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ORIGINAL RESEARCH ARTICLE

Development of a municipal sludge-based water-retaining material for soil improvement and plant growth

Yanfeng He[1], Qiao Li[1], Jiuxian Yang[1], Wenyou Wu[1], Jiyuan Jin[1], Yipeng Wang[1], and Dongdong Ge[2,3]*

[1]Powerchina Chengdu Engineering Corporation Limited, Chengdu, Sichuan, China
[2]School of Resources and Environmental Engineering, Jiangsu University of Technology, Changzhou, Jiangsu, China
[3]Shanghai Engineering Research Center of Solid Waste Treatment and Resource Recovery, School of Environmental Science and Engineering, Shanghai Jiao Tong University, Shanghai, China
***Corresponding author:** Dongdong Ge (ddge1118@sjtu.edu.cn)

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Abstract: Crop production is threatened by both water scarcity and poor soil water retention in arid or semi-arid regions. At the same time, the industrial-scale accumulation of municipal sludge creates substantial environmental and resource pressures. The goal of this work was to recycle municipal sludge into a low-cost, environmentally friendly, and multifunctional sludge-based water-retaining material (SBWRM) for enhancing soil water retention capacity and nutritional status. Sludge was used as the primary raw material, and extracellular polymeric substances were extracted using a combined alkaline ultrasonic method. These extracts were then mixed with polyvinyl alcohol to prepare the sludge-based material. The water retention capacity of the material, as well as its effects on seed germination and plant growth in a planting substrate, were systematically evaluated. The results suggested that the SBWRM achieved a maximum water retention capacity of 18.7 times its own weight. The addition of 40% SBWRM effectively promoted ryegrass seed germination and plant height, increased soil moisture and pH value, and enhanced the nutrient contents of nitrogen, phosphorus, and potassium. The findings indicate that SBWRM can effectively enhance water conservation, soil quality, and nutrient supply, thereby providing a practical approach for utilizing sludge resources and supporting ecological restoration in agricultural systems.

Keywords: Sludge-based water-retaining material; Extracellular polymeric substances; Soil improvement; Plant growth; Water retention

1. Introduction

With the current global climate crisis and the rapid depletion of freshwater resources, there is unprecedented pressure on global agroecosystems. Over one-third of the world's land surface is currently experiencing varying degrees of drought stress,[1] while agriculture still accounts for more than 70% of global water usage.[2,3] Despite having one of the largest water resources in the world, China's per capita water availability is only a quarter of the global average. Additionally, the spatial distribution and seasonal variation of water in China are highly uneven, with severe aridity and semi-aridity in the northwestern and northern regions.[4] With the development of modern agriculture in China, it is imperative to develop agricultural practices that are more water-efficient and have higher water retention efficiency.

Soil water-retention materials have garnered significant attention for their abilities to decrease the loss of water, retard evaporation, and enhance water use efficiency for crops.[5] Compared to irrigation actions based solely on engineering or agronomical manipulations, the application of such materials improves the soil's physical and chemical properties. The hydrophilic groups form a network that absorbs water, transforming it into hydrogels, which gradually release the retained water into the soil.[6] This inherent capacity is particularly advantageous in arid and semi-arid regions. Moreover, the increasing importance of sustainable agriculture and ecological environment protection in China has promoted new high-efficiency and eco-friendly water-retention materials.[7]

Water-retention products can be grouped into four categories: natural amendments, synthetic polymers, natural–synthetic copolymers, and biological amendments. However, each category exhibits its own set of shortcomings. Vermiculite, gypsum, and fly ash, which are natural inorganic materials, have been utilized due to their availability and low cost; however, their water content retention value is insufficient. Natural organic materials, such as peat and lignin, exhibit moderate water retention capacity and rapid decomposition characteristics, which limit their longevity in use. In contrast, certain synthetic polymer materials, including polyacrylate and polyurethane hydrogels, possess specific mechanical and functional properties. However, they lack bioactivity and can endanger the environment and soil fertility as chemicals accumulate.[8]

Meanwhile, the rapid development of urban wastewater treatment needs in China resulted in a steady growth in sewage sludge generation. As of 2023, the amount of dry sludge in China has exceeded 1.505×10^7 tons.[9] Inadequate sludge treatment occupies a significant amount of land, which not only poses risks of heavy metal pollution and microorganism transmission but also fails to fully utilize these resource materials when recycled.[10] Therefore, achieving stabilization (through anaerobic digestion),[11] volume reduction (coagulation dewatering),[12] harmless treatment, and high-value utilization of sludge has become an urgent environmental and resource-management challenge. Consequently, it is an urgent environmental protection and resource development issue to achieve sludge reduction and recycling with high added value. Municipal sludge is highly organic (usually surpassing 50% of the dry matter) and contains essential elements such as nitrogen, phosphorus, and potassium for plants.[13] It is also worth noting that extracellular polymeric substances (EPS) are present in sludge at high concentrations and play a crucial role in the water-absorption/retention capabilities of sludge. EPS are mainly composed of proteins, polysaccharides, and humic substances, which are inherently hydrophilic macromolecules that have been shown to significantly enhance soil aggregation[14,15] and nutrient-release dynamics. Moreover, sludge applications in soil have previously been shown to improve phosphorus availability, adjust the soil pH, and enhance biodiversity.[16]

Notably, sludge-based materials containing EPS extracted from municipal sludge could help overcome the limitations associated with synthetic hydrogels, including poor biodegradation, high production costs, and environmental issues,[17] in addition to promoting the circular utilization of organic solid waste. Materials derived from sludge may also have the advantages of soil improvement and nutrient supplementation over conventional products. Recent progress in the EPS extraction and modification technologies, such as alkaline treatment, ultrasonic disruption, thermal hydrolysis, and hydro-thermal reaction, has greatly enhanced the extraction efficiency.[18] Under optimized conditions, high-yield and high-efficiency EPS recovery from sludge can be commonly achieved at relatively low energy consumption and cost, providing technical support for developing a novel type of efficient water-retention agent using sludge. In addition, adding environmentally friendly stabilizing agents (e.g., polyvinyl alcohol) may effectively improve the structural stability of the materials[19] and expand their practical applications in planting substrates, ecological restoration, and desertification control.

