Journal of Materials, Processing and Design (2024)
Clausius Scientific Press, Canada
DOI: 10.23977/jmpd.2024.080208
ISSN 2516-0923 Vol. 8 Num. 2

Progress in the utilization of coal gangue for soilification and the preparation of soil amendment

Ruizhi Yang

Shaanxi Provincial Land Engineering Construction Group Co., Ltd., Xian, Shaanxi, China

Keywords: Coal gangue; soilification; soil amendment

Abstract: As the main solid waste resource in mining areas, the large-scale utilization and disposal of coal gangue is crucial to resource and ecological issues. The soilification of coal gangue and its application as a soil amendment to improve soil quality and enhance agricultural productivity have become research focuses for waste reduction and harmless treatment. This paper aims to investigate the fundamental components and properties of coal gangue, analyze the principles of its soilification, summarize the methods of preparing soil amendments from coal gangue and their effects, and provide a brief analysis of the challenges and issues faced in the soilification process. It is intended to serve as a reference for further research and engineering applications.

1. Introduction

Coal gangue, an inevitable byproduct of coal mining, generates enormous quantities worldwide each year. Piled up for extended periods, it not only occupies vast land resources but also poses potential environmental pollution risks, particularly through the leaching of heavy metals into soil and groundwater [1]. However, this "waste" presents an opportunity to address environmental challenges.

In recent years, researchers have increasingly focused on the resourceful utilization of coal gangue, especially converting it into soil amendments to enhance soil quality and agricultural productivity while reducing waste and ensuring harmless treatment [2]. Wang et al. [3] suggested that coal gangue possesses potential for use as a fertilizer based on its comparison with soil properties. Luoguanhua et al. [4] conducted pot experiments studying the effects of different coal gangue applications on nutrient-poor soil quality and Chinese cabbage growth, revealing that coal gangue could increase plant nutrients and serve as a soil amendment for coal gangue recycling and environmental restoration in mining areas. Zhang Yuhang et al. [5] and Kong Tao et al. [6] found through pot trials that coal gangue could improve saline soil quality and promote plant growth. Sun Haireng et al. [7] discovered that high-sulfur coal gangue, when applied to alkaline soils, could neutralize soil bases, lower pH, and contribute to improved crop growth and stable yields.

The accumulation of coal gangue not only consumes land resources but also negatively impacts the mining areas ecological environment [8]. Moreover, coal gangue contains nutrients essential for plant growth [9]. By processing it appropriately, coal gangue can be transformed into soil amendments for soil remediation and improvement, paving the way for a synergistic approach to coal gangue utilization and mining area ecological restoration.

2. Coal Gangue Composition and Basic Characteristics

2.1 Main Components of Coal Gangue

Coal gangue is rich in major components such as aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), and iron oxide (Fe_2O_3) [10], as shown in Table 1. Its chemical composition is diverse, primarily consisting of silicates, aluminates, and ferrites, along with a certain amount of organic matter, water, sulfides, carbonates, oxides, and trace elements like calcium, magnesium, potassium, sodium, phosphorus, iron, aluminum, manganese, zinc, copper, lead, cadmium, and others. These characteristics are similar to those of natural soils in terms of both chemical and mineral compositions.

Table 1: Main Components of Coal Gangue [10]

Types	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	loi
Carbonaceous Shale	46~62	17~23	0.2~20	0.5~7.5	0.6~1.3	20~45
Muddy Shale	44~55	44~55	0.2~26	9~25	1~5	10~28
Sandy Shale	45~52	6~15	0.2~21	14~21	2~6	6~20

2.2 Basic Properties of Coal Gangue

The density of coal gangue generally ranges between 2.0-2.8 g/cm^3 Due to the breaking during mining and stacking, it exhibits a high porosity, facilitating the storage and transport of water and gases. Coal gangue particles vary in size, from fine powders to large blocks, which directly influences its usability in soilification and soil amendment production processes. Furthermore, its pH is usually alkaline, capable of neutralizing acidic soils.

The chemical stability of coal gangue varies depending on its composition, with some minerals prone to weathering or dissolution under specific conditions, releasing nutrients or potentially harmful substances. High concentrations of heavy metals, such as lead, cadmium, and mercury, are often present, posing key concerns for controlled utilization.

3. Coal Gangue Utilization for Soilification

3.1 Mineral Transformation and Nutrient Release

Coal gangue is rich in minerals such as silicon, aluminum, iron, calcium, and magnesium. Under suitable conditions, these elements can be transformed into forms available to plants. For instance, silicate minerals can be broken down by soil microorganisms and chemical reactions, releasing plant-available silicon and aluminum ions. In an alkaline environment, coal gangue can neutralize acidic soils, liberating alkaline metal ions like calcium and magnesium, increasing the soil's pH and promoting crop growth.

3.2 Improvement of Soil Structure

The high porosity and porous nature of coal gangue increase soil pore space, enhancing soil aeration and water holding capacity. This promotes root development and microbial activity. Additionally, the size and shape of coal gangue particles can alter soil particle size distribution, contributing to improved soil aggregation and enhancing its physical properties.

