	Rice hull	Bentonite	Polyacrylamide
JZ	49.36 %	32.91 %	16.45 %	/	1.23 %	4.52*10^{-2} %
DK	53.78 %	35.86 %	/	8.96 %	1.34 %	5.38*10^{-2} %

Note: JZ and DK represent two types of artificial soils, respectively.

JZ and DK both possessed certain aggregate and porosity structures and contained major elements similar to those commonly seen in common natural soil, such as O, Si, Al, Fe, Ca, Na, K, and Mg (Figs. S2, S3). The pH values of JZ and DK were significantly different ($pH_{JZ} < pH_{DK}$) and dropped to 7.6 and 8.3 over time, respectively, indicating neutrality or weak alkalinity and could satisfy plant growth. The W_{H2O} of DK and JZ varied slightly across different stages, ranging from 27.3 % to 34.9 %, which is the basis of the moisture retention and the nutrient transport for plant. As one of the most important soil fertility indicator, OM content in DK and JZ ranged from 6.0 % to 6.3 % and 3.4 % to 4.8 %, respectively. The CEC refers to the total amount of various cations adsorbed by soil colloids, and its values of DK and JZ at 30 d were 9.2 and 7.2 cmol/kg, respectively, and tended to be similar over time, reaching 8.6 and 8.5 cmol/kg (Fig. 1).

(2) Nutrient characteristics

As shown in Fig. 2, the TN of JZ was significantly higher than that of DK; they both peaked at 30 d, reaching 960.6 and 337.1 mg/kg, respectively. At 90 d and 150 d, they dropped to 631.9 and 215.3 mg/kg, respectively. The differences in AN between JZ and DK were smaller than those of TN. The AN of JZ was slightly higher than that of DK, and both peaked at 30 d, reaching 153.7 and 100.9 mg/kg, respectively. At 150 d, the AN of JZ declined slightly to 120.0 mg/kg, while that of DK varied slightly across different stages. The TP of JZ and that of DK both peaked at 30 d, reaching 2510.5 and 2273.1 mg/kg, respectively. They declined to varying extents at 90 d and 150 d, and reached their minimums of 1056.1 and 935.5 mg/kg at 90 d, respectively. The differences in AP content between JZ and DK were small, with low variation across different stages. The AP of JZ and that of DK were within the ranges of 194.3–233.4 and 237.7–276.5 mg/kg, respectively. They both declined to some extent at 150 d. The TK of JZ and that of DK were close and both peaked at 30 d, reaching 72.3 and 65.0 g/kg, respectively. They both dropped at 90 d and 150 d to 34.8 and 35.1 g/kg, respectively. Overall, the AK content of JZ and that of DK were both low and peaked at 90 d, reaching 15.6 and 14.2 mg/kg, respectively. They then dropped sharply at 150 d to only 8.5 and 10.2 mg/kg, respectively.

(3) Soil enzyme activity

Both JZ and DK had significantly different enzyme activity (Fig. 3). On the whole, the S-CAT enzyme activity of JZ was the highest, with minimal variations at 30 d and 90 d (ranging from 1.2 to 1.3 mg/g, 24 h). The S-SC enzyme activity of JZ was low at 30 d but significantly increased at 90 d (reaching 1.0 mg/g, 24 h). The S-AKP enzyme activity of JZ was moderate with small overall variations, ranging from 2.4×10^{-1} to 3.0×10^{-1} mg/g, 24 h. The S-UE enzyme activity and S-AP enzyme activity of JZ were low; only 2.4×10^{-2}–6.3×10^{-2} and 6.6×10^{-3}–6.8×10^{-3} mg/g, 24 h, respectively. S-SC had the highest enzyme activity in DK, reaching up to 7.4 mg/g, 24 h at 30 d, but it dropped sharply at 90 d to 2.4 mg/g, 24 h (still significantly higher than that of JZ). S-CAT ranked second in terms of enzyme activity in DK, with 8.7×10^{-1} mg/g, 24 h at 30 d, which slightly increased at 90 d to 9.6×10^{-1} mg/g, 24 h. The enzyme activity of S-AKP and that of S-UE were similar, with small variations, at 8.4×10^{-2}–8.6×10^{-2} and 5.5×10^{-2}–7.6×10^{-2} mg/g, 24 h, respectively. The enzyme activity of S-AP was the lowest, with a value of 1.0×10^{-2} mg/g, 24 h at 30 d, which slightly declined at 90 d to only 6.2×10^{-3} mg/g, 24 h.

(4) Chemical forms of heavy metals

The content of each of the several typical heavy metals was low and similar between JZ and DK (Fig. 3). On the whole, heavy metals could be ranked as follows in descending order of content: Mn > Cu > Pb ≈ Zn > Sb > Cd. Mn had the highest content at 251.7 and 275.0 mg/kg in JZ and DK, respectively, while Cd had the lowest at 1.5 and 1.0 mg/kg. The chemical forms of the several typical heavy metals in JZ and DK were all dominated by non-bioavailable F_{RES}, with proportions of 69.0 %–98.0 % and 75.6 %–98.3 %, respectively. The bioavailable F_{H2O} and F_{EXC} each had a low content; specifically, the F_{H2O} and F_{EXC} of the several typical heavy metals in JZ only accounted for 0.2 %–1.0 % and 0.1 %–2.1 %, while those of them in DK only accounted for 0.1 %–1.2 % and 0.2×10^{-1}–4.6 %, respectively.

3.2. Plant growth evaluation

(1) Plant growth status

Approximately five months of observation preliminarily indicated

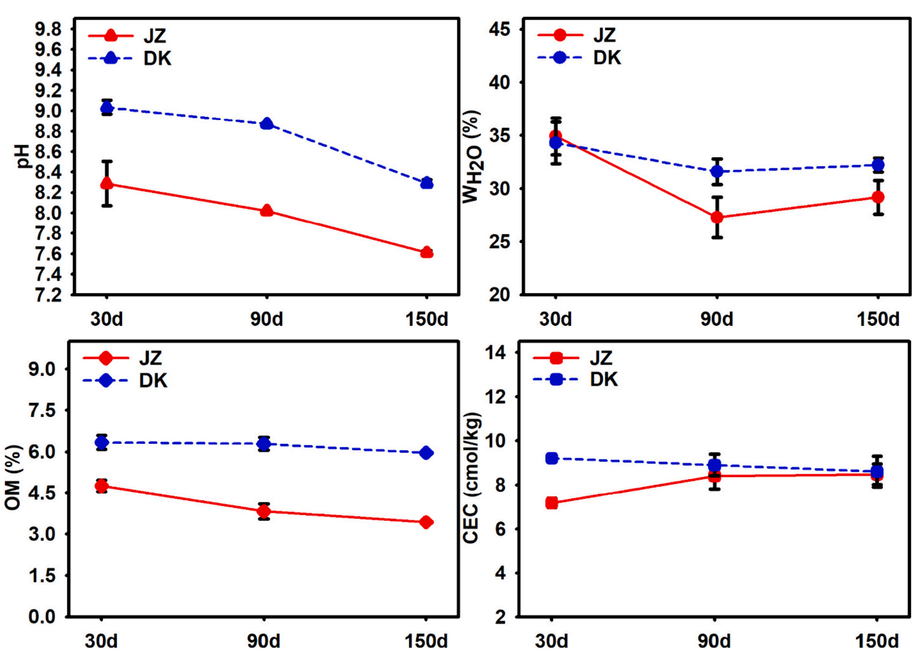


Fig. 1. Basic physicochemical (pH, moisture content (W_{H2O}), organic matter (OM), cation exchange capacity (CEC)) characteristics of two types of artificial soils at the test site. (Note: JZ and DK represent two types of artificial soils, respectively).

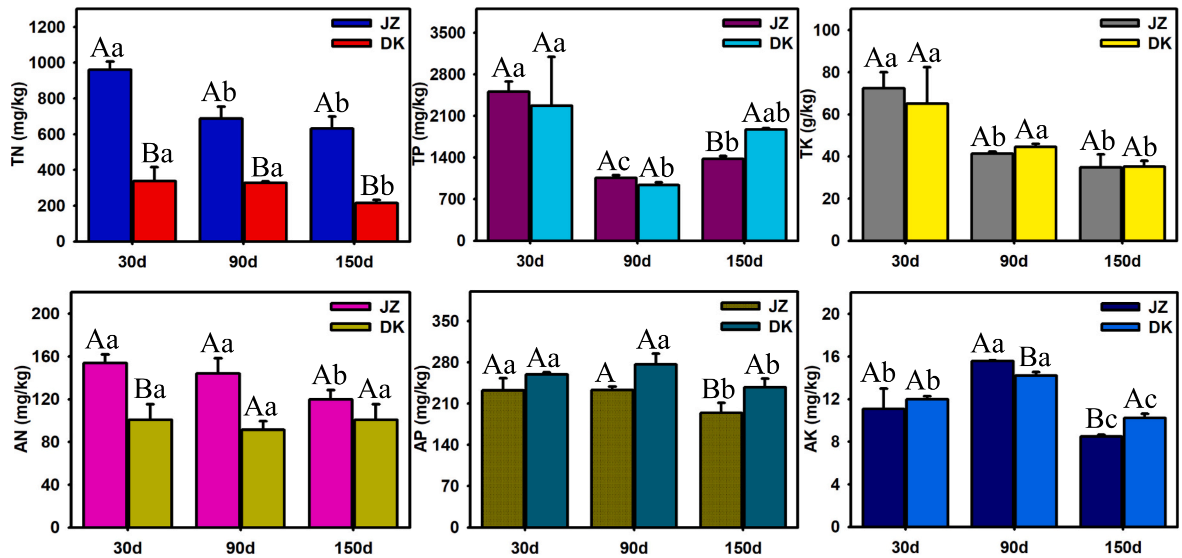


Fig. 2. Nitrogen, phosphorus and potassium contents of two types of artificial soils at the test site. (Note: Different lowercase letters indicated that the nutrient content in same artificial soil have significant differences in different time periods ($p < 0.05$; Single factor ANOVA, LSD); Different capital letters indicated that the nutrient content in different artificial soils had significant differences in the same time period ($p < 0.05$; Paired sample t-test); Nitrogen: total nitrogen (TN) and available nitrogen (AN); phosphorus: total phosphorus (TP) and available phosphorus (AP); potassium: total potassium (TK) and available potassium (AK); JZ and DK represent two types of artificial soils, respectively).

