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Plant Adaptability to Improved Dredged Sediment

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Abstract: Traditional dredged sludge disposal methods are characterized by low resource utilization and high carbon emissions, leading to serious environmental pollution. This study used dredged sludge, composted pig manure, and sawdust as raw materials, and supplemented them with composite biological agents to prepare improved soil. Plant adaptability to the improved soil was comprehensively evaluated using factors such as seed germination index (GI). The alkaline nitrogen content in the improved soil increased by 78.61% compared to the dredged sludge, and the content of other nutrients such as available potassium also increased to varying degrees. Ryegrass seed GI increased by 51.06% in improved soil (IS1) compared to dredged sludge. The main dominant fungi in the improved soil (IS1) were *Tausonia*, *Trichoderma*, and *Cystoflobasidium*, which promote soil nutrient activation and antagonize pathogenic bacteria, making the environment more conducive to plant growth. Dredged sludge was successfully converted into planting soil. Fully utilizing the nitrogen, phosphorus, and other substances enriched in dredged sludge to provide nutrients for plant growth is an efficient method to achieve dredged sludge resource utilization.

Keywords: planting soil; dredged sludge; microbial diversity; germination index; plants

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1. Introduction

Dredged sludge is usually regarded as waste. Traditional methods of disposing of dredged sludge from inland rivers include ocean dumping and land disposal [1]. Land disposal involves using designated areas as storage yards and construction of embankments, allowing dredged sludge to be deposited as fill material. This traditional disposal method faces numerous problems, with the most significant being its unsystematic nature, characterized by low resource utilization rates, substantial carbon emissions, and severe environmental pollution [2].

Methods for resource utilization of dredged sludge include construction, backfill, and land utilization. Dredged sludge used as construction and backfill material has high water content and porosity, making it difficult to use directly and requiring it to be dehydrated before use [3]. The use of alkali-activated recycled concrete powder to solidify sludge reduces the leaching of the heavy metals total cadmium (Cd) and total chromium (Cr) by 48.1–66.3% and 68.8–77.5%, respectively [4]. Despite stabilization efforts, concerns persist regarding stabilizing agent degradation and potential heavy metal remobilization. Dredging sludge is predominantly comprised of inorganic minerals including silicates

with substantial SiO_2 and Al_2O_3 content [5], and closely resembles terrestrial soil and clay matrices. This composition facilitates granular structure formation, trace element retention, and nutrient preservation, making it a valuable biological resource.

Land application presents an efficient nutrient recovery pathway, with toxicity reduction achievable through composting or leaching protocols [6]. However, these remediation techniques demonstrate limited efficacy in complete removal of persistent organic pollutants and heavy metals. Experimental studies with wheat indicate that controlled sludge application significantly enhances all vegetative and yield-related parameters. Nevertheless, as the application rate of brewery sludge increases, heavy metals, including total zinc (Zn) and total copper (Cu), have shown increased bioaccumulation in plant tissues [7]. Direct use of dredging sludge in agricultural production may cause metals to flow into the food chain and cause harm to humans [8]. Converting dredged sludge into planting soil before use not only prevents environmental risks but also enables efficient utilization of its enriched nutrients (nitrogen, phosphorus, and others) for plant growth, efficiently achieving the resource utilization of dredged sludge.

After conducting physical and chemical analysis on the substrates, this study used dredged sludge, composted pig manure (CPM), and sawdust as raw materials to make planting soil by adding biological agents for improvement according to established standards [9]. For improved soils with different proportions, the seed germination index (GI) was used to comprehensively evaluate their potential toxic effects on plants. The microbial diversity in the dredged sludge before and after improvement was analyzed to investigate plant adaptability to the improved soil, providing technical support for upgrading dredged sludge into planting soil.

2. Materials and Methods

2.1. Materials and Instruments

2.1.1. Test Materials

Pak choi (*Brassica chinensis* L.) seeds were purchased from China Guangdong Xingyan Seed Co., Ltd. (Guangzhou, China), and ryegrass (*Lolium perenne* L.) and bermudagrass (*Cynodon dactylon* L. Pers.) seeds were purchased from Changsha Red Star Flower Market (Changsha, China). The dredged sludge and eucalyptus topsoil (0–20 cm, local topsoil) used to make the improved soil were collected from the Pinglu Canal Project in Hengzhou City, Nanning City, Guangxi Zhuang Autonomous Region. The CPM was prepared under laboratory conditions through controlled decomposition of raw pig manure mixed with sawdust, superphosphate, and microbial inoculants from China Hunan Aojun Technology Co., Ltd. (Changsha, China). The composite biological agent (CBA) was made by mixing two biological agents, *Trichoderma harzianum* AJ-11 and *Bacillus velez* AJ-14, at a ratio of 1:1 (*w*/*w*), both of which were purchased from Hunan Aojun Technology Co., Ltd.

The reagents used in the experiment, such as concentrated sulfuric acid (H_2SO_4), hydrochloric acid (HCl), potassium chloride (KCl), calcium chloride ($CaCl_2$), potassium dichromate ($K_2Cr_2O_7$), sodium hydroxide (NaOH), potassium antimony tartrate ($KSbC_4H_4O_7 \cdot ½H_2O$), ammonium molybdate ($(NH_4)_6Mo_7O_{24} \cdot 4H_2O$), potassium dihydrogen phosphate (KH_2PO_4), anhydrous ethanol (C_2H_5OH), and ascorbic acid ($C_6H_8O_6$), were all of high-grade purity and purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China).

