Scientific and Social Research, 2024, Volume 6, Issue 5
https://ojs.bbwpublisher.com/index.php/SSR

Microbial Chaff Reinforcement: Preparation and Performance Study of a Soil Stabilizer

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Abstract: The fungus bran is the waste of the fruiting body of edible fungi, which is rich in a variety of protein and fiber, amino acids, polysaccharides, enzymes, and other nutrients, and has high reuse value. In this study, the fungus bran produced by desert Tremella was used as the raw material to prepare the fungus bran which could provide plant nutrients and water retention function. After 7 days of experiments, it was found that the sand fixation material had good water retention performance and significantly increased the aggregate performance of the sand. The results of FTIR and SEM analysis showed that the sand chaff was involved in the agglomeration process of sand, and the sand and the chaff were well combined, with a better spatial network structure and surface morphology. Therefore, it is a great prospect to explore the reuse of solid waste of fungal bran in desert afforestation.

Keywords: Fungus chaff; Recycling; Environmental protection; Desert planting

Online publication: June 11, 2024

1. Background

Desertification knows no borders, posing a daunting challenge to all humanity. The global expanse of desertified land exceeds 36 million square kilometers and continues to expand. China is among the most severely affected countries. The country has initiated the sixth national monitoring of desertification and land degradation, with desertified land covering 27.3% of the total land area, with approximately 99.6% distributed across 12 provinces in North and Northwest China [1]. Desertification results in fragmented ecosystems and reduced carbon storage. With the introduction of carbon goals and the implementation of carbon plans in various regions, preventing and controlling desertification holds significant and far-reaching implications.

Desertification in the country is guided by the principles of prevention as a priority, scientific management, and reasonable utilization. It follows natural and economic laws, aiming to improve ecology and livelihoods, constructing a green ecological barrier. Many strategies have been developed to prevent and control desertification, including better protection of original arid ecosystems and desert restoration. In desert restoration, commonly used techniques involve using materials to stabilize sand dunes and provide an environment for seed germination. Current common techniques for sand stabilization include traditional biological, engineering, physical, mechanical, chemical, and comprehensive methods [2]. Mechanicians have proposed a new solution, applying constraints between desert sand grains. As a result, the discrete sand body obtains the ecological and mechanical properties of soil, becoming optimal for plant growth, known as desert soilification [3]. However, traditional sand-fixing materials, including physical barriers such as gravel, straw, heavy oil, asphalt emulsions, and biological soil crusts, have their limitations in terms of cost, effectiveness, and implementation convenience. Therefore, new materials for wind erosion prevention, water conservation, and sand improvement have attracted much attention [4].

The experiment was conducted in the Tengger Desert, located in the vicinity of Maran Lake, which is the fourth largest desert in China, spanning an area of 43,000 square kilometers [5]. Positioned on the border between the southwestern part of Alxa Left Banner, Inner Mongolia Autonomous Region, and the central part of Gansu Province, it aims to achieve sustainable development. On one hand, afforestation is underway, while on the other, economically viable crops like desert tremella mushrooms are being cultivated, yielding favorable ecological and economic outcomes. However, due to the fragile nature of desert ecosystems, the solid waste generated from mushroom production, such as fungal bran, needs careful management to prevent secondary harm to the desert system [6]. This study builds upon existing research to turn waste into treasure, turn sand into gold, and convert mushroom residue into "soil" without increasing the burden on desert ecosystems. This not only improves soil structural integrity but also enhances functions such as water storage, nutrient retention, air circulation, and microbial habitat. Mushroom residue sand-fixing materials can serve as plant carriers, playing a role in stabilizing deserts and ecological restoration.

2. Materials and methods

2.1. Experimental materials

The sand used in this experiment was selected from the mobile sand dunes around Malan Lake, located on the border between southwestern Alxa Left Banner, Inner Mongolia Autonomous Region, and central Gansu Province. (Approximately between 37°30'N to 40°N and 102°20'E to 106°E). The texture grade of the sand was analyzed according to the Unified Soil Classification System (ASTM D2487). The main component of the sand consists of particles with a diameter smaller than 0.25 mm, accounting for 96.91% of the total (**Table 1**), with poor/weak alkalinity. The fungal bran as shown in **Figure 1** is selected from Ar Horqin Banner Yuanhui Linmu Livestock Co., Ltd.