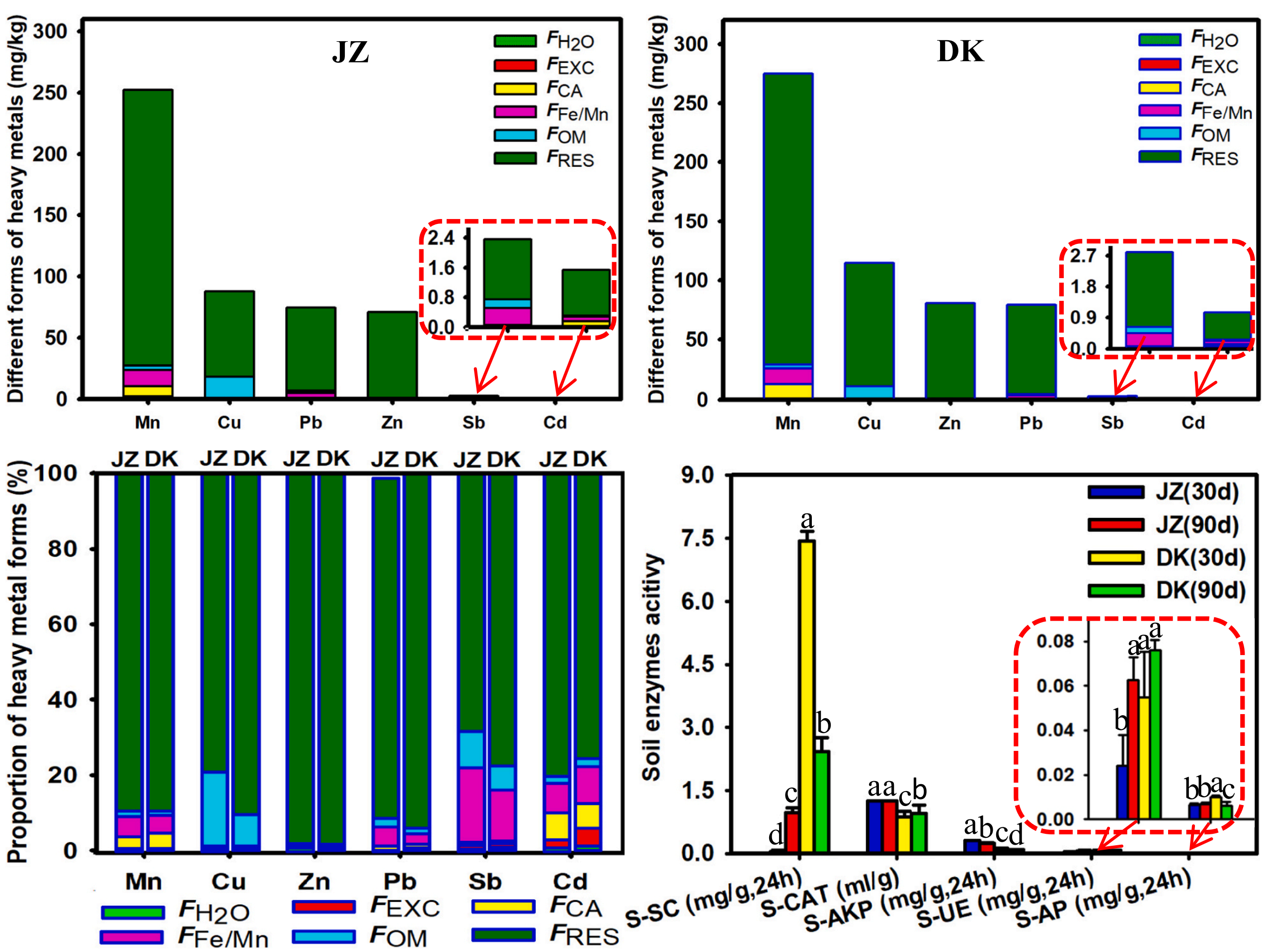


Fig. 3. Content and proportion of different heavy metal forms and enzyme activity of two types of artificial soils at the test site. (Note: Different lowercase letters indicated that the activity of the same enzyme in the two artificial soils was significantly different ($p < 0.05$; Single factor ANOVA, LSD); Chemical forms of heavy metals: water-soluble (F_{H2O}), exchangeable (F_{EXC}), carbonate-bound (F_{CA}), iron-manganese oxide-bound ($F_{Fe/Mn}$), organic-bound (F_{OM}), and residual (F_{RES}); Soil enzymes: catalase (S-CAT), phosphatase (S-AP/AKP), urease (S-UE), sucrase (S-SC); JZ and DK represent two types of artificial soils, respectively).

that there were at least 18 different types of plants that grew well on the test site (Fig. 4), which could be prioritized for vegetation restoration and ecological reconstruction: shrubs, including *Amorpha fruticosa* (JZ/DK); gramineous plants, including ryegrass (JZ/DK), *Paspalum vaginatum* (JZ/DK), *Pteris vittata* (JZ), and wheat (JZ/DK); Compositae plants, including sunflower (JZ/DK) and *Sonchus oleraceus* (JZ); Caprifoliaceae plants, including *Lonicera japonica* (JZ/DK); Chenopodiaceae plants, including *Suaeda glauca* (JZ/DK) and *Chenopodium hybridum* (JZ); liliaceous plants, including *Aloe vera* (JZ/DK); Cactaceae plants, including cactus (JZ/DK); Caryophyllaceae plants, including *Vaccaria segetalis* (JZ); Amaranthaceae plants, including *Gomphrena globosa* (JZ); Cruciferae plants, including rape (JZ); leguminous plants, including clover (JZ/DK); Crassulaceae, including *Sempervivum tectorum* (DK); and Rosaceae, including loquat (JZ/DK). Many other plant seeds also germinated to varying extents and presented great potential for becoming adaptable plants (*Agrostemma githago*, *Oenothera biennis*, heronsbill, lavender, black sesame, pepper, *Hippophae rhamnoides*, *Silybum marianum*, *Gypsophila paniculata*, perpetual strawberry) (Table S1).

(2) Different enzyme activity and stress resistance indicators of plants

As shown in Fig. 5, in JZ, rape had the highest CAT enzyme activity, followed by wheat, reaching as high as 927.3 and 686.1 U/g, FW/min, respectively. The CAT enzyme activity levels of *Gomphrena globosa*, *Suaeda glauca*, cactus, and clovers were relatively low, ranging from 57.7 to 131.3 U/g, FW/min. In DK, wheat had the highest CAT enzyme activity, followed by clover, reaching as high as 290.0 and 132.6 U/g, FW/min, respectively. The CAT enzyme activity levels of *Suaeda glauca*, ryegrass, and cactus were relatively low, ranging from 31.1 to 73.6 U/g, FW/min. In JZ and DK, wheat had the highest POD enzyme activity (7074.2 and 7780.4 U/g, FW/min, respectively), followed by clover (4679.2 to 6409.9 U/g, FW/min). The POD enzyme activity levels of *Suaeda glauca* and cactus were relatively low, with ranges of 87.2–161.3 and 8.1–27.1 U/g, FW/min, respectively. In JZ, the SOD enzyme activity levels of rape and *Gomphrena globosa* were 205.8 and 203.1 U/g, respectively. In DK, clover had the highest SOD enzyme activity, followed by wheat, reaching as high as 221.9 and 164.0 U/g, respectively. The SOD enzyme activity levels of cactus and ryegrass were relatively low in both JZ and DK. In JZ, the APX enzyme activity levels of *Paspalum vaginatum* were significantly higher than those of other plants, reaching 6.0 and 3.3 μmol/g, FW/min, respectively. In DK, the APX enzyme activity level of wheat (3.0 μmol/g, FW/min) was significantly higher than that of any other plant. *Suaeda glauca* had the lowest APX enzyme activity in both JZ and DK, with specific values of 0.2 and 0.3 μmol/g, FW/min, respectively.

The stress resistance indicators of several representative plants are shown in Fig. 6. In JZ, wheat and *Paspalum vaginatum* each had an MDA content of about 0.3×10^{-1} μmol/g, significantly higher than that of any other plant; cactus had the lowest MDA content of only about 0.3×10^{-2} μmol/g. In DK, *Lonicera japonica* had the highest MDA content of about 0.1 μmol/g, while the MDA contents of cactus and *Suaeda glauca* were 0.4×10^{-2} and 0.3×10^{-2} μmol/g, respectively, both significantly lower than that of any other plant. In JZ, *Paspalum vaginatum* had the highest SS content (4.6 %), while in DK, *Lonicera japonica* had the highest SS content (7.9 %). *Suaeda glauca* had the lowest SS content in both JZ and DK, at only 0.7 and 1.2 %, respectively. Clover had the highest SP content in both JZ and DK at 13.5 and 8.8 mg/g, FW, respectively, while ryegrass, *Suaeda glauca*, and cactus each had a relatively low SP content. In JZ, rape had the highest PRO content (up to 75.1 μg/g), while ryegrass had the lowest (only 4.0 μg/g). In DK, clover had the highest PRO content (up to 8.3 μg/g), while *Suaeda glauca* had the lowest (only 0.4 μg/g).

3.3. Bacterial and fungal diversity

Only 30 days after the test site was constructed, both JZ and DK accumulated relatively rich microbial (fungal and bacterial) communities. A total of 17 bacterial phyla and over 50 bacterial genera, as well as five fungal phyla and over 50 fungal genera, were detected in JZ; 26 bacterial phyla and over 50 bacterial genera, as well as eight fungal phyla and over 50 fungal genera, were detected in DK (combined abundance <50; Figs. S3, S4, S5, S6). Fig. 7 lists the bacterial and fungal phyla/genera with a combined abundance of <10. In JZ, the dominant bacterial phyla included Firmicutes (40.6 %), Proteobacteria (26.0 %), and Bacteroidota (22.5 %), totaling 93.1 %. The relatively dominant bacterial genera included *Bacteroides* (10.1 %), *Exiguobacterium* (8.2 %), *Arcobacter* (6.8 %), and *Enterobacter* (6.4 %), with the remaining genera each accounting for <5 %. In DK, the dominant bacterial phyla included Proteobacteria (48.5 %), Firmicutes (20.8 %), Bacteroidota (16.1 %), and Actinobacteriota (7.4 %), totaling 92.8 %. The relatively dominant bacterial genera included *Exiguobacterium* (8.4 %), *Pseudomonas* (6.5 %), *Enterobacter* (6.1 %), and *Brevundimonas* (5.4 %), with the remaining bacterial genera each accounting for <5 %. The dominant fungal phyla in JZ and DK were Ascomycota (90.8 % and 69.7 %, respectively) and Basidiomycota (9.1 % and 12.5 %, respectively). In addition, Mortierellomycota accounted for 13.0 % of fungal abundance in DK. At the genus level, *unclassified-f-Dipodascaceae* accounted for 88.4 % in JZ, followed by *Apiotrichum* at 5.7 %, while the remaining fungal genera each accounted for <5 %. The dominant fungal genera in DK were *Aspergillus* (21.4 %), *Fusarium* (15.7 %), *Gibberella* (13.6 %), and *Mortierella* (13.0 %), totaling 63.7 %.