2.1.2. Test Instruments and Equipment

A biochemical incubator (SPX-250B) was purchased from Shanghai Lichen Instrument Technology Co., Ltd. (Shanghai, China). An electronic analytical balance (AUY120) and UV-visible spectrophotometer (UV-2600) were purchased from Shimadzu Testing Equipment

Co., Ltd. (Shanghai, China). A pH meter (PHSJ-3F) and conductivity meter (LC-DDB-1A) were purchased from Ray-Magnetic Co., Ltd. (Dongguan, China). An inductively coupled plasma spectrometer (5110 ICP-OES) was purchased from Agilent Technologies Co., Ltd. (Shanghai, China). An inductively coupled plasma mass spectrometer (ICP-MS NexlON 1000G) was purchased from PerkinElmer Instrument Co., Ltd. (Suzhou, China).

2.2. Experimental Design

2.2.1. Preparation of Improved Soil

Eucalyptus topsoil, dredged sludge, and CPM were dried naturally in a cool and dry environment, ground through a 2 mm-pore nylon sieve, and further ground through a 0.149 mm-pore nylon sieve to obtain the raw materials for improved soil preparation. In this study, planting soil refers to improved soil, dredged sludge, and eucalyptus topsoil, and M refers to the total wet weight of the planting soil.

Using different mixture ratios of materials (Table 1), nine groups of samples—Ctrl1 (deionized water), Ctrl2 (eucalyptus topsoil), Ctrl3 (dredged sludge), IS0 (improved soil with 0% M CPM), IS1, IS3, IS5, IS7, and IS9—were created to test the germination of pak choi seeds. There were three control groups (Ctrl1, Ctr2, and Ctrl3) and six test groups (IS0–IS9, comprising 0%, 1%, 3%, 5%, 7%, and 9% M, respectively, in the CPM content). Each experimental group was supplemented with 0.01% M CBA.

Table 1. Planting soil composition.

Item	Raw Material (g)				
	Eucalyptus Topsoil	**Desilting Mud**	**CPM**	**Sawdust**	**CBA**
Ctrl1	0	0	0	0	0
Ctrl2	100	0	0	0	0
Ctrl3	0	100	0	0	0
IS0	0	100	0	0	0.01
IS1	0	89	1	10	0.01
IS3	0	87	3	10	0.01
IS5	0	85	5	10	0.01
IS7	0	83	7	10	0.01
IS9	0	81	9	10	0.01

CPM: composted pig manure; CBA: composite biological agent.

2.2.2. Seed Germination Test

To prepare the culture medium, 2.5 g of planting soil was mixed with 25 mL of deionized water and placed in a 50 mL centrifuge tube. The centrifuge tube was placed in a constant temperature shaker set at 298.15 K and 180 $r \cdot min^{-1}$, shaken for 30 min, and let stand for 10 min before the supernatant was filtered using medium-speed quantitative filter paper. This filtrate was the culture medium required for the study.

For cultivation, 5 mL of culture solution was pipetted into a dry, sterile 9 cm culture dish with two layers of filter paper on the bottom, making sure that the filter paper was completely soaked in the culture solution and no bubbles were present. Fifty seeds of uniform size and fullness were selected and placed evenly in the culture dish, making sure that they were in the culture solution and attached to the filter paper to avoid floating. The culture dish was covered with plastic film with two to three even air holes and was carefully placed in a 303.15 K incubator. Three biological replicates were established for each treatment group.

After two days of incubation, Vernier calipers were used to non-destructively measure the seed root length. The indicator values were calculated according to previously derived equations [10], with deionized water (Ctrl1) serving as the control group:

$$Germinationrate\ (GR) = \frac{Number\ of\ germinated\ seeds}{Total\ number\ of\ seeds} \times 100\% \quad (1)$$

$$Average\ root\ length\ (AL) = \frac{\sum Root\ length}{Total\ number\ of\ seeds} \quad (2)$$

$$Relative\ germinationrate\ (RP) = \frac{GR\ of\ test\ group}{GR\ of\ control\ group} \times 100\% \quad (3)$$

$$Relative\ root\ length\ (RL) = \frac{AL\ of\ test\ group\ (RL)}{AL\ of\ control\ group\ (RL_{CK})} \times 100\% \quad (4)$$

$$Germination\ index\ (GI) = RP \times RL \quad (5)$$

2.3. Analytical Methods

Cd, Cu, lead (Pb), Zn, mercury (Hg), and Cr were measured using microwave digestion–inductively coupled plasma mass spectrometry [11]. Total arsenic content (As) was measured using atomic fluorescence spectrometry (AFS) [12]. pH and electrical conductivity (EC) were measured using a pH meter and conductivity meter at a soi–water ratio of 1:5 (w/w), respectively. Bulk density (ρ) was measured using the ring knife method. Total nitrogen (TN) was measured using a Kjeldahl nitrogen analyzer, total phosphorus (TP) was measured using a spectrophotometer, and total potassium (TK) was measured using inductively coupled plasma emission spectrometry. Alkaline hydrolysis nitrogen (AN) was detected using an alkaline diffusion method. Available potassium (AK) was measured using flame photometry. Available phosphorus (AP) was measured using molybdenum–antimony colorimetry. Available iron (AFe), effective calcium (ECa), effective magnesium (EMg), and extractable manganese were (EMn) measured using inductively coupled plasma emission spectrometry [13].

2.4. Biodiversity Detection

Samples were collected from Ctrl2, Ctrl3, and IS1 at five points (IS1 was chosen as per the results of the seed germination test [Section 2.3]). Genomic DNA was extracted from samples using an E.Z.N.A.® soil DNA Kit (Omega Bio-tek, Norcross, GA, USA). Purity and concentration of DNA were measured by a NanoDrop2000 spectrophotometer (Thermo Scientific, Waltham, MA, USA) and integrity was detected by agarose gel (1.0%) electrophoresis. The V3–V4 hypervariable region of the bacterial 16S rRNA gene was amplified using primers 338F (5′-ACTCCTACGGGAGGCAGCAG-3′) and 806R (5′-GGACTACHVGGGTWTCTAAT-3′) using a thermocycler PCR system (GeneAmp 9700, ABI, Foster City, CA, USA). PCR formal testing was conducted using a TransGen AP221-02: TransStart Fastpfu DNA polymerase 20 μL reaction system. Sequencing was accomplished using Illumina's Miseq PE300 platform (Shanghai Meiji Biomedical Technology Co., Ltd., Shanghai, China) [14].