Table 1. Sand particle size analysis

Sand Particle Size Analysis				
Particle Size Distribution	1.0–2.0	0.5–1.0	0.5–0.25	≤ 0.25
Sand	-	-	3.09%	96.91%

Figure 1. Experimental materials: sand (left), fungal bran material (right)

2.2. Preparation process of new materials for fungal bran and sand fixation

The new material synthesis is carried out through the following steps. The fungus residue is pulverized and sieved through a 20–30 mesh screen, then mixed with water and NaOH solution. It is kept warm at 50°C for 12–24 hours, followed by pH adjustment to 6.5–7.0 using HCl. The mixture is then filtered, washed with water, and dried to obtain the fungus processing material. The mass ratio of fungus residue to water is 1:10–15, the mass fraction of NaOH solution is 3%–7%, and the mass ratio of NaOH to fungus residue is 1:150–300. 500 g of fungus residue is added with 100 ml of 30%–50% acrylic acid. Then, 0.5 g of the mixture is added to each of the initiator and crosslinkers, and heated at a reaction power for 6 minutes to obtain the bacterial husk solid sand material [7].

A certain proportion of acrylic acid initiator, potassium persulfate, and crosslinking agent N, N-methylene bisacrylamide are added and heated to synthesize a fungus bran sand-fixing composite material. After drying, crushing, and sieving yields desert sand-fixing material with biodegradability, nutrient provision, and high water retention properties [8]. The general process for the synthesis of fungal chaff solidification sand new materials is outlined in the scheme (**Figure 2**).

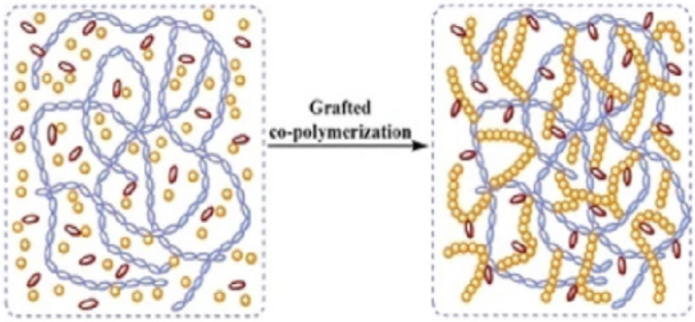

Figure 2. Schematic diagram of the synthesis principle of fungal chaff solid sand fixation material

2.3. Analytical methods

2.3.1. Determination of water retention rate in mushroom bran solidification material

After fully absorbing water, the fungus substrate composite is laid flat on a surface dish, and placed outdoors in sunlight. The weight change is measured every 24 hours. The relationship between the water retention rate of the fungus substrate composite and time is shown in the graph below, and the specific formula for calculating the water retention rate is as follows.

$$Q_r = \frac{M - m}{M_0 - m}$$

In the formula: Q_r represents the water retention rate, %; *M* represents the weight of the water retention agent, g; *m* represents the original weight of the water retention agent, g; and M_0 represents the weight after initial swelling, g [9].

2.3.2. FT-IR analysis

The fungal chaff solidifying sand material is ground into prescribed-sized powder and pressed into pellets with KBr, and then its FTIR spectrum is measured using an infrared spectrometer.

2.3.3. SEM analysis

The surface functional groups of the prepared water-retaining agent were scanned and analyzed using Fourier-transform infrared spectroscopy; the apparent morphology of the water-retaining agent was observed using SEM.

2.3.4. Nutrient analysis

The nutritional content of fungal chaff solidifying materials was analyzed and evaluated through relevant data-driven research, to determine the relationship between fungal chaff solidifying materials and the primary properties of the soil.

3. Results and discussion

3.1. Macroscopic analysis of fungal straw materials

Comparing the sand with the processed material, it is visually evident that the sand treated with fungal bran has a deeper color. Furthermore, by separately shaking the sand in the Petri dishes with the fungal bran-treated material, it can be observed that the fungal bran-treated material exhibits better cohesion and is less prone to dispersion even under vigorous shaking (**Figure 3**) [10].