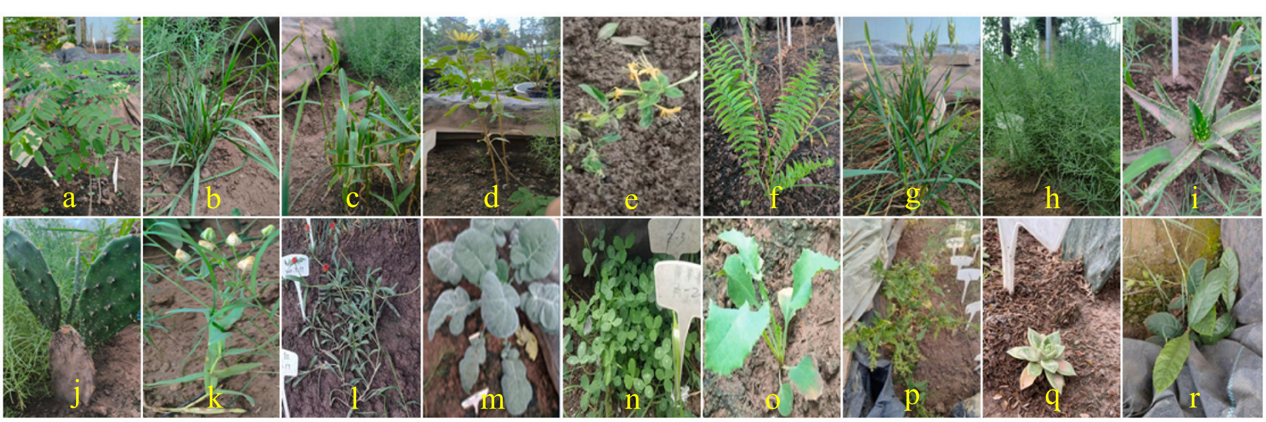


Fig. 4. Some well-growing plant species in two types of artificial soils at the test site. (Note: a. *Amorpha fruticosa*; b. Ryegrass; c. *Paspalum vaginatum*; d. Sunflower; e. *Lonicera japonica*; f. *Pteris vittata*; g. Wheat; h. *Suaeda glauca*; i. *Aloe vera*; j. Cactus; k. *Vaccaria segetalis*; l. *Gomphrena globosa*; m. Rape; n. Clover; o. *Sonchus oleraceus*; p. *Chenopodium hybridum*; q. Succulent; r. loquat).

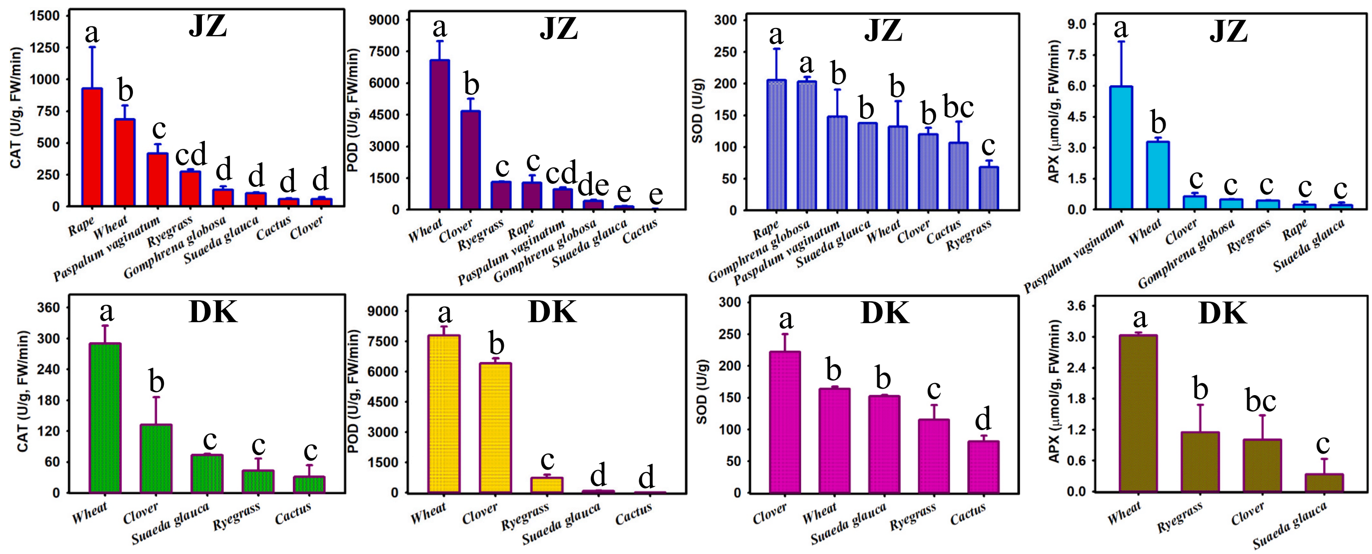


Fig. 5. Different enzyme activity of some plant species in two types of artificial soils at the test site. (Note: Different lowercase letters indicated that the enzyme activity values of different plant species in artificial soil were significantly different ($p < 0.05$; Single factor ANOVA, LSD); Plant enzymes: superoxide dismutase (SOD), catalase (CAT), peroxidase (POD) and ascorbate peroxidase (APX); JZ and DK represent two types of artificial soils, respectively).

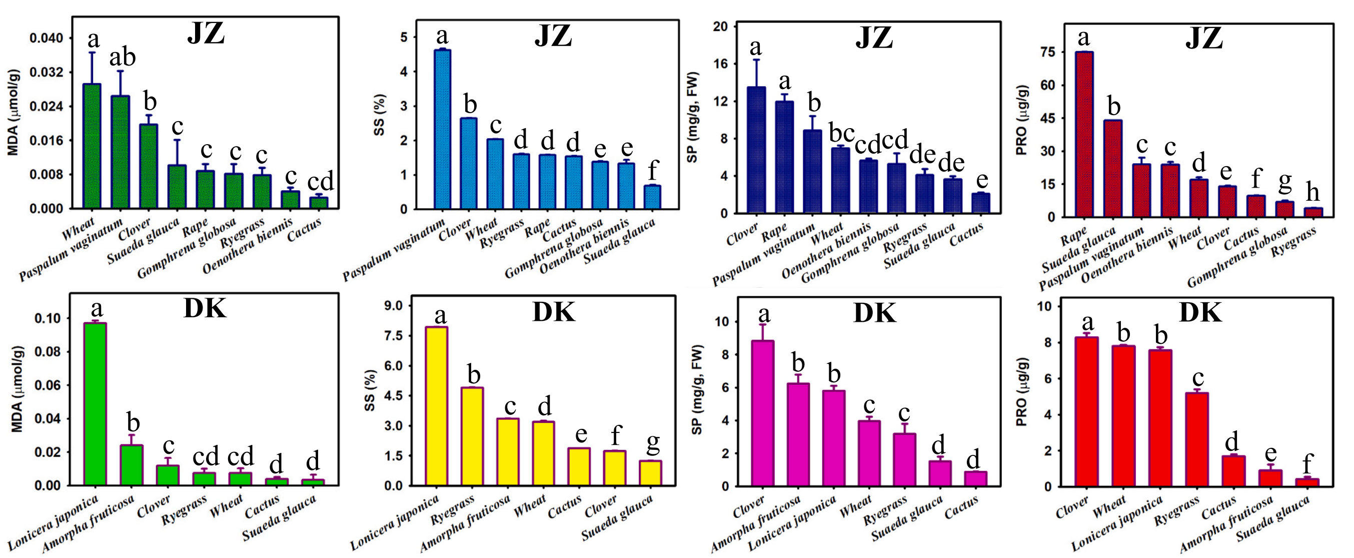


Fig. 6. Stress resistance indicators of some plant species in two types of artificial soils at the test site. (Note: Different lowercase letters indicated that the stress resistance indicator values of different plant species in artificial soil were significantly different ($p < 0.05$; Single factor ANOVA, LSD); Stress resistance indicators of plant: malondialdehyde (MDA), soluble sugar (SS), soluble protein (SP), and proline (PRO); JZ and DK represent two types of artificial soils, respectively).

3.4. Characteristics of soil arthropods

As the test site had limited space, the group numbers of arthropods in JZ and DK were relatively small at 180 d, with mean values of only three and one and summing values of four and three, respectively (Fig. 8). The Shannon-Wiener index values of JZ and DK were relatively small (0.6 and 0.4, respectively), both significantly lower than that of the NS without human interference surveyed at the same stage (mean value of nine, a summing value of 16, and a Shannon-Wiener index of 1.8). Six months later, at 360 d, the group numbers in JZ and DK both slightly increased, with mean values of four and five, summing values of nine and 11, and increased Shannon-Wiener index values of 0.8 and 1.0, respectively. These were already closer to those of the NS surveyed at the same stage (6, 15, and 1.5, respectively). It is worth mentioning that, at 360 d, the densities of soil arthropods in JZ and DK increased significantly from 7200/m^2 to 26,666.7/m^2 and from 400/m^2 to 25,466.7/m^2, respectively, significantly higher than the population seen in the NS surveyed at the same stage. The dominant arthropod species with relatively high detected quantitative proportions mainly included *Poduridae, Achipteriidae, Uropodidae, Isotomidae, Ameroseiidae,* and *Scolopendridae* (Fig. 9).