2.5. Data Analysis

All data in this study were statistically analyzed by Microsoft Excel 2016 and plotted by Origin 2022 (Origin Lab, Northampton, MA, USA). IBM SPSS Statistics 26 was used to analyze the standard deviation and significance of different indicators ($p < 0.05$).

3. Results and Discussion

3.1. Heavy Metal Content Analysis

Excessive heavy metal content reduces the abundance and diversity of soil microorganisms. Heavy metals can also easily accumulate in plants, especially crops, threatening plant growth and food security. The heavy metal analysis of planting soil is shown in Figure 1:

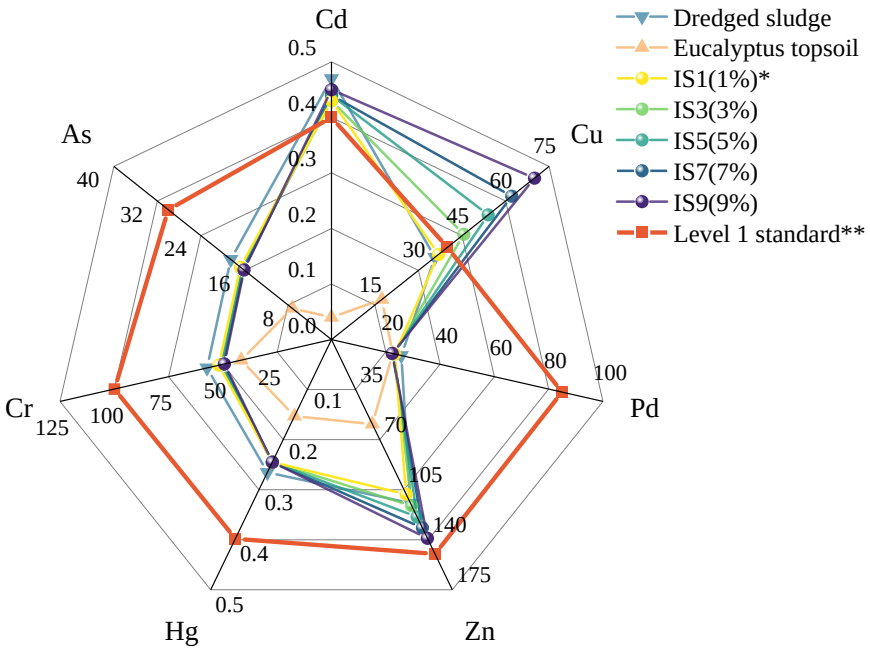

Figure 1. Heavy metal content in artificial soil. * Corresponding to the amount of CPM added: 1% is the content of CPM in the corresponding planting soil. ** From stand: planting soil for greening [9]. The content of each heavy metal is expressed in mg·kg^{-1}.

The heavy metal content in the eucalyptus topsoil was significantly lower than the first-grade standard for planting soil (Figure 1). The levels of most heavy metals in the dredged sludge and improved soil were also lower. The total cadmium content of the soil was higher than the first-grade standard (0.4 mg·kg^{-1}), as was the total copper content of the improved soil (40 mg·kg^{-1}). This may be because of pesticide application and the discharge of breeding wastewater containing cadmium, copper, and other heavy metals to tributaries of the Yujiang River (Xijin Reservoir Area). These metals were enriched in the dredging sludge, making the heavy metal content in the improved soil and dredging sludge higher than that of eucalyptus topsoil.

Plants take up metals from soil and then transport them throughout their systems. The heavy metal content in plant roots is the highest compared to other parts of the plant body, as after heavy metals accumulate, the roots will hinder their migration. Under the stress caused by accumulated heavy metals, root nutrient absorption efficiency is hindered, destroying the antioxidant system and affecting plant growth and development [15]. Heavy metals can enter the human body through the consumption of plants that have bioaccumulated them, causing harm to human health [16].

Total cadmium and copper levels of the improved soil and dredged sludge were lower than the corresponding secondary standards (total cadmium < 0.6 mg·kg^{-1}, total copper < 150 mg·kg^{-1}). Overall, the heavy metal levels of the improved soil, eucalyptus topsoil, and dredged sludge were relatively low and would not be expected to cause heavy metal pollution to the environment.

3.2. Main Control Indicators and Nutritional Composition

The main control indicators of soil include pH, EC, and bulk density (Table 2). Ctrl2 is red, caused by its rich iron and aluminum compounds. Nanning has a subtropical monsoon climate with abundant rainfall. This causes many compounds in the soil, including most alkali and alkaline earth metals, to be washed away, leaving insoluble iron and aluminum oxides that appear acidic red.

Table 2. Main control indicators and total nutrition of soil.

Treatment	pH	EC ($mS \cdot cm^{-1}$)	ρ ($g \cdot cm^{-3}$)	TN ($g \cdot kg^{-1}$)	TP ($g \cdot kg^{-1}$)	TK ($g \cdot kg^{-1}$)
Ctrl2	4.48	0.51	1.32	1.24	0.16	20.69
Ctrl3	7.59	0.77	1.58	1.02	0.65	14.50
CPM	5.91	3.68	0.43	18.3	12.5	5.37
IS0	7.32	0.79	1.58	1.03	0.65	14.54
IS1	7.26	0.84	1.45	1.09	0.71	13.12
IS3	7.19	0.88	1.43	1.40	0.92	12.98
IS5	7.14	0.98	1.42	1.69	1.12	12.85
IS7	7.03	1.09	1.40	1.98	1.31	12.72
IS9	6.95	1.12	1.38	2.25	1.50	12.60

ρ: bulk density; TN: total nitrogen; TP: total phosphorus; TK: total potassium; CPM: composted pig manure.