3.3 Modulation of Soil Chemical Properties

The alkalinity of coal gangue helps neutralize acidic soils, decreasing soil acidity. This reduces the mobility and bioavailability of heavy metals, mitigating their potential harm to crops and the environment. Furthermore, it buffers soil pH fluctuations, contributing to the stability of soil fertility.

3.4 Promotion of Biological Activity

Coal gangue contains organic matter and microorganisms that can enhance soil biodiversity and stimulate microbial activity. This accelerates the decomposition of organic matter and nutrient cycling within the soil ecosystem.

4. Research on the Preparation of Soil Amendments from Coal Gangue

4.1 Overview of Preparation Methods

The conventional method for preparing soil amendments from coal gangue typically involves the following steps and techniques:

1) Crushing and Screening. Initially, collected coal gangue is crushed to achieve an appropriate particle size range, generally between 0.1-5 mm, to facilitate mixing with soil and enhance soil structure.

2) Pretreatment. Depending on the coal gangue's composition and potential environmental hazards, pretreatment might be necessary. This could involve acid washing to remove some heavy metals or thermal treatment (such as calcination) to alter its chemical properties for increased stability and suitability as a soil amendment.

3) Addition of Other Components. To adjust pH, increase organic matter content, improve soil structure, or supply additional nutrients, coal gangue may be blended with substances like lime, gypsum, organic fertilizers, or biochar.

4) Homogenization. The crushed and screened coal gangue is thoroughly mixed with additives in a blender to ensure even distribution of all components.

5) Drying and Packaging. The mixed amendment may need to be dried at a suitable temperature to reduce moisture content, making it easier to store and transport. After drying, it is packaged into bags or other containers for convenient use.

6) Field Application. Based on soil conditions and crop requirements, the amendment is applied to the soil at specified ratios and depths. Then, plowing is done to ensure thorough mixing of the amendment with the soil.

4.2 Impact of Additives

Additives play a crucial role in the preparation of coal gangue-based soil amendments, affecting various aspects as follows:

1) pH Regulation. Adding alkaline substances like lime or gypsum can neutralize the acidity or neutrality of coal gangue, raising the soil pH, which is beneficial for crop growth and reduces the bioavailability of heavy metals.

2) Nutrient Supply. Incorporating organic fertilizers (like compost or poultry manure) or inorganic fertilizers enriches soil nitrogen, phosphorus, potassium, and other nutrients, improving

soil fertility.

3) Soil Structure Enhancement. Materials rich in organic carbon, such as biochar or rice husk ash, increase soil organic matter, enhancing pore structure and improving water and nutrient retention.

4) Microbial Activity. Certain additives, like microbial inoculants, boost soil microorganism activity, accelerating organic matter decomposition and fostering a healthier soil ecosystem.

5) Heavy Metal Stabilization. Specific additives like phosphates or iron oxides can bind with heavy metals, forming stable compounds that decrease their mobility in soil and minimize environmental and crop risks.

6) Enhanced Cation Exchange Capacity. Introducing clay minerals or organic matter increases soil's cation exchange capacity, improving its ability to adsorb and retain nutrient cations.

7) Improved Workability. Adjusting the moisture content or using binding agents makes the amendment more manageable for application, ensuring better distribution in the soil.

By selecting and combining different additives, the performance of the coal gangue soil amendment can be optimized to suit various soil types and crop requirements while minimizing environmental risks.

5. Effects of Coal Gangue Soil Amendments in Application

5.1 Heavy Metal Contaminated Soil Remediation

In agricultural lands contaminated with heavy metals, applying coal gangue amendments can adsorb and immobilize these metals, reducing their bioavailability and limiting their uptake by crops, thereby lowering the heavy metal content in harvested products. For example, a study applying coal gangue to cadmium-contaminated soil observed a significant decline in soil cadmium levels, concurrent with improved crop yield and quality.

5.2 Enhancing Soil Fertility

In nutrient-poor or acidic soils, coal gangue amendments provide essential minerals and trace elements, increasing soil pH and promoting crop growth. A trial conducted in China's acidic red soil region showed that after applying coal gangue, soil pH increased, leading to improved crop growth conditions and increased yields.

5.3 Improved Water and Nutrient Retention

The porous structure of coal gangue amendments increases soil porosity, enhancing water holding and nutrient retention capabilities. In arid regions, application of coal gangue led to substantial improvements in soil moisture retention, reducing irrigation demands and improving water use efficiency.

5.4 Soil Structure Amendment

In soils with poor structure, coal gangue amendments can promote the formation of aggregates, improving soil aeration and drainage. Research has demonstrated that in sandy soils, the use of coal gangue significantly enhances soil structure, fostering better root development for crops.

These case studies highlight the promising applications of coal gangue soil amendments in improving soil quality, remediating environments, and boosting agricultural productivity. However, it is crucial to tailor formulations and conduct field trials according to local soil conditions and crop requirements.