4. Discussion

Two types of red mud/phosphogypsum-based artificial soils were prepared and a small-scale test site was constructed for simulating the engineering application in vegetation restoration and ecological reconstruction in this study. The basic thought is that the red mud and phosphogypsum were mixed into a neutral matrix. Minimal amounts of auxiliary materials were added to modify the matrix's physicochemical properties, increase its nutrients, and promote its development, and form an artificial soil with good fertility. Then, the growth of different

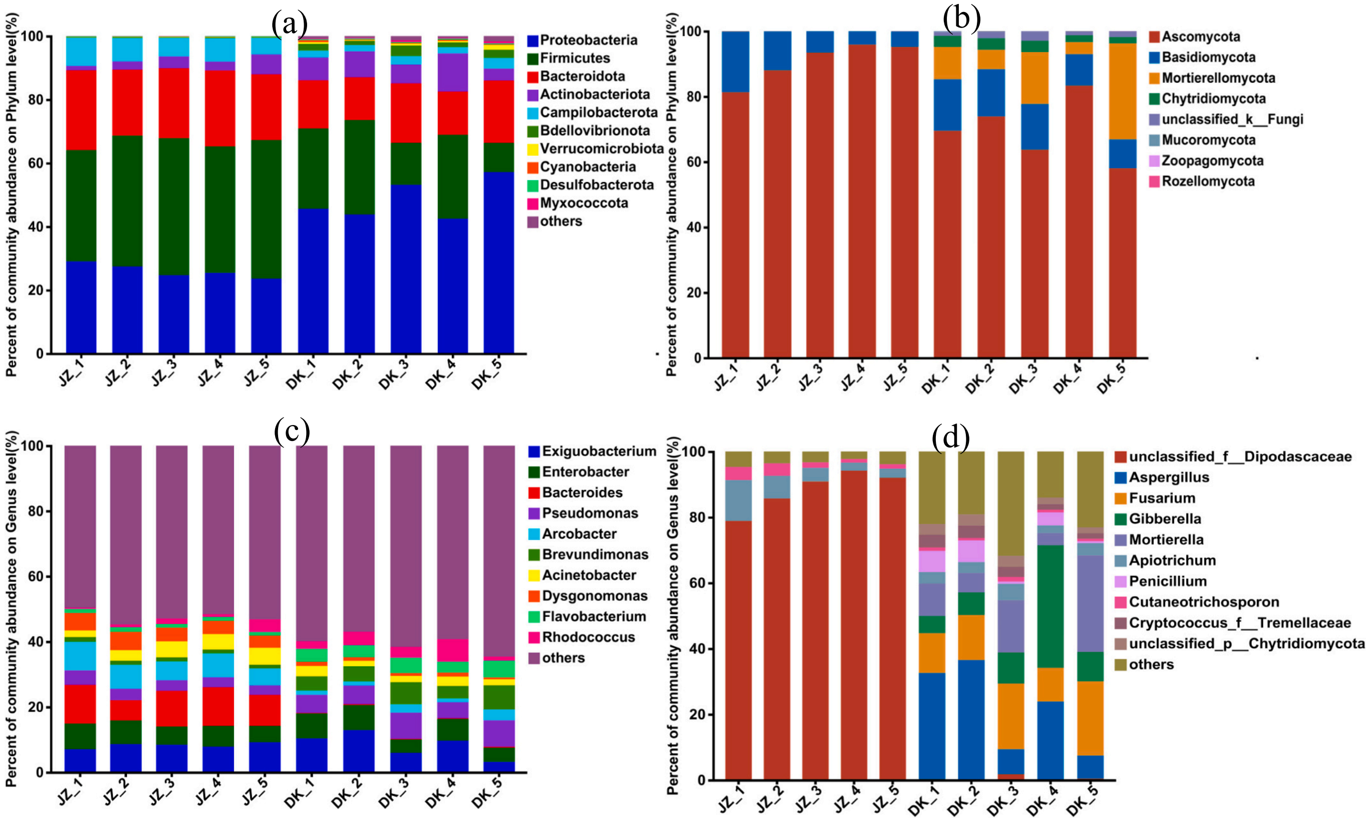


Fig. 7. Percent of community abundance of bacteria and fungi in two types of artificial soils at the test site. (Note: (a) Phylum level of bacteria; (b) Phylum level of fungi; (c) Genus level of bacteria; (d) Genus level of fungi; JZ and DK represent two types of artificial soils, respectively).

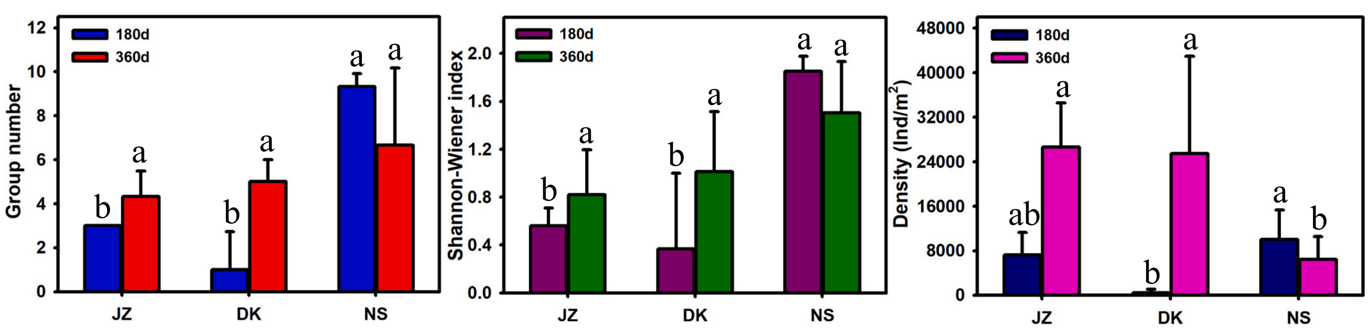


Fig. 8. Characteristics of soil arthropods in two types of artificial soils at the test site. (Note: Different lowercase letters indicated that the soil arthropods values of different soils have significant differences at the same time ($p < 0.05$; Single factor ANOVA, LSD); JZ and DK represent two types of artificial soils, respectively; NS represents the natural soil without human interference).

types of adaptable plants and the continuous enrichment of microbial and arthropod communities led to the preliminary formation of simple ecosystems, which in turn promoted the further development, evolution, and maturation of the artificial soil. The final step involved the use of the artificial soil for vegetation greening and landscaping and the formation of sounder ecosystems.

4.1. Basic physicochemical characteristics

The two artificial soils contained major elements, similar to those contained by common natural soil, such as O, Si, Fe, Al, Ca, C, S, and Mg, mainly sourced from the red mud (e.g. O, Fe, Al, Si) and phosphogypsum (e.g. Ca, S, and O) (Tayibi et al., 2009; Liu and Wu, 2012). The two artificial soils possessed certain aggregate and porous that were conducive to the water storage, aeration, permeability, and material exchange, providing a basis for the continuous occurrence of various physical, chemical, and biological processes and the cycling and transformation of materials and nutrients (Yang et al., 2022b). The basic physicochemical indicators (pH, W_{H2O}, OM, and CEC) all were consistent with most plant growth, especially the OM content was high. According to the latest nutrient grading standards of the Second National Soil Survey of China, they both reached the level of "Rich (3–4 %)" or "Very rich (> 4%)", mainly because of the addition of organic auxiliary materials such as rice husks and distiller's grains, which gradually formed plant nutrients through humification and mineralization and promoted further development of soil ecosystem functions (Hoffland et al., 2020; Villa et al., 2021). However, the CEC values of the two artificial soils were relatively low ("Medium low"), indicating that they had relatively weak fertility retention capacity, that may be due to the relatively high artificial soil pH or alkalinity, so that the cations (such as Ca^{2+}, Mg^{2+}, etc.) originally adsorbing to the soil colloid may be replaced by H^+ or Na^+ (Khalediana et al., 2017; Gao et al., 2024b).

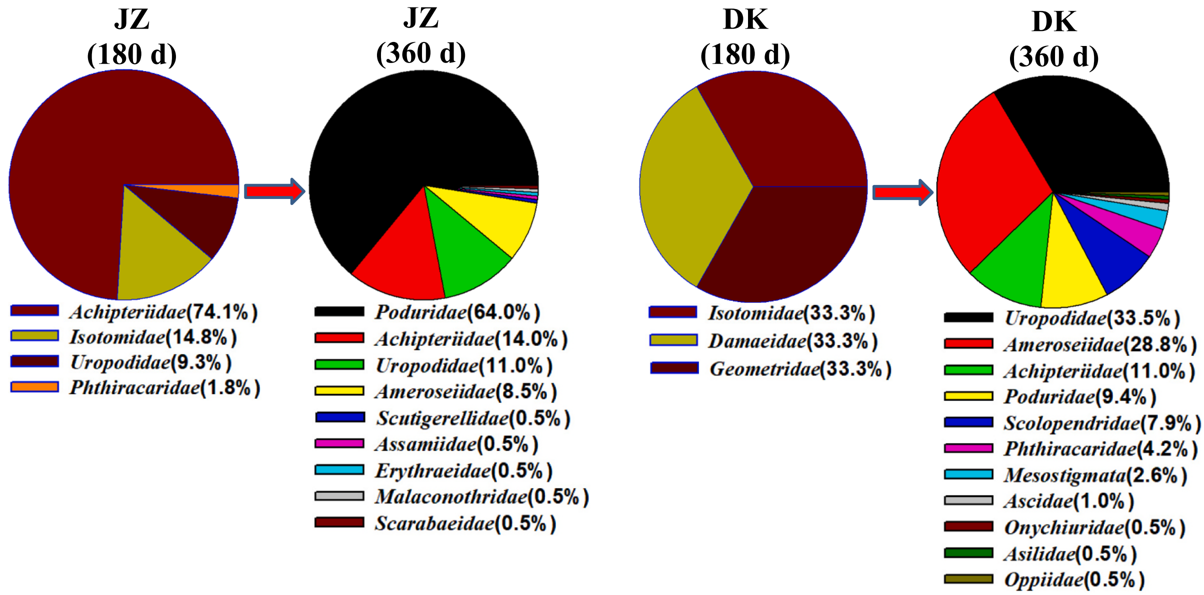


Fig. 9. Percent of soil arthropods in two types of artificial soils at the test site. (Note: JZ and DK represent two types of artificial soils, respectively).

4.2. Main nutrient characteristics

The two artificial soils already possessed high content of TP and AP; according to the above nutrient grading standards, they reached the level of "Extremely rich", mainly because of the large amounts of phosphorus contained in phosphogypsum (Hu et al., 2023). TN content of JZ belonged to the level of "Medium low" or "Insufficient", while that of DK belonged to the level of "Extremely insufficient". AN content of JZ and DK belonged to the levels of "Rich" and "Medium", respectively. The nitrogen partly resulted from auxiliary material addition such as distiller's grains and rice husks, which provided relatively rich OM but are still insufficient nitrogen sources, especially the rice husks mainly contain carbon-rich organic matter but little nitrogen (Leconte et al., 2009; Reuter et al., 2016). The nitrogen also possibly sourced from biological nitrogen fixation. For example, clover, as a typical nitrogen-fixing plant, grew well in both artificial soils (Høgh-Jensen and Schjoerring, 2001). Meanwhile, as two dominant bacteria in both artificial soils, Proteobacteria and Firmicutes are generally considered to have the function of nitrogen-fixing (Roesch et al., 2008; Supramaniam et al., 2016). In addition, it can supplement additional N by applying nitrogen fertilizers, cultivating nitrogen-fixing bacteria or leguminous plants in future engineering applications (Lei et al., 2022). TK content of JZ and DK reached the level of "Extremely rich", while AK content of them were at the level of "Extremely insufficient". Potassium mainly sourced from the red mud, which contains some potassium-rich minerals (e.g., feldspar, nepheline), but the bioactivity of potassium was low, thus how to convert a large amount of soil mineral-bound potassium into dissolved potassium that can be directly absorbed and utilized by plants is very meaningful (Rengel and Damon, 2008; Yang et al., 2020).