Due to the addition of superphosphate and sawdust during the decomposition process, the CPM was acidic and had a low bulk density, alleviating the problem of soil compaction caused by the large bulk density of dredged sludge (Table 2). Within a certain range, the EC value can indicate the concentration of soluble salts in the soil [17,18]. Ctrl2 had the lowest EC value, indicating the lack of nutrient elements in this soil type. This was consistent with Table 3, showing that Ctrl2 was low in available nutrients except for effective iron.

Table 3. Available nutrients in soil.

Treatment	AN ($mg \cdot kg^{-1}$)	AP ($mg \cdot kg^{-1}$)	AK ($mg \cdot kg^{-1}$)	AFe ($mg \cdot kg^{-1}$)	EGa ($mg \cdot kg^{-1}$)	EMn ($mg \cdot kg^{-1}$)	EMg ($mg \cdot kg^{-1}$)
Ctrl2	28.7	0.363	47.07	50.30	114	22.0	12.3
Ctrl3	45.9	22.1	84.34	9.78	224	30.3	25.2
CPM	574	3643.3	2720.0	397	979	201	37.5
IS0	45.8	22.4	84.30	9.73	222.86	30.0	25.1
IS1	46.52	52.73	100.49	12.39	210.62	32.7	23.0
IS3	55.86	116.27	146.85	19.19	224.22	35.8	23.3
IS5	64.87	177.61	191.60	25.77	237.35	38.7	23.5
IS7	73.57	236.85	234.82	32.11	250.03	41.4	23.8
IS9	81.98	294.09	276.59	38.24	262.28	44.1	24.0
Standards	40~200	5~60	60~300	4~350	200~500	50~280	0.6~25

Standards: Technical requirements in Table 2 of "Planting soil for greening" [9]. AN: available nitrogen; AP: available phosphorus; AK: available potassium; AFe: available iron; ECa: exchangeable calcium; EMn: exchangeable manganese; EMg: exchangeable magnesium.

The total nitrogen, phosphorus, and potassium content of the soil reflects its potential fertility. Total nitrogen and phosphorus in the improved IS1 showed almost no change compared to Ctrl3, as the sawdust added during improvement had low N and P. Because of this, the effect of the small amount of CPM (1% M) added was diluted. When the amount of added CPM gradually increased, the total nitrogen and phosphorus in DN2–IS9 increased significantly compared with Ctrl3.

Effective nutrients can be directly taken up by plants from the soil and used for plant growth and development [19]. Although Ctrl2 had high total nitrogen and potassium content, it had low alkaline nitrogen (effective nitrogen) and available potassium,

indicating that most of the nitrogen and potassium were not biologically available. Additionally, most of its effective elements, including alkaline nitrogen and effective phosphorus, did not meet standards (Table 3). Most indicators of Ctrl3 (dredged sludge) met the standards, but its effective magnesium was low. After improvement, the total nitrogen in IS1–IS9 increased significantly by 6.8%, 37.3%, 65.7%, 94.1%, and 120.6%, respectively, compared with the original dredged sludge. The corresponding effective nutrient alkaline nitrogen content increased by 1.4%, 21.7%, 41.3%, 60.3%, and 78.6%, respectively. The effective phosphorus content of IS1, which had the least CPM, increased by 138.6% compared with dredged sludge. Compared with dredged sludge, the effective magnesium in IS1–IS9 increased by 7.8%, 18.3%, 27.7%, 36.6%, and 45.6%, respectively. Although still below the standards, the nutrient content of the dredged sludge was improved through modification.

In general, the bulk density of the improved soil with CPM added was greatly reduced compared with that of the dredged sludge, and most of the effective nutrients including alkaline nitrogen and effective phosphorus, potassium, and magnesium were increased. Compared with the dredged sludge and eucalyptus topsoil, the improved soil was more suitable for plant germination and growth.

3.3. Seed Germination Analysis

The GI is an important indicator for judging the maturity of compost and also reflects soil toxicity [20]. In this study, the GI was calculated from the seed germination rate and average root length. As shown in Figure 2, the germination rates and average root lengths of different seeds differed in this study. The germination rates, average root lengths, and germination indexes of the pak choi seed experimental groups were higher than those of Ctrl2 and Ctrl3. The IS0 group was the most significantly improved compared with Ctrl3, at 4.29%, 16.66%, and 21.66% higher, respectively. The average root lengths of the ryegrass seed experimental groups IS0, IS1, IS3, and IS9 were significantly higher than that of Ctrl3. The germination index of ryegrass IS1 was 50.97% higher than that of Ctrl3, which was the most significant difference. In the bermudagrass seed experimental groups, as the amount of CPM increased, the germination rate first increased and then decreased, and root length gradually decreased. From the germination index, IS0 increased most significantly, followed by IS1, at 47.18%, and 35.85% higher than Ctrl3, respectively. The improvement in the germination rate, average root length, and germination index in the improved soil may be related to factors such as enzymes, polysaccharides, and plant growth hormones produced by microbial metabolism in the added biological inoculants, which can promote germination and growth [21].

Examining the germination of the three seed types, IS1 demonstrated the most significant promoting effect on seed germination and root development among all treatments, indicating its optimal characteristics as a planting medium. Based on these promising results, IS1 was selected for further biodiversity analysis alongside Ctrl2 and Ctrl3.