6. Challenges and Issues in Coal Gangue Soilification Utilization

6.1 Heavy Metal Migration Risks

The main concerns regarding heavy metal migration in coal gangue soilification include:

1) Dissolution and Mobility. Under specific environmental conditions (such as acid rain, high humidity, and microbial activity), heavy metals in coal gangue may leach into soil solution, potentially being absorbed by crops or infiltrating groundwater, posing threats to ecosystems and human health.

2) Soil Chemical Interactions. Interactions between heavy metals and other soil constituents (like organic matter and phosphates) can alter their forms, influencing their stability and mobility in the soil.

6.2 Long-Term Stability Issues

Long-term stability challenges in coal gangue soilification encompass:

1) Mineral Transformation and Loss. Minerals in coal gangue may undergo chemical and biological transformations in soil, changing their forms and effectiveness. They might be decomposed by microorganisms or converted into unstable forms through oxidation or reduction reactions.

2) Re-activation of Heavy Metals. Initial treatments may temporarily reduce heavy metal bioavailability, but over time, changes in pH, microbial activity, or other chemical reactions can re-activate these metals, increasing their mobility and toxicity.

3) Soil Structure Degradation. While coal gangue initially improves soil structure, its physical properties may deteriorate over time, causing particle breakdown, loss of pore structure, and increased soil compaction, negatively impacting crop growth and water retention.

4) Ecological Adaptation. Soil microorganisms and plant communities may require time to adapt to the addition of coal gangue. If the ecosystem fails to adjust, it could affect soil biodiversity and productivity in the long run.

To overcome these challenges, researchers need to conduct extensive field trials monitoring the performance of coal gangue amendments under varying climates and soil conditions. They should also develop new stabilization techniques and amendment formulations. Establishing effective monitoring and management systems to regularly assess soil quality and crop health is crucial for timely adjustment of amendment strategies, ensuring the sustainability of coal gangue soilification utilization.

7. Conclusion

The utilization of coal gangue for soilification and the production of soil amendments represents a crucial strategy for waste management and soil improvement. Despite challenges like heavy metal contamination and long-term stability, ongoing technological advancements and research efforts are addressing these issues effectively.

In the future, the focus of coal gangue soilification will shift towards green, intelligent, and sustainable practices. This includes incorporating advanced technologies such as nanotechnology, biocomposite materials, remote sensing, and machine learning. Additionally, the development of eco-friendly additives and cost-effective pre-treatment methods will be vital. Establishing comprehensive evaluation systems for precise amendment application and long-term monitoring is another key area for progress.

Overall, the use of coal gangue in soil improvement not only facilitates waste recycling but also enhances soil quality and agricultural productivity. It plays a significant role in promoting circular economy and sustainable agriculture, demonstrating the potential for transforming a waste product into a valuable resource for environmental and economic benefits.

References

[1] Guan Jie, Li Yingshun. Comprehensive Utilization of Coal Gangue and Its Prospects [J]. Environmental Protection and Sustainable Development, 2008, (01): 34-36.

[2] Liu Fanyu, Song Huiping, Wu Haibin, et al. Advances in the Research on Soilification of Coal Gangue and Soil Amendments [J]. Mineral Resources Protection and Utilization, 2023, 43(06): 14-26.

[3] Wang T, Wang Y, Wang J. Research on Potential Fertilization of Coal Gangue in the Weibei Coalfield, China [J]. Acta Geologica Sinica-English Edition, 2008, 82(3): 717-721.

[4] Luo Genhua, Rao Menggang, Wang Shuai, et al. Effects of Coal Gangue-Soil Mixtures on Lettuce Growth and Pb Migration Patterns [J]. Earth and Environment, 2015, 43(1): 14-20.

[5] Zhang Yuhang, Song Zilin, Kong Tao, et al. Improvement of Saline-Alkali Soil Physical and Chemical Properties by Coal Gangue [J]. Chinese Journal of Eco-Agriculture, 2021, 30(1): 195-204.

[6] Kong Tao, Zheng Shuang, Zhang Ying, et al. Effects of Coal Gangue on Vegetation Greening and Soil Microbes in Saline-Alkali Soils [J]. Journal of Soil and Water Conservation, 2018, 32(6): 321-326.

[7] Sun Hairong, Zhao Aidong. Discussion on Using High-Sulfur Coal Gangue to Improve Soil [J]. Coal Processing and Comprehensive Utilization, 1999(3): 16-18.

[8] Zhang Hongmin, Li Shuwei, Hu Bin. Destruction of Mining Ecological Environment by Coal Gangue and Its Resource Utilization [J]. Mining Technology, 2008(5): 62-64.

[9] Shi Longqing, Han Jin, Yin Zengde, et al. Application Research on Coal Gangue for Soil Improvement [J]. China Coal, 1998(5): 37-39.

[10] Guo Yanxia, Zhang Yuanyuan, Cheng Fangqin. Industrialization and Prospects of Comprehensive Utilization of Coal Gangue [J]. Chinese Journal of Chemical Engineering, 2014, 65(7): 2443-2453.