4.3. Main enzyme activities

Soil enzymes are produced by microorganisms, plant roots, and animals, and they play important roles in promoting the decomposition of organic matter, nutrient cycling, and the formation of soil structure. The two artificial soils have accumulated a certain amount of different enzyme activities, which indicated the high metabolism and biotransformation activity. Although more systematic data on the enzyme activity are lacking, the activity of the same enzyme was significantly different between the two artificial soils, and also had differences in different time periods, which initially indicated the respectively different characters of biological metabolism characteristics, biological transformation activity, and self-regulation of biological adaptation to external environmental stresses (Tyler, 2020; Yang et al., 2022a). For example, the activity of S-SC in DK was significantly higher than that in JZ ($p < 0.05$), possibly because of the high content of sugars such as cellulose and pentosan in rice husks in DK, the metabolic decomposition of which requires more sucrase involvement (Liu et al., 2020). The higher S-CAT activity in JZ than in DK could mean better protection of plants from hydrogen peroxide in JZ (Hu et al., 2018).

4.4. Typical heavy metals

The typical heavy metals (Cd, Cu, Mn, Pb, Sb, and Zn) in JZ and DK all had low concentrations, which all fall within the China's latest *Soil environmental quality - Risk control standard for soil contamination of agricultural land* (GB15618–2018) screening value ranges, except for Cd, preliminarily indicating that these heavy metals posed no risk of potential contamination. The total content of Cd in the two artificial soils was higher than the screening value (0.6 mg/kg when soil pH > 7.5) but lower than the contamination risk control value (4.0 mg/kg when soil pH > 7.5), indicated that the risk of Cd contamination is relatively low, and real-time monitoring of crops would be necessary when the artificial soil is used for agricultural land. All heavy metals were dominated by non-bioavailable F_{RES}, while the highly bioavailable F_{H2O} and F_{EXC} each accounted for <5 %. Due to the alkalinity of artificial soil, it is conducive to the conversion of heavy metals into insoluble forms of hydroxides, oxides and carbonates (Jiang et al., 2022). Addtionally, red mud is the main possible source of heavy metals, many of which generally exist in the form of sulfides, silicates, carbonates and other insoluble minerals or are firmly adsorbed by iron oxide in red mud (Santona et al., 2006; Zhu et al., 2023). These further significantly reduced the risk of heavy metal contamination when artificial soil was used for agricultural land. If artificial soil was to be used in forestry land or for vegetation ecological restoration in mining areas, there would be almost no need to be concerned about heavy metal contamination.

4.5. Adaptable plants

Both artificial soils were preliminarily confirmed to be able to support the long-term survival and growth of at least 18 different types of plants, as well as the seed germination of about ten other plants. This is a good initial step demonstrating the enormous potential of the artificial soils for use in vegetation coverage, biodiversity, and ecosystem construction. As an increasing number of plant types are selected for cultivation tests, more adaptable plants are expected to be discovered, continuously enriching the variety of plants available for the future engineering applications of the artificial soils in ecological restoration and landscaping in mining areas.

The different enzyme activity and stress resistance indicators of plants often describe their enzymatic catalytic reaction ability and environmental stress resistance under certain environmental conditions (Kiran, 2019; Cunha et al., 2022), which can be used to comprehensively assess the physiological status, environmental adaptability, self-protection, and self-restoration behavior of plants. On the whole, there were certain differences in the in vivo enzyme activity and stress resistance indicators of several representative plants, as well as different enzyme activity and stress resistance indicators from the same plant between JZ and DK (Figs. S7, S8). There were significant differences in the CAT enzyme activity of wheat, ryegrass, and *Suaeda glauca* between JZ and DK, as well as the POD enzyme activity of several other plants except wheat, and the SOD enzyme activity of clover and *Suaeda glauca* ($p < 0.05$). There were also significant differences between the two soils in the MDA content of wheat, the SS and PRO content of several plants, and the SP content of other tested plants except for clover and ryegrass ($p < 0.05$). Since the artificial soils are mainly composed of solid wastes such as red mud and phosphogypsum, they naturally impose significant stress on the physiological and biochemical characteristics of different plants. Such differences reflect the diversity and complexity of plant adaptability and regulatory feedback (stress) mechanisms in different plants responding to the same external environmental stress or the same plant responding to different external environmental stresses (Hahm et al., 2017). Although this study did not examine the variations or influencing factors of the different enzymatic activity and stress resistance indicators of plants through simulation tests under different conditions, which still provided valuable references for the selection of adaptable plants (Laffray et al., 2018; Cabañas-Mendoza et al., 2023; Shams et al., 2024). In the future, it is still necessary to explore the adaptability of different plants to the artificial soils in a more systematic way, examining plant physiological indicators.

4.6. Microbes and arthropods

Microbes, as the most active component of soil ecosystems, play a crucial role in soil material cycling, energy flow, and other processes. They can promote soil development, improve soil fertility, and provide a favorable environment for plant growth (Wang and Li, 2019). The synergistic effect of microbes and plants is of great importance to the gradual formation of stable soil ecosystems (Wang and Li, 2019; Le Roux et al., 2023). The two types of artificial soils had initially accumulated relatively rich microbial (fungal and bacterial) communities, which is a very positive signal indicating the relatively good environmental quality of artificial soil. Although red mud and phosphogypsum significantly inhibited the growth of microorganisms due to their strong alkali/acid, heavy metal content, high salinity characteristics, the artificial soil environmental quality can enable microorganisms to survive and form rich microbial communities, and these microorganisms in turn had a significant influence on the fertility enhancement of artificial soil. On one hand, the dominant bacterias (e.g. Firmicutes, Proteobacteria and Bacteroidota) had good adaptability and a series of complex biochemical processes occurred, including the decomposition of OM (cellulose and humus), biological nitrogen fixation, nitrification, denitrification, and nutrient transport and cycling, can continuously improve soil quality and fertility; Ascomycota, as the dominant fungal, in addition to decomposing organic matter, can co-exist with plants and improve their tolerance to external chemicals (Spagnoletti and Chiocchio, 2020). On the other hand, changes in the micro-environments and fertility of the artificial soils also have a significant positive feedback effect on microbial community diversity, which further promotes the continuous development and ecosystem construction of artificial soils (Marrs, 2016; Moreira-Grez et al., 2019). It is worth noting that there are still some differences in the microbial communities of the two artificial soils. For example, at the phylum level, DK has more fungal and bacterial phyla than JZ; The dominant bacteria and fungi genera of JZ and DK were also different in composition. These reflect the differences in physical and chemical characteristics and environmental quality of the two artificial soils, and also indicate that the development direction and ecosystem diversity of the two artificial soils may show different evolutionary characteristics.

Soil arthropods, as a type of small invertebrate living in the soil, are vital part of soil ecosystem (Neher and Barbercheck, 2019). They can improve soil structure, increase soil moisture and gas exchange, decompose OM, promote soil nutrient conversion, and effects on plant growth (Jernigan et al., 2023). The diversity of soil arthropod communities has an important indicative function in evaluating soil quality (Menta and Remelli, 2020). Arthropod communities were observed in JZ and DK, and over time, their group number, diversity index, and density significantly increased, gradually approaching the conditions of the NS (without human interference) surveyed at the same stage; the density of arthropods in the artificial soils even exceeded that in NS. This reflected the constantly improved quality and micro-environment of the artificial soils and the formation of gradually enriched arthropod community diversity (Bai et al., 2017). As an important component of soil micro-ecosystems, arthropods, like plants and microbes, also produced a positive feedback effect; they gradually exerted a positive effect on soil micro-environment and fertility improvement, ecosystem construction, and functional enhancement of the artificial soils (Mordkovich and Lyubechanskii, 2017). Notably, the larvae of *Eisenia foetida* initially added into the artificial soils grew and reproduced instead of dying (especially in JZ). After ten months, they had a body length more than twice the initial value, with a nearly five-times increase in body diameter. There were also some small earthworms (about 1–2 cm in body length) visible to the naked eye. The changes in the earthworms, as an indicator of soil quality, suggested that the artificial soils had good soil quality, few harmful substances, and provided favorable local micro-environmental conditions for the survival and reproduction of earthworms (Medina-Sauza et al., 2019; Sofo et al., 2023).

4.7. Engineering application analysis

From the systematic research results of the above test site, the engineering applications of these artificial soils in vegetation restoration and ecological reconstruction are potentially feasible, making it possible to achieve the large-scale, low-cost, and efficient synergistic recycling of red mud and phosphogypsum. Red mud and phosphogypsum constituted the matrix for the two artificial soils, occupying absolute proportions of 82.27 % and 89.64 %, respectively; this is very important, as it ensures that the two are recycled in large amounts. Distiller's grains and rice husks, as common organic solid wastes, are synergistically recycled as resources (accounting for 16.45 % and 8.96 %, respectively). Taking this into account, the total proportions of solid wastes in JZ and DK exceeded 98.72 % and 98.60 %, respectively, and only very small amounts of bentonite and polyacrylamide need to be purchased. The microbial inocula added (such as microbial agents and yeast) are also consumed at low doses and are readily available. Additionally, after the materials making up the artificial soils were evenly mixed and injected with water, they were sealed with a membrane and balanced for a period, rather than being periodically turned over for ventilation. This is a very simple method with low production costs, little nutrient loss, and almost no odor generation that promotes the humification, mineralization, and anaerobic decomposition of OM and the release, stabilization, and homogenization of nutrients (Long et al., 2023; Wang et al., 2024a). Overall, the materials used for the artificial soil preparation are common and readily available, without the need to add any proportion of natural soil. The preparation process is very simple and inexpensive. These significant advantages will contribute to the large-scale engineering applications of artificial soil in the future.