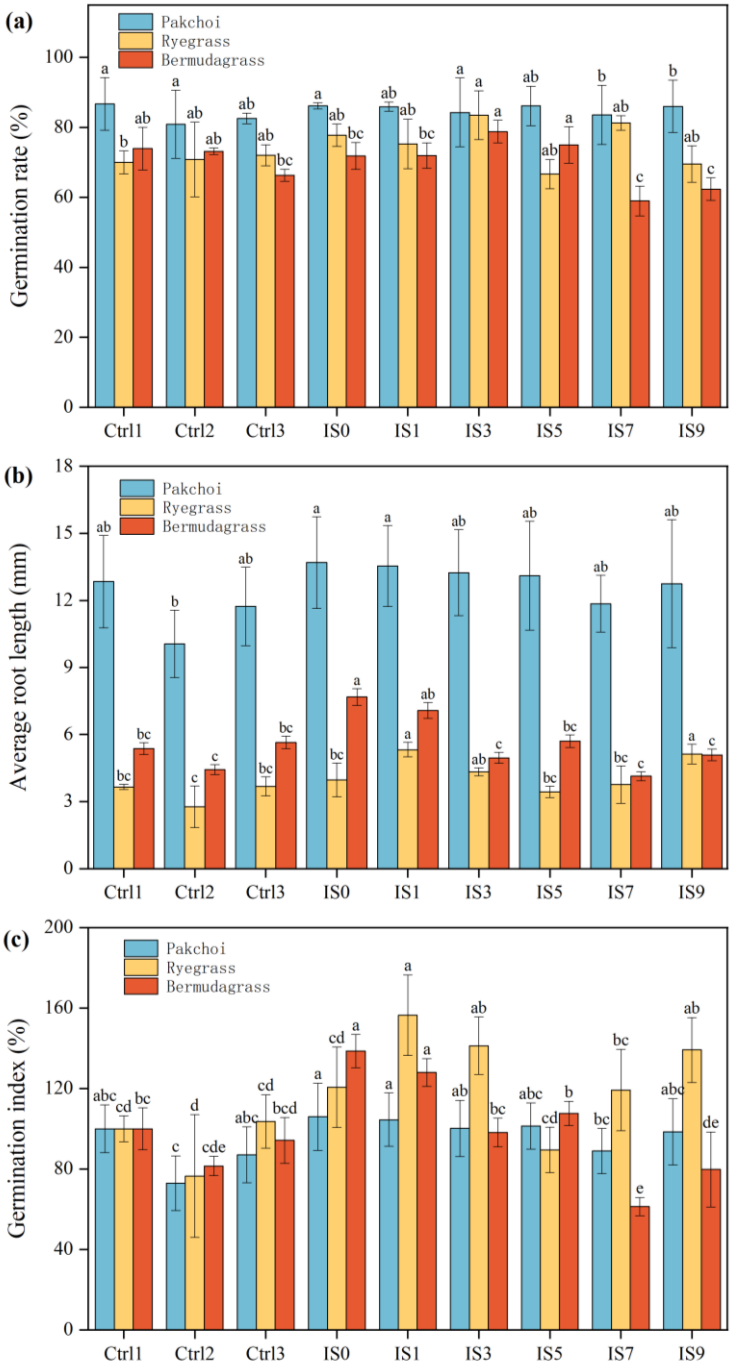

Figure 2. Effect of different planting soils on seed germination. (**a**) Germination rate. (**b**) Average root length. (**c**) Germination index. Different letters (a, b, c, d, e) above bars indicate significant differences between treatments ($p < 0.05$) based on Duncan's multiple range test.

3.4. Analysis of Fungal Diversity in Planting Soil

After analysis, 624 fungal operational taxonomic units (OTUs) were obtained from the three planting soils. Ctrl2 (eucalyptus topsoil) had the most (284), while IS1 (improved dredged sludge) had 248 OTUs, 38.5% higher than the 179 OTUs in Ctrl3 (dredged sludge) (Figure 3). The number of OTUs in the three planting soils gradually decreased with the increase in pH, similar to the results of Shi [22]. After soil improvement, the number of fungal OTUs increased significantly, and fungal diversity increased.

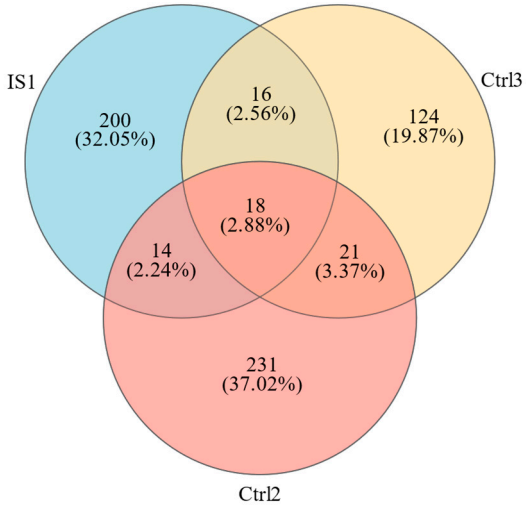

Figure 3. Venn diagram of planting soil fungal OTU distribution.

To further understand the changes in soil fungal communities and species composition, community abundance analysis at the genus level was performed for IS1, Ctrl2, and Ctrl3 (Figure 4). The top 10 fungal genera for average relative abundance IS1 were *Tausonia*, *Trichoderma*, *Cystofilobasidium*, *Coniochaeta*, *Pseudogymnoascus*, *Plectophomella*, *Mycothermus*, *Candida*, *Mrakia*, and *Cephalotrichum*, accounting for 47.68%, 26.22%, 3.67%, 1.97%, 1.32%, 0.87%, 0.76%, 0.76%, 0.67%, and 0.58% of the total fungal abundance, respectively. *Tausonia* and *Coniochaeta* are important for soil organic matter decomposition [23], synthesizing key enzymes that decompose cellulose and accelerate the decomposition of lignocellulose [24]. This is beneficial to the mineralization of nutrients in the soil and the production of humus to improve soil structure.