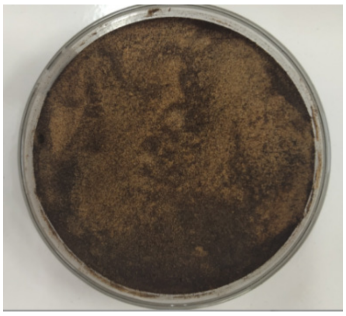

Figure 3. State diagram after the synthesis of fungal chaff solid sand material

3.2 Analysis of sand fixation performance

3.2.1. Aggregation ability

Soil aggregates are the fundamental units of soil structure and are also one of the main indicators of soil structure stability and erosion resistance [11]. Properties of soil, such as water, nutrients, air, and temperature, are all related to the stability of soil aggregates. A stable soil structure not only retains water and nutrients, improves soil quality, and reduces soil erosion but also promotes plant growth and microbial activity. Studies have shown that good aggregation and soil quality go hand in hand, with the stability of soil aggregates widely used as a key indicator of soil health [12]. In terms of aggregation performance, the flowability of sand was significantly reduced after treatment with fungal chaff composite material. The combination of sand and fungal bran composite material aggregates the sand particles together, increasing the sand's crust formation rate, with the highest increase of 17.32% observed in particle sizes ranging from 0.5 to 2.0 cm.

3.2.2. Stable performance

Due to the adsorption and ion exchange functions of water-retaining agents, other research results show that water-retaining agents can improve the utilization efficiency of N and K fertilizers by promoting the combination of soil moisture and fertilizers, and incorporating water-retaining agents into the soil can reduce fertilizer usage by 30%. Studies have shown that an appropriate amount of nitrogen can reduce the inhibitory effect of water stress on photosynthetic organs, and increase the photosynthetic activity of leaf cells, thereby enhancing photosynthetic efficiency [13]. Therefore, the soil moisture content is closely related to the mineralization, transport, absorption, and utilization of plants. Adequate soil moisture can promote root growth, enhance nutrient utilization, and thus improve crop drought resistance [14]. Simultaneously, in terms of water and fertilizer utilization mechanisms, water and nutrients affect crop absorption and utilization of water and fertilizer by regulating crop growth, development, and physiological characteristics. The use of soil water-retaining agents can control soil moisture and nutrients, achieve synchronization of water and fertilizer, and promote crop absorption and utilization of water and fertilizer, thereby achieving the goal of water conservation, drought resistance, and increased yield [15]. Sand treated with fungal husk composite material exhibits good overall integrity and is less prone to dispersion (**Table 2**).

Table 2. Changes in the composition of experimental sand (weight percentage)

Particle size distribution (mm)				
Texture	1.0–2.0	0.5–1.0	0.5–0.25	≤ 0.25
Sand			3.09%	96.91%
Fungi bran material	2.71%	14.61%	27.59%	55.1%

3.3. Moisture retention capability

After fully absorbing water, the mushroom bran composite material is spread evenly on the surface dish, then placed outdoors, and exposed to sunlight, and its weight changes are measured every 24 hours [16]. According to the experimental results, the water retention of the mushroom bran material reaches 22.5% on the first day, 13.5% on the second day, 10% on the third day, decreases to 5% on the fourth day, and 2.5% on the fifth day, stabilizing its water retention performance. Regarding water retention performance, it was found through a 7-day water retention experiment that the addition of mushroom bran composite material significantly enhances the water retention of sand, and the retention time of water is significantly prolonged.

3.4. Microscopic analysis of fungal bran materials

3.4.1. FT-IR analysis

The absorption peaks in the infrared spectrum of the sample reflect the characteristic functional groups present in the sample, and the success of the graft copolymerization reaction of the polymer can be determined based on the changes in these peaks [17].

The infrared spectrum of the prepared moisturizer is shown in **Figure 4**. As seen in the figure, the moisturizer exhibits absorption peaks at 3433 cm^{-1} corresponding to O-H stretching vibration, around 1636 cm^{-1} indicating the stretching vibration absorption peak of amide C=O, at 1319 cm^{-1} representing the stretching vibration absorption peak of NH2, and at 1018 cm^{-1} indicating the stretching vibration absorption peak of C-O. Additionally, absorption peaks of symmetric and asymmetric stretching vibrations of the sulfonic acid group appear at 1036 cm^{-1} and 772 cm^{-1} respectively. At 606 cm^{-1} and 462 cm^{-1}, different substitution peaks appeared, indicating preliminarily that each monomer has formed a cross-linked network polymer under the action of the cross-linking agent, which is a copolymer with numerous hydrophilic groups (**Figure 4**).