It is worth noting that the pH of red mud and phosphogypsum may change depending on industrial production batches, stockpiling time, and other factors, causing the ratio between them in the neutralization reaction to change as well. For example, in our previous study, the mass ratio between red mud and phosphogypsum was 2.5:1, while in this study it was 1.5:1. This change may affect the basic physicochemical characteristics and later development of the artificial soils. Similarly, the addition ratios of distiller's grains and rice husks as OM sources can be adjusted artificially or replaced based on the local OM sources, such as furfural, mushroom, fruit, and vegetable residue, straws, sludge, and other organic wastes. This is because, in large-scale engineering applications, although the proportions of materials used are small, the total amount will still be large; using local materials can significantly lower transport and production costs. One important reason for choosing distiller's grains and rice husks in this study was that distiller's grains are typical solid wastes in the brewing industry of Guizhou, a major brewing province in China; rice husks are also typical agricultural solid wastes in this region. The main purpose of adding other auxiliary materials, such as bentonite, polyacrylamide, and microbial agents, is to enable the red mud-phosphogypsum matrix to conserve moisture, facilitate gas exchange and microbial colonization, and create a series of basic physical, chemical, and biological reaction conditions to enhance soil fertility and ultimately prepare artificial soils with desirable fertility characteristics (Lentz, 2015; Mi et al., 2017; Ahsan et al., 2023). These materials involve costs and are likely to be replaced by more cost-effective auxiliary materials. Overall, the artificial soils are more of a broad definition of the synergistic soilization of red mud and phosphogypsum, and their material ratios and sources are not constant.

The test site was merely a preliminary simulation project, which would help to make scientific evaluation of future large-scale engineering applications and find the shortcomings as early as possible to facilitate continuous improvement. Although the artificial soils contained high N, P, and K, these nutrients mainly come from the added materials; different materials and ratios may impact soil nutrient content. There is the problem of nutrient imbalance, as embodied in the sufficiency of TP, TK, AN, and AP but the deficiency of TN and AK. This makes further regulation necessary to balance different nutrients (Carmo et al., 2017). For example, AN and AP were both high, and often exist in the form of dissolved ions such as NH_4-N, NO_3-N, and PO_4^{3-}. Fixing these nutrients stably in artificial soils for a long time is very important (Mehnaz et al., 2019; Wang et al., 2022). The loss of nutrients causes a significant loss of artificial soil fertility (Li et al., 2023); moreover, when the nutrients enter water bodies as a result of leaching by rainwater, resulting in the pollution of N and P in water (Wang et al., 2022). Besides, although the study indicated that the total content of the several heavy metals in the artificial soils was not as high as expected (except for Cd), and the chemical forms of these heavy metals were dominated by non-bioavailable F_{RES}. However, red mud and phosphogypsum are generally considered potential sources of heavy metal contamination (Pan et al., 2023; Wang et al., 2023b). Long-term attention and further in-depth research are needed to determine whether large-scale engineering applications of the artificial soils will cause heavy metal contamination, and how targeted engineering measures can be used to prevent this (Rostami et al., 2021; Wang et al., 2021). Additionally, the artificial soils were characterized by high salinity, mainly due to the high salinity of red mud (Gao et al., 2024a). Since high salinity hurts the growth of some plant species, salinity regulation of the artificial soils also requires close attention. Finally, the artificial soils are still in the primary stage of soils with regard to fertility characteristics. In practical engineering applications, they need to be continuously developed through the long-term breeding of various types of plants, the continuous diversification of microbial and arthropod communities, and the implementation of necessary artificial regulation and optimization measures, to eventually form mature soils with stable fertility (Ke et al., 2021).

5. Conclusions

By constructing a small-scale test site, this study simulated the engineering applications of two types of red mud/phosphogypsum-based artificial soils for vegetation restoration and ecological reconstruction. It was found that the artificial soils contained a series of major elements similar to those contained by common natural soil, and preliminarily possessed the basic physicochemical properties, main nutrient (nitrogen, phosphorus and potassium) conditions, and biochemical characteristics that could meet the demands of plant growth. The discovery of 18 different types of adaptable plants, as well as the possibility of more potential adaptable plants growing in the future, directly demonstrated that the artificial soils could be used for vegetation greening and landscaping. The preliminary formation of microbial (fungal and bacterial) community diversity and the gradual enrichment of soil arthropod community diversity played an important role in promoting microenvironment development, ecosystem construction, and functional capacity of the artificial soils. The engineering applications of the artificial soils still require long-term coordination of natural and artificial measures (such as balancing different nutrients, preventing nutrient loss, and reducing salinity), as well as a systematic and continuous assessment of environmental quality and potential contamination risks such as heavy metal contamination. Overall, the artificial soils provide a feasible solution for the large-scale, low-cost, simple, and highly efficient synergistic disposal of red mud and phosphogypsum, with enormous potential for future engineering applications. They are expected to be used for vegetation coverage and ecological environment improvement in tailings, collapse, and soil-deficient areas, and green belt construction and landscaping along municipal roads.

CRediT authorship contribution statement

Yong Liu: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Lishuai Zhang:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Binbin Xue:** Visualization, Data curation, Conceptualization. **Li Chen:** Investigation, Formal analysis. **Guocheng Wang:** Formal analysis, Data curation. **Jingfu Wang:** Writing – review & editing, Project administration. **Hefeng Wan:** Investigation, Formal analysis. **Xiaohong Lin:** Investigation. **Guangxu Zhu:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This study is supported jointly by the Guizhou Provincial Key Technology R&D Program (QianKeHe Support [2023] general 097), the National Natural Science Foundation of China (No. 42367036), the Sixth Batch of Guizhou Province High-level Innovative Talent Training Programs (ZhuKeHeTong-GCC[2022]001), the Initiated Funding Projects for Introduced Talent of Guiyang University (GYU-KY-[2024]), the Guizhou Provincial Science and Technology Program (Qiankehe Platform Talents-YQK [2023]034). Our deepest gratitude goes to the anonymous reviewers for their careful work and thoughtful suggestions

that have helped improve this paper substantially.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.175656.

References

Ahsan, T., Tian, P.C., Gao, J., Wang, C., Liu, C., Huang, Y.Q., 2023. Effects of microbial agent and microbial fertilizer input on soil microbial community structure and diversity in a peanut continuous cropping system. J. Adv. Res. https://doi.org/10.1016/j.jare.2023.11.028.

Akfas, F., Elghali, A., Aboulaich, A., Munoz, M., Benzaazoua, M., Bodinier, J.L., 2024. Exploring the potential reuse of phosphogypsum: a waste or a resource? Sci. Total Environ. 908, 168196 https://doi.org/10.1016/j.scitotenv.2023.168196.

Anagnostopoulos, A., Navarro, M.E., Stefanidou, M., Ding, Y., Gaidajis, G., 2021. Red mud-molten salt composites for medium-high temperature thermal energy storage and waste heat recovery applications. J. Hazard. Mater. 413, 125407 https://doi.org/10.1016/j.jhazmat.2021.125407.

Bai, X., Zhao, S., Duo, L., 2017. Impacts of carbon nanomaterials on the diversity of microarthropods in turfgrass soil. Sci. Rep. 7, 1779. https://doi.org/10.1038/s41598-017-01920-z.

Cabañas-Mendoza, M. d R., Andrade, J.L., Sauri-Duch, E., Hernández-Terrones, L., Fuentes, G., Santamaría, J.M., 2023. *Lead tolerance of Laguncularia racemosa* is associated to high proline accumulation and high antioxidant capacities. Biometals 36, 887–902. https://doi.org/10.1007/s10534-023-00488-8.

Cai, Q.S., 2013. Plant Physiology Experiment. China Agricultural University Press, Beijing (In Chinese). https://xueshu.baidu.com/usercenter/paper/show?paperid=94590afdc5b615aeb97248ef70961e5c&site=xueshu_se.

Carmo, M., García-Ruiz, R., Ferreira, M., et al., 2017. The N-P-K soil nutrient balance of Portuguese cropland in the 1950s: the transition from organic to chemical fertilization. Sci. Rep. 7, 8111. https://doi.org/10.1038/s41598-017-08118-3.

Chernysh, Y., Yakhnenko, O., Chubur, V., Roubík, H., 2021. Phosphogypsum recycling: a review of environmental issues, current trends, and prospects. Appl. Sci. 11, 1575. https://doi.org/10.3390/app11041575.

Cunha, J.G. d, Cavalcante, Í.H.L., Silva, M.A. d, Amariz, R.A. e, Carmo, R.N. d, Lobo, J.T., 2022. Proline and Algal Extract to Alleviate the Abiotic Stress in Mango 'Tommy Atkins' in the Tropical Semiarid, vol. 64. Erwerbs-Obstbau, pp. 115–126. https://doi.org/10.1007/s10341-021-00628-9.

Gao, B., Sun, C., Yang, T., Cheng, H., Zhou, H., Wang, Y., Chen, Z., 2024a. Simultaneous dealkalization of red mud and recovery of valuable metals by a novel marine fungus tolerating high alkalinity and salinity. J. Environ. Chem. Eng. 12 (1), 111775 https://doi.org/10.1016/j.jece.2023.111775.

Gao, G., Yan, L., Tong, K., Yu, H., Lu, M., Wang, L., Niu, Y., 2024b. The potential and prospects of modified biochar for comprehensive management of salt-affected soils and plants: a critical review. Sci. Total Environ. 912, 169618 https://doi.org/10.1016/j.scitotenv.2023.169618.

Guan, S.Y., 1986. Soil Enzymes and their Research Methodology. Agricultural Press, Beijing (In Chinese). https://xueshu.baidu.com/usercenter/paper/show?paperid=55fbdba99838eb3658bcb4f693a24a38&site=xueshu_se.

Hahm, M.S., Son, J.S., Hwang, Y.J., Kwon, D.K., Ghim, S.Y., 2017. Alleviation of salt stress in pepper (*Capsicum annum L.*) plants by plant growth-promoting rhizobacteria. J. Microbiol. Biotechnol. 27 (10), 1790–1797. https://doi.org/10.4014/jmb.1609.09042.

Hoffland, E., Kuyper, T.W., Comans, R.N.J., Creamer, R.E., 2020. Eco-functionality of organic matter in soils. Plant and Soil 455, 1–22. https://doi.org/10.1007/s11104-020-04651-9.

Høgh-Jensen, H., Schjoerring, J.K., 2001. Rhizodeposition of nitrogen by red clover, white clover and ryegrass leys. Soil Biol. Biochem. 33 (4–5), 439–448. https://doi.org/10.1016/S0038-0717(00)00183-8.

Hu, W., Yang, Z., Zheng, X., Jiang, H., Cai, H., Chen, H., 2018. Response of soil CO_2 emission to soil catalase activity and tomato growth under aerated condition (in Chinese). Water Saving Irrigation 12 (12–16), 23 (Chinese Journal). https://doi.org/10.3969/j.issn.1007-4929.2018.12.004.

Hu, X., Wang, J., Wu, F., Li, D., Yang, J., Chen, J., Liang, J., Lou, X., Chen, H., 2023. Phosphorus recovery and resource utilization from phosphogypsum leachate via membrane-triggered adsorption and struvite crystallization approach. Chem. Eng. J. 471, 144310 https://doi.org/10.1016/j.cej.2023.144310.