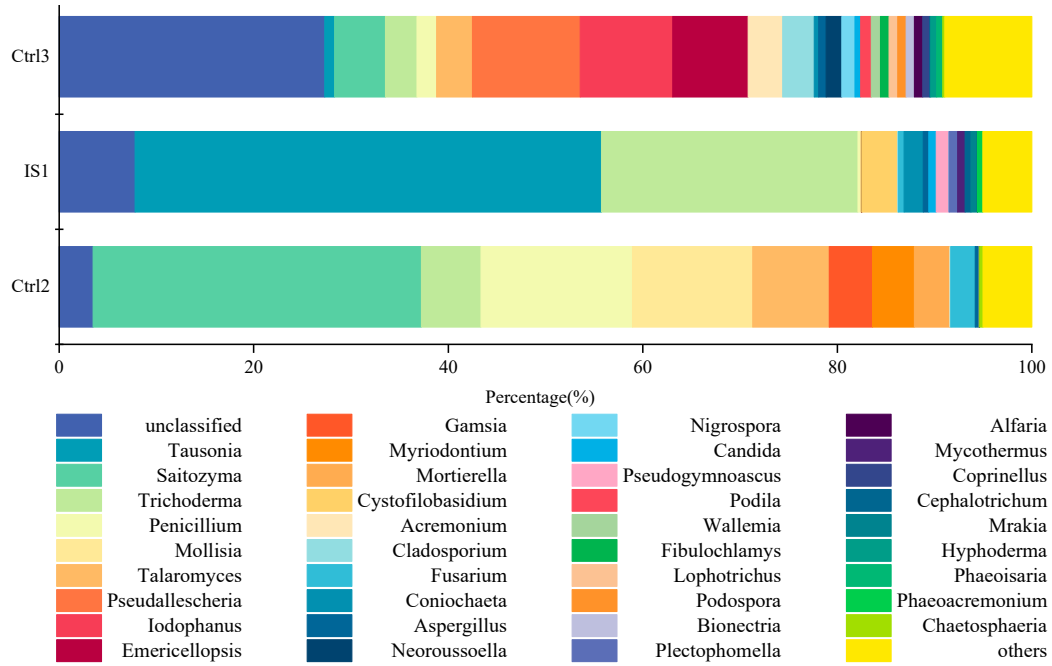

Figure 4. Relative abundance and composition of fungal community of different planting soils at the phylum level.

To further analyze the correlation between fungal communities and planting soil at the genus level, characteristics of fungal assemblages were compared across different treatments (Figure 5). Saitozyma exhibited high relative abundance in both Ctrl2 and Ctrl3

(33.76% and 5.23%, respectively). While it does not directly induce plant pathogenesis, it significantly influences soil nutrient transformation: decreased enzymatic activity associated with *Saitozyma* can result in reduced bioavailable nutrient content and diminished fungal diversity in soil [25]. In IS1, the relative abundance of *Saitozyma* decreased significantly compared to the controls to 0.02%.

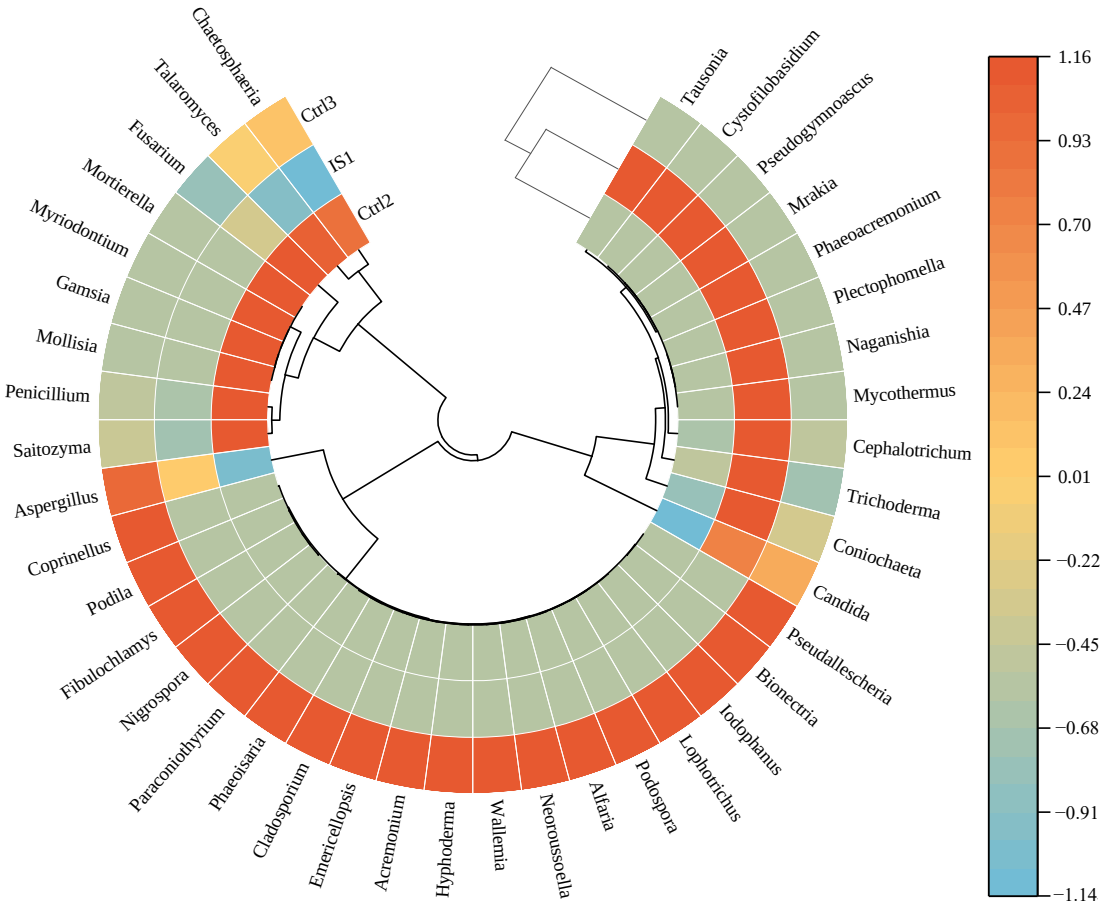

Figure 5. Community heatmap of planting soil and fungal at genus level.