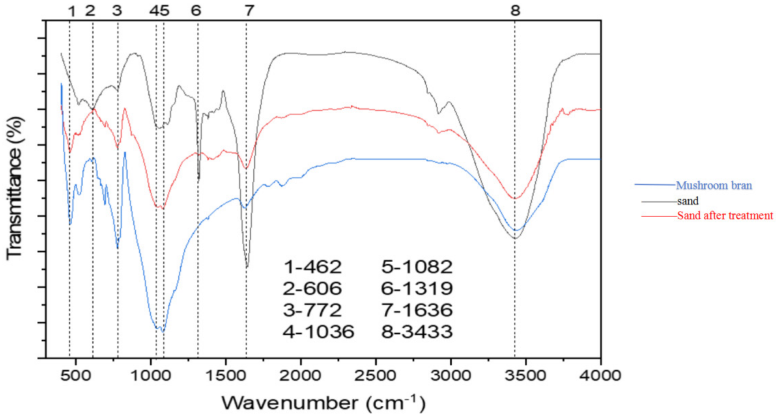

Figure 4. FT-IR analysis

3.4.2. The micromorphology of fungus bran material

Figure 5 shows the scanning results of the obtained fungal bran material magnified 1000 times in SEM. It can be seen that the fiber microcrystals are distributed in a white strip shape in the water-retaining agent. The fiber microcrystals are tightly wrapped by copolymers, with particles of different sizes, irregular shapes, and uneven surfaces. The surface is covered with micropores, and there are surface layers, grooves, and vertical and horizontal furrows [18]. This layered structure and the pores on the surface enable the fungal bran water-retaining agent to have a strong water absorption performance. This indicates that the obtained fungal bran material is not physically filled, but polymerization occurs between monomers, forming new copolymers.

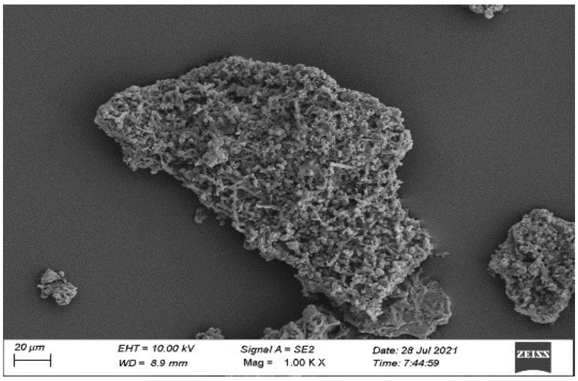

Figure 5. SEM image of moisturizer agent

3.5. Nutrient analysis

In terms of plant growth, fungi bran contains a large amount of organic matter and nutrients such as nitrogen, phosphorus, and potassium. It plays an important role in promoting plant growth and can improve the survival rate and growth cycle of trees in afforestation.

4. Cost analysis

The cost of use is a key factor in the economic and feasibility evaluation of water-retaining agents. According to the preparation conditions of fungal materials, the cost analysis of producing 1 ton of fungal materials is shown in **Table 3**. After calculation, the cost of producing 1 ton of fungal materials is 1097.5 yuan, which has obvious cost advantages compared to commercially available water-retaining agents [19]. Furthermore, large-scale production can further reduce the cost of water-retaining agents, basically achieving the expected low-cost effect and having a feasible market application value.

Table 3. Analysis of fungal bran material costs

Material	Main ingredients	Amount	Market pricing	Subtotal/yuan	Total/yuan
Fungal bran material	Fungal bran	1000 kg	0	0	1097.5
	Sodium hydroxide	5 kg	2.2 yuan/kg	11	
	Acrylic acid	80 kg	8.5 yuan/kg	680	
	ammonium persulfate	1 kg	75 yuan/kg	75	
	N.N-Dimethylacrylamide	1 kg	8 yuan/kg	8	
	Water consumption	1 t	3.5 yuan/t	3.5	
	Power consumption	400 kw/h	0.8 yuan/kw/h	320	

5. Conclusion

With mushroom bran, loose sand material can form a crust on the loose sand surface, enhancing water retention and wind erosion resistance. It is cost-effective, generates no additional pollution, easy to produce and apply, making it an ideal sand-fixing and water-retaining agent.

Preventing desertification and promoting technological innovation are important pathways to achieving both increasing revenue and reducing carbon emissions. They have already been embedded in China's carbon action plan, together forming the zero-carbon landscape of ecological civilization construction [20]. Achieving carbon peak, carbon neutrality, and protecting ecological interests are closely related to human sustainable development. Ecological civilization requires green safeguards, and the achievement of carbon peak and carbon neutrality goals represents profound social change.

Disclosure statement

The authors declare no conflict of interest.

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