Jernigan, A., Kao-Kniffin, J., Pethybridge, S., Wickings, K., 2023. Soil microarthropod effects on plant growth and development, 483, pp. 27–45. https://doi.org/10.1007/s11104-022-05766-x.

Jiang, Q., He, Y., Wu, Y., Dian, B., Zhang, J., Li, T., Jiang, M., 2022. Solidification/stabilization of soil heavy metals by alkaline industrial wastes: a critical review. Environ. Pollut. 312, 120094 https://doi.org/10.1016/j.envpol.2022.120094.

Ke, W., Zhang, X., Zhu, F., Wu, H., Zhang, Y., Shi, Y., Hartley, W., Xue, S., 2021. Appropriate human intervention stimulates the development of microbial communities and soil formation at a long-term weathered bauxite residue disposal area. J. Hazard. Mater. 405, 124689 https://doi.org/10.1016/j.jhazmat.2020.124689.

Khalediana, Y., Brevik, E.C., Pereira, P., Cerdà, A., Fattah, M.A., Tazikeh, H., 2017. Modeling soil cation exchange capacity in multiple countries. Catena 158, 194–200. https://doi.org/10.1016/j.catena.2017.07.002.

Kiran, S., 2019. Effects of vermicompost on some morphological, physiological and biochemical parameters of lettuce (*Lactuca sativa var. crispa*) under drought stress. Notulae Botanicae Horti Agrobotanici Cluj-Napoca 47 (2), 352–358. https://doi.org/10.15835/nbha47111260.

Kong, X., Meng, Li, Xue, S., Hartley, W., Chen, C., Wu, C., Li, X., Li, Y., 2017. Acid transformation of bauxite residue: conversion of its alkaline characteristics. J. Hazard. Mater. 324 (Part B), 382–390. https://doi.org/10.1016/j.jhazmat.2016.10.073.

Laffray, X., Alaoui-Sehmer, L., Bourioug, M., Bourgeade, P., Alaoui-Sossé, B., Aleya, L., 2018. Effects of sodium chloride salinity on ecophysiological and biochemical parameters of oak seedlings (*Quercus robur L.*) from use of de-icing salts for winter road maintenance. Environ. Monit. Assess. 190, 266. https://doi.org/10.1007/s10661-018-6645-z.

Le Roux, J.J., Leishman, M.R., Geraghty, D.M., Manea, A., 2023. Rewiring critical plant–soil microbial interactions to assist ecological restoration. Am. J. Bot. 110 (9), e16228 https://doi.org/10.1002/ajb2.16228.

Leconte, M.C., Mazzarino, M.J., Satti, P., Iglesias, M.C., Laos, F., 2009. Co-composting rice hulls and/or sawdust with poultry manure in NE Argentina. Waste Manag. 29 (9), 2446–2453. https://doi.org/10.1016/j.wasman.2009.04.006.

Lei, Z., Li, Q., Tang, Y., Zhang, H., Han, C., Wang, X., Zhao, X., Shi, G., 2022. Selenium enhanced nitrogen accumulation in legumes in soil with rhizobia bacteria. J. Clean. Prod. 380 (Part1), 134960 https://doi.org/10.1016/j.jclepro.2022.134960.

Lentz, R.D., 2015. Polyacrylamide and biopolymer effects on flocculation, aggregate stability, and water seepage in a silt loam. Geoderma 241-242, 289–294. https://doi.org/10.1016/j.geoderma.2014.11.019.

Li, H.S., 2000. Principles and Techniques of Plant Physiological Biochemical Experiment. Higher Education Press, Beijing (In Chinese). https://xueshu.baidu.com/usercenter/paper/show?paperid=9451ba3beb65814b9b02a7667177c1b5&site=xueshu_se.

Li, S., Liu, S., Zhou, J., Luo, T., 2007. Measuration of catalase vigor in plants with spectrophotometry (in Chinese). Anhui Agricultural Science Bulletin (Chinese Journal) 13 (02), 72–73. https://doi.org/10.16377/j.cnki.issn1007-7731.2007.02.031.

Li, L., Chen, P., Wang, K., Zhang, R., Yuan, X., Ge, L., Li, Q., Liu, Y., Zhang, X., Li, Z., 2023. Gramineae-legumes mixed planting effectively reduces soil and nutrient loss in orchards. Agric Water Manag 289, 108513. https://doi.org/10.1016/j.agwat.2023.108513.

Liu, D.Y., Wu, C.S., 2012. Stockpiling and comprehensive utilization of red mud research progress. Materials 5 (7), 1232–1246. https://doi.org/10.3390/ma5071232.

Liu, H., Huang, Y., Wang, H., Shen, Z., Qiao, C., Li, R., Shen, Q., 2020. Enzymatic activities triggered by the succession of microbiota steered fiber degradation and humification during co-composting of chicken manure and rice husk. J. Environ. Manage. 258, 110014 https://doi.org/10.1016/j.jenvman.2019.110014.

Liu, S., Liu, Z., Zhu, H., Wang, Z., Guo, J., Zhang, X., Yu, H., Yue, X., Ning, P., Li, B., 2023. The roles of red mud as desulfurization and denitrification in flue gas: a review. J. Environ. Chem. Eng. 11 (3), 109770 https://doi.org/10.1016/j.jece.2023.109770.

Liu, Y., Zhang, L., Chen, L., Xue, B., Wang, G., Zhu, G., Gou, W., Yang, D., 2024. Potential of artificial soil preparation for vegetation restoration using red mud and phosphogypsum. Sci. Total Environ. 941, 173553 https://doi.org/10.1016/j.scitotenv.2024.173553.

Long, S., Yang, J., Hao, Z., Shi, Z., Liu, X., Xu, Q., Wang, Y., Wang, D., Ni, B.J., 2023. Multiple roles of humic substances in anaerobic digestion systems: a review. J. Clean. Prod. 418, 138066 https://doi.org/10.1016/j.jclepro.2023.138066.

Luu, T.T., Dinh, V.P., Nguyen, Q.H., Tran, N.Q., Nguyen, D.K., Ho, T.H., Nguyen, V.D., Tran, D.X., Kiet, H.A.T., 2022. Pb(II) adsorption mechanism and capability from aqueous solution using red mud modified by chitosan. Chemosphere 287 (3), 132279. https://doi.org/10.1016/j.chemosphere.2021.132279.

Lv, X., Xiang, L., 2023. Investigating the novel process for thorough removal of eutectic phosphate impurities from phosphogypsum. J. Mater. Res. Technol. 24, 5980–5990. https://doi.org/10.1016/j.jmrt.2023.04.224.

Marrs, R.H., 2016. Ecological restoration: soil microbes call the shots. Nature Plants 2, 16117. https://doi.org/10.1038/nplants.2016.117.

Medina-Sauza, R.M., Álvarez-Jiménez, M., Delhal, A., Reverchon, F., Blouin, M., Guerrero-Analco, J.A., Cerdán, C.R., Guevara, R., Villain, L., Barois, I., 2019. Earthworms building up soil microbiota, a review. Front. Environ. Sci. 7, 81. https://doi.org/10.3389/fenvs.2019.00081.

Mehnaz, K.R., Keitel, C., Dijkstra, F.A., 2019. Phosphorus availability and plants alter soil nitrogen retention and loss. Sci. Total Environ. 671, 786–794. https://doi.org/10.1016/j.scitotenv.2019.03.422.

Menta, C., Remelli, S., 2020. Soil health and arthropods: from complex system to worthwhile investigation. Insects 11 (1), 54. https://doi.org/10.3390/insects11010054.

Mi, J., Gregorich, E.G., Xu, S., McLaughlin, N.B., Ma, B., Liu, J., 2017. Effect of bentonite amendment on soil hydraulic parameters and millet crop performance in a semi-arid region. Field Crop Res 212, 107–114. https://doi.org/10.1016/j.fcr.2017.07.009.

Mordkovich, V.G., Lyubechanskii, I.I., 2017. The role of large arthropods in the development of halomorphic soils in the south of Siberia. Eurasian Soil Sci. 50, 688–700. https://doi.org/10.1134/S1064229317040068.

Moreira-Grez, B., Muñoz-Rojas, M., Kariman, K., Storer, P., O'Donnell, A.G., Kumaresan, D., Whiteley, A.S., 2019. Reconditioning degraded mine site soils with exogenous soil microbes: plant fitness and soil microbiome outcomes. Front. Microbiol. 10, 1617. https://doi.org/10.3389/fmicb.2019.01617.

Neher, D.A., Barbercheck, M.E., 2019. Soil microarthropods and soil health: intersection of decomposition and pest suppression in agroecosystems. Insects 10 (12), 414. https://doi.org/10.3390/insects10120414.