Compared to the controls, IS1 demonstrated higher abundance of beneficial fungi, including *Trichoderma*, *Cystofilobasidium*, and *Plectophomella*. *Trichoderma* showed particularly high relative abundance (26.22%). *Trichoderma* is recognized as a common plant growth-promoting rhizobacterium that synthesizes phytohormones to enhance seed germination and plant development [26,27], suggesting their potential role in promoting the conversion positively correlated with available nitrogen. *Trichoderma* metabolites exhibit antagonistic effects against soil-borne pathogens and facilitate soil nutrient mobilization. *Cystofilobasidium* demonstrates antagonistic properties against yeasts and effectively suppresses postharvest diseases in various fruits, including sweet cherries and apples [28].

The heatmap in Figure 6 provides a visual representation of the correlations between various fungal genera and environmental factors. Genera including *Saitozyma*, *Penicillium*, and *Mollisia* were negatively correlated with pH, indicating their preference for acidic growth conditions. *Saitozyma* demonstrated significant negative correlations with EC and effective Mg, as well as with most available nutrient elements, such as nitrogen, phosphorus, and potassium. This observation aligns with previous findings showing that *Saitozyma* can lead to decreased enzyme activities related to nutrient transformation, resulting in reduced available nutrient content.

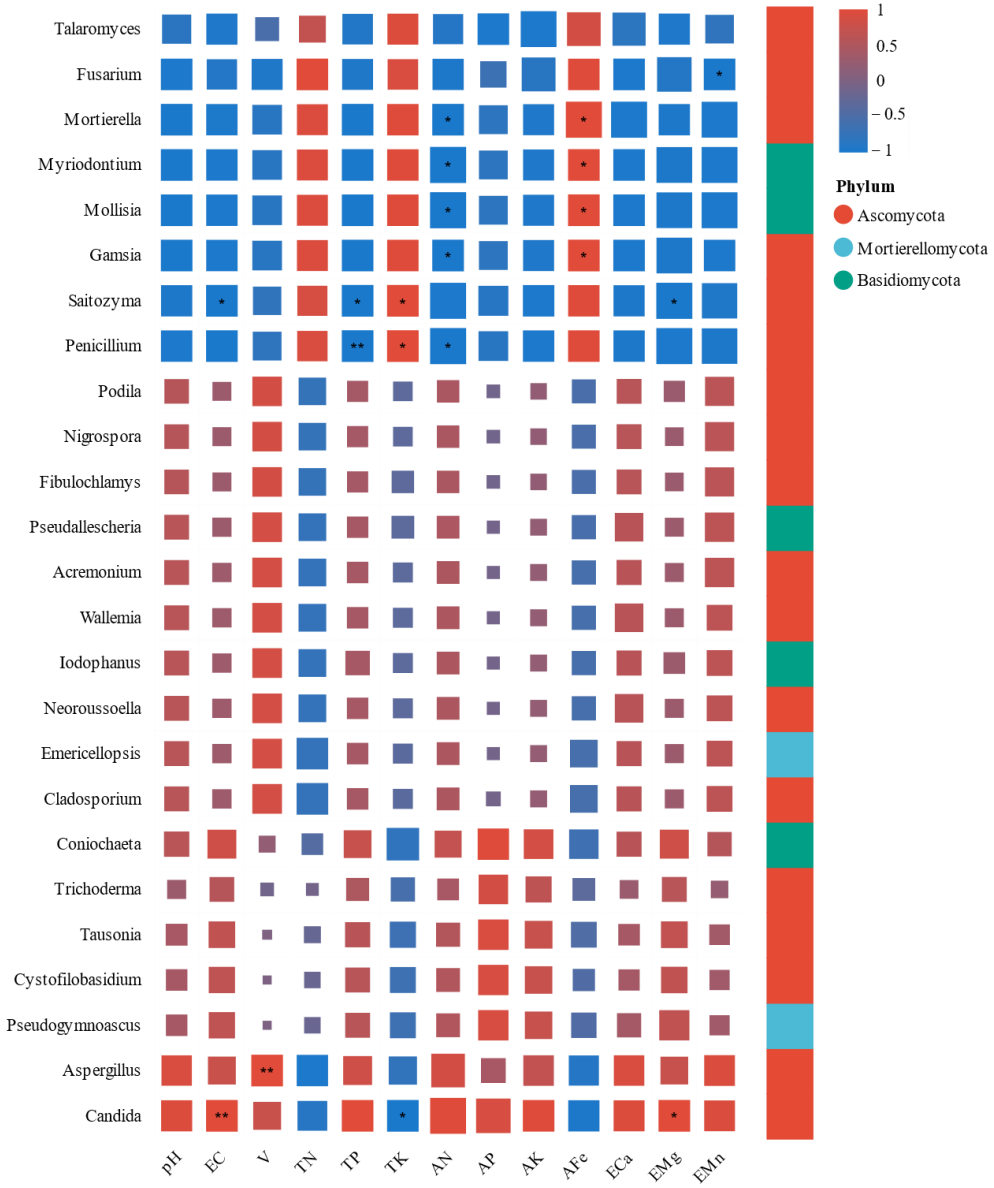

Figure 6. Heatmap of correlations between fungal genera and soil physicochemical properties. * $0.01 < p \leq 0.05$; ** $0.001 < p \leq 0.01$. The p indicates statistical significance, with smaller values representing stronger evidence of correlation.