Outbakat, M.B., Mejahed, K.E., Gharous, M.E., Omari, K.E., Beniaich, A., 2022. Effect of phosphogypsum on soil physical properties in Moroccan salt-affected soils. Sustainability 14 (20), 13087. https://doi.org/10.3390/su142013087.
Pan, X., Wu, H., Lv, Z., Yu, H., Tu, G., 2023. Recovery of valuable metals from red mud: a comprehensive review. Sci. Total Environ. 904, 166686 https://doi.org/10.1016/j.scitotenv.2023.166686.
Rashad, A.M., 2017. Phosphogypsum as a construction material. J. Clean. Prod. 166, 732–743. https://doi.org/10.1016/j.jclepro.2017.08.049.
Remisha, S.R., Reshmi, R., Nithyalakshmi, B., 2024. Sustainable management of red mud: life cycle assessment and treatment techniques. International Journal for Multidisciplinary Research (IJFMR) 6 (1), 1–9. https://doi.org/10.36948/ijfmr.2024.v06i01.12525.
Rengel, Z., Damon, P.M., 2008. Crops and genotypes differ in efficiency of potassium uptake and use. Physiol. Plant. 133, 624–636. https://doi.org/10.1111/j.1399-3054.2008.01079.x.
Reuter, R., Lancaster, P.A., Horn, G.W., Wallis, B.D., Gunter, P.A., 2016. Distiller's grains as a substitute for fertilizer in summer grazing systems: performance, nitrogen recovery, and profit. J. Anim. Sci. 94, 29. https://doi.org/10.2527/ssasas2015-059.
Roesch, L.F.W., Camargo, F.A.O., Bento, F.M., Triplett, E.W., 2008. Biodiversity of diazotrophic bacteria within the soil, root and stem of field-grown maize. Plant and Soil 302, 91–104. https://doi.org/10.1007/s11104-007-9458-3.
Rostami, S., Kamani, H., Shahsavani, S., Hoseini, M., 2021. Environmental monitoring and ecological risk assessment of heavy metals in farmland soils. Hum. Ecol. Risk. Assess. 27 (2), 392–404. https://doi.org/10.1080/10807039.2020.1719030.
Rychkov, V.N., Kirillov, E.V., Kirillov, S.V., Semenishchev, V.S., Bunkov, G.M., Botalov, M.S., Smyshlyaev, D.V., Malyshev, A.S., 2018. Recovery of rare earth elements from phosphogypsum. J. Clean. Prod. 196, 674–681. https://doi.org/10.1016/j.jclepro.2018.06.114.
Santona, L., Castaldi, P., Melis, P., 2006. Evaluation of the interaction mechanisms between red muds and heavy metals. J. Hazard. Mater. 136 (2), 324–329. https://doi.org/10.1016/j.jhazmat.2005.12.022.
Shams, M., Yildirim, E., Khadivi, A., Ekinci, M., Muhie, S.H., 2024. Differences in seed germination, plant growth, and proline content of some pepper (*Capsicum annuum L.*) genotypes under salinity stress. J. Crop Health 76, 309–316. https://doi.org/10.1007/s10343-023-00962-w.
Sofo, A., Khanghahi, M.Y., Curci, M., Reyes, F., Briones, M.J.I., Sarneel, J.M., Cardinale, D., Crecchio, C., 2023. Earthworm-driven changes in soil chemico-physical properties, soil bacterial microbiota, tree/tea litter decomposition, and plant growth in a mesocosm experiment with two plant species. Plants 12 (6), 1216. https://doi.org/10.3390/plants12061216.
Spagnoletti, F.N., Chiocchio, V.M., 2020. Tolerance of dark septate endophytic fungi (DSE) to agrochemicals *in vitro*. Rev. Argent. Microbiol. 52 (1), 43–49. https://doi.org/10.1016/j.ram.2019.02.003.
Sun, Y., Jiang, C., Lai, Z., Shao, W., Wang, X., 2008. Determination and observation of the changes of the ascorbate peroxidase activities in the fresh leaves of tea plants (in Chinese). Chinese Journal of Tropical Crops 29 (05), 562–566. https://doi.org/10.3969/j.issn.1000-2561.2008.05.006.
Supramaniam, Y., Chong, C.W., Silvaraj, S., Tan, I.K.P., 2016. Effect of short term variation in temperature and water content on the bacterial community in a tropical soil. Appl. Soil Ecol. 107, 279–289. https://doi.org/10.1016/j.apsoil.2016.07.003.
Syczewski, M.D., Borkowski, A., Gąsiński, A., Raczko, J., Mordak, K., Grądziel, I., Krzesicka, M., Kałaska, M., Siuda, R., 2020. Phosphogypsum and clay mineral/phosphogypsum ceramic composites as useful adsorbents for uranium uptake. Appl. Geochem. 123, 104793 https://doi.org/10.1016/j.apgeochem.2020.104793.
Tayibi, H., Choura, M., López, F.A., Alguacil, F.J., López-Delgado, A., 2009. Environmental impact and management of phosphogypsum. J. Environ. Manage. 90 (8), 2377–2386. https://doi.org/10.1016/j.jenvman.2009.03.007.
Tessier, A., Campbell, P.G.C., Bisson, M., 1979. Sequential extraction procedure for the speciation of particulate trace metals. Anal. Chem. 51 (7), 844–851. https://doi.org/10.1021/ac50043a017.
Tian, T., Liu, Z., Zhu, F., Hartley, W., Ye, Y., Xue, S., 2020. Improvement of aggregate-associated organic carbon and its stability in bauxite residue by substrate amendment addition. Land Degrad. Dev. 31 (16), 2405–2416. https://doi.org/10.1002/ldr.3609.
Tyler, H.L., 2020. Winter cover crops and no till management enhance enzyme activities in soybean field soils. Pedobiologia 81-82, 150666. https://doi.org/10.1016/j.pedobi.2020.150666.
Villa, Y.B., Khalsa, S.D.S., Ryals, R., Duncan, R.A., Brown, P.H., Hart, S.C., 2021. Organic matter amendments improve soil fertility in almond orchards of contrasting soil texture. Nutr. Cycl. Agroecosyst. 120, 343–361. https://doi.org/10.1007/s10705-021-10154-5.
Wagh, A.S., Thompson, B., 1988. A study of inter-particle bonds in dry bauxite waste resulting in atmospheric aerosols. Phys. Scr. 37 (2), 305. https://doi.org/10.1088/0031-8949/37/2/020.
Wang, L., Li, X., 2019. Steering soil microbiome to enhance soil system resilience. Crit. Rev. Microbiol. 45 (5–6), 743–753. https://doi.org/10.1080/1040841X.2019.1700906.
Wang, M., Liu, X., 2021. Applications of red mud as an environmental remediation material: a review. J. Hazard. Mater. 408, 124420 https://doi.org/10.1016/j.jhazmat.2020.124420.
Wang, W., Wang, Z., Wang, J., 2010. Optimization of determination method of peroxidase activity in plant (in Chinese). Research and Exploration in Laboratory (Chinese Journal) 29 (4), 21–23. https://doi.org/10.3969/j.issn.1006-7167.2010.04.007.
Wang, L., Rinklebe, J., Tack, F.M.G., Hou, D., 2021. A review of green remediation strategies for heavy metal contaminated soil. Soil Use Manage. 37 (4), 936–963. https://doi.org/10.1111/sum.12717.
Wang, S., Guo, S., Zhai, L., Hua, L., Khoshnevisan, B., Wang, H., Liu, H., 2022. Comprehensive effects of integrated management on reducing nitrogen and phosphorus loss under legume-rice rotations. J. Clean. Prod. 361, 132031 https://doi.org/10.1016/j.jclepro.2022.132031.
Wang, C., Liu, H., Wu, D., Liu, X., 2023a. Engineering and environmental evaluation of red mud amended volcanic ash as a sustainable subgrade material. J. Clean. Prod. 393, 136353 https://doi.org/10.1016/j.jclepro.2023.136353.
Wang, C.Q., Wang, Z.Y., Huang, D.M., Huang, Q.C., Chen, Y., Zhang, H., Shui, Z.H., 2023b. Recovery and recycling core of phosphogypsum: characteristic hazardous elements risk assessment and analysis. Process Saf. Environ. Prot. 170, 738–756. https://doi.org/10.1016/j.psep.2022.12.062.
Wang, J., Li, Z., Liu, F., Han, K., Ma, Q., Wu, L., 2024a. Membrane-covered systems improve compost quality and alter microbial communities during composting with microbial inoculation. J. Clean. Prod. 447, 141501 https://doi.org/10.1016/j.jclepro.2024.141501.
Wang, M., Guo, Z., Du, J., Lu, H., Liu, L., Wang, T., Pan, S., 2024b. Assessing the hepatotoxicity of phosphogypsum leachate in zebrafish (*Danio rerio*). Sci. Total Environ. 926, 172018 https://doi.org/10.1016/j.scitotenv.2024.172018.
Xie, Y., Huang, J., Wang, H., Lv, S., Jiang, F., Pan, Z., Liu, J., 2022. Simultaneous and efficient removal of fluoride and phosphate in phosphogypsum leachate by acid-modified sulfoaluminate cement. Chemosphere 305, 135422. https://doi.org/10.1016/j.chemosphere.2022.135422.
Xue, S., Zhu, F., Kong, X., Wu, C., Huang, L., Huang, N., Hartley, W., 2016. A review of the characterization and revegetation of bauxite residues (red mud). Environ. Sci. Pollut. Res. 23, 1120–1132. https://doi.org/10.1007/s11356-015-4558-8.
Yang, S.H., 2022. Effects of salt stress on seed germination and seedling growth of Prunus glume (in Chinese). Seed Science and Technology (Chinese Journal) 10, 10–12. https://xueshu.baidu.com/usercenter/paper/show?paperid=120h04w0te7p0as0ju0s02p051034022&site=xueshu_se.
Yang, Z.X., Yu, S.Z., Lin, Y.C., Zhang, W.J., Wang, Y., Wang, R.G., Xu, S.X., Yang, T.Z., Xue, G., 2020. Activation of potassium released from soil by root-secreted organic acids in different varieties of tobacco (*Nicotiana tabacum*). Funct. Plant Biol. 47 (4), 318–326. https://doi.org/10.1071/FP19137.
Yang, D., Tang, L., Cui, Y., Chen, J., Liu, L., Guo, C., 2022a. Saline-alkali stress reduces soil bacterial community diversity and soil enzyme activities. Ecotoxicology 31, 1356–1368. https://doi.org/10.1007/s10646-022-02595-7.
Yang, T., Xing, X., Chamindu Deepagoda, T.K.K., Fu, W., Ma, X., Lakshani, M.M.T., 2022b. Relationships among water and gas transport properties in soils from natural and induced clay gradients. Vadose Zone J. 21 (2), e20180 https://doi.org/10.1002/vzj2.20180.
Yang, D.X., Dong, Y.X., Li, C., 2023. Community structure of soil arthropod under different land use types in karst region: taking Guiyang as an example (in Chinese). Guizhou Agricultural Sciences (Chinese Journal) 51 (7), 112–123. https://doi.org/10.3969/j.issn.1001-3601.2023.07.016.
Yang, J., Dong, S., Ma, L., Dai, Q., Zheng, D., Huang, B., Sun, M., Hu, B., Du, W., Xie, L., Duan, L., Yan, X., 2024. Review on high-value utilization of phosphogypsum: utilization of calcium and oxygen resources present in phosphogypsum. Sep. Purif. Technol. 344, 127246 https://doi.org/10.1016/j.seppur.2024.127246.
Yi, Z., Zhu, W., Wang, Z., 2013. Study on low temperature resistance of physiological changes of two kinds of *Vitis amurensis* and *poplar* (in Chinese). Journal of Agricultural Science Yanbian University (Chinese Journal) 35 (3), 243–248. https://doi.org/10.13478/j.cnki.jasyu.2013.03.014.
Zhu, X., 2018. Effects of different extracted conditions on SOD, POD and CAT enzyme activities in plant tissues (in Chinese). Food Science and Technology (Chinese Journal) 43 (05), 265–269. https://doi.org/10.13684/j.cnki.spkj.2018.05.048.
Zhu, Y., Duan, C., Wang, H., Dai, J., Wang, H., 2023. Analysis of main mineral composition and symbiosis in red mud (in Chinese). World Nonferrous Metals (Chinese Journal) 12, 88–92. https://d.wanfangdata.com.cn/periodical/sjysjs202312029.