Mollisia, *Gamsia*, *Myriodontium*, and *Mortierella* were significantly positively correlated with available iron. This may be attributable to their status as representative genera in Ctrl2 (eucalyptus topsoil), where available iron content was highest among all cultivation soils. *Tausonia*, *Trichoderma*, and *Cystofilobasidium* exhibited positive correlations with most soil physicochemical properties, particularly total and available nutrients. While these genera were negatively correlated with total nitrogen, they were positively correlated with available nitrogen, suggesting their potential role in promoting the conversion of total nitrogen to its more available forms. These three genera were also the most abundant fungal taxa in IS1.

The five most abundant fungal genera in the bubble plot of IS1 were *Tausonia*, *Trichoderma*, *Cystofilobasidium*, *Coniochaeta*, and *Pseudogymnoascus* (Figure 7). These genera were positively correlated with germination rate, average root length, and GI in all three seed species. This pattern suggests that these genera may facilitate seed germination and promote root development.

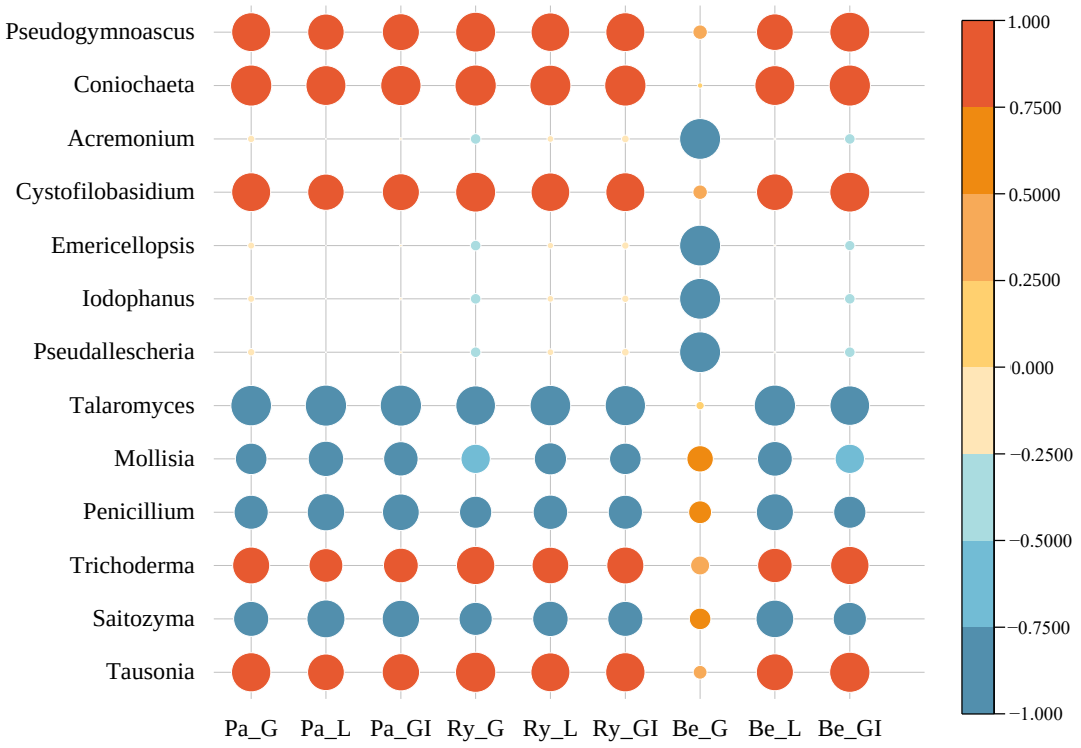

Figure 7. Bubble plot of fungal genus-level correlation with seed germination parameters. The size of bubbles is proportional to the absolute value of correlations. The genera were selected from the five most abundant taxa in the IS1, Ctrl2, and Ctrl3 groups. Pa_G: Germination rate of pak choi; Pa_L: average root length of pak choi; Pa_GI: germination index of pak choi; Ry_G: germination rate of ryegrass; Ry_L: average root length of ryegrass; Ry_GI: germination index of ryegrass; Be_G: germination rate of bermudagrass; Be_L: average root length of bermudagrass; Be_GI: germination index of bermudagrass.

Overall, the improved planting soil IS1 demonstrated a significant increase in fungal abundance compared to the unimproved Ctrl3. Compared to both Ctrl2 and Ctrl3, IS1 showed a substantial increase in beneficial soil microorganisms. The dominant fungal genera in IS1 were positively correlated with both total and available nutrient content, as well as with seed germination parameters, indicating that it was conducive to plant growth.

4. Conclusions

This study used eucalyptus topsoil, dredged sludge, and pig manure compost to convert dredged sludge into planting soil. Seed germination experiments were conducted, and soil heavy metals, main control indicators and nutrients, and soil microbial diversity were analyzed. The content of heavy metals in the improved planting soil was low, indicating that they would not cause toxicity to the environment. Compared with eucalyptus topsoil and dredged sludge, the improved soil had a more neutral pH and richer effective nutrients. In the seed germination test, the germination rate and average root length of pak choi in the planting soil of each experimental group were significantly better than that in the control groups Ctrl2 and Ctrl3. Examining these parameters, IS1 was found to be the most suitable for plant growth.

The dominant fungal genera in planting soil IS1 were *Tausonia*, *Trichoderma*, and *Cystofilobasidium*. *Tausonia* plays an important role in the decomposition of organic matter, and together with *Trichoderma*, promotes the activation of soil nutrients through metabolism. *Trichoderma* and *Cystofilobasidium* can antagonize pathogenic bacteria, reduce the concentration of pathogenic bacteria in the soil, and benefit plant growth [29].

The results of this study show that improving dredged sludge into planting soil is a good method to accomplish its resource utilization and reduction. However, it is still necessary to further explore the mechanism of different fungi promoting plant growth at the microscopic level, as well as to study the effect of improved dredged sludge soil on plant growth over a longer period.

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