Therefore, in this work, we aim to efficiently extract EPS from municipal sludge, prepare sludge-based water-retention materials, and study them as additives in planting substrates. First, to determine the treatment parameters that maximize EPS yield (such as proteins and polysaccharides), different extraction processes were explored. Second, the recovered EPS were flocculated and stabilized using polyvinyl alcohol to form sludge-based water-retention materials. Scanning electron microscopy and Fourier transform infrared (IR) spectroscopy were used to examine the microstructure and chemical composition of the material. Third, the water retention capacity of the material was determined, and the effects of the planting substrate on plant growth and soil physicochemical properties were investigated. The sludge-based water-retaining material (SBWRM) developed in this study, with its green, low-cost, and multifunctional characteristics, may offer theoretical support and technical demonstration for the development of new water-retaining agents, as well as contribute to the high-value utilization of sludge resources. Furthermore, this study holds significant scientific and socioeconomic importance for agricultural production, water conservation, soil preservation, and ecological restoration in arid and semi-arid regions.

2. Materials and methods

2.1. Materials

The experimental sludge used in this study was collected from the return sludge of the secondary sedimentation tank at a wastewater treatment plant located in Linzhi, Xizang, which operates a typical three-stage anaerobic–anoxic–aerobic biological process. During sampling, the sludge was passed through a 1.0 mm sieve to remove large particles and immediately dewatered using a centrifuge (3,000 rpm, 10 min) to a moisture content of approximately 90%. Samples were stored at 0–4°C before use. At the time of sampling for the experiments, the sludge had an initial moisture content of 91.1% and a pH of 5.7. The soil used for the plant growth experiment was collected from a slope in Xizang, and its details are presented in Table 1.

The main chemical reagents included sodium hydroxide (Chengdu Clone Chemical Co., Ltd., China), polyvinyl alcohol (Aladdin Industrial Co., Ltd., China), and hydrogen peroxide (Chengdu Clone Chemical Co., Ltd., China).

2.2. Treatment processes for EPS extraction

To determine the optimal EPS extraction method, four processes were tested: heat treatment (HT), alkaline HT (ATT), ultrasonication treatment (UT), and alkaline UT (AUT). The extraction efficiency was evaluated using the soluble chemical oxygen demand (SCOD) concentration as the main indicator. For the HT, a sludge slurry (100 mL; moisture content of 98%; pH 7) was heated in a water bath at 80°C for 4 h, cooled to room temperature, and then centrifuged at 7,000 rpm for 10 min. The supernatant was collected as the EPS solution. For the AT, the sludge slurry pH was adjusted to 12, and the remaining steps were the same as in the HT. For the UT, sludge slurry at pH 7 was treated with continuous ultrasonication at 600 W for 2 h, followed by the same post-treatment as the HT. For the AUT, the sludge slurry at pH 9 was subjected to ultrasonication at 600 W for 2 h, with all other subsequent steps identical to those used for HT. A single-factor experimental design was applied to investigate the effects of sludge moisture content (96%, 97%, 98%, and 99%), pH (8, 9, 10, 11, and 12), treatment time (0.5, 1, 1.5, 2, and 2.5 h), and centrifugation speed (4,000, 6,000, 8,000, and 10,000 rpm) and time (5, 10, 15, and 20 min) on EPS extraction efficiency. All experiments were performed in triplicate.

2.3. Preparation of the SBWRM

Polyvinyl alcohol (35% of the suspended solids mass) was added to the extracted EPS solution, mixed for flocculation, and then centrifuged. The solid fraction was subsequently harvested. The solid material was piled at room temperature for stabilization and turned every 24 h. The material was then crushed after stabilization, sieved through a 60-mesh screen, and subsequently sprayed with a 3% (v/v) hydrogen peroxide solution (30 wt%) for deodorization and sterilization. It was dried under solar conditions for 7 days to obtain the SBWRM. All experiments were conducted 3 times.

2.4. Plant growth experiment

Five treatment groups were established with various SBWRM contents of 0%, 20%, 40%, 60%, and 80%. Pots (10 cm × 10 cm × 10 cm) were filled with 60 g of soil, and 5 g of ryegrass seeds were sown and covered with 0.5 cm of soil. After initial watering, irrigation was conducted every 3 days for 26 days. Germination time and seedling numbers were recorded daily, and plant height was measured at regular intervals. Once plants reached a stable growth stage, soil pH, nitrogen, phosphorus, potassium, electrical conductivity (EC), and moisture were measured using an SN-3001 soil parameter tester (Shandong Sane Electronics Co., Ltd., China) to evaluate the soil-improvement effects of the SBWRM. All experiments were performed in triplicate.

2.5. Analytical methods

The main experimental instruments involved a Model 85-2 constant-temperature magnetic stirrer (Changzhou

Table 1. Nutrient content and basic properties of the slope soil used in the plant growth experiment

Item	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	pH	Electrical conductivity (μS/cm)	Moisture content (%)
Slope soil	23.6	100.2	93.5	5.9	297	31.3

Guohua Electric Appliance Co., Ltd., China), an HH-8 water bath (Changzhou Ronghua Instrument Manufacturing Co., Ltd., China), a JY98-IIIDN ultrasonic cell disruptor (Ningbo Licheng Instrument Co., Ltd., China), a 6B-80 water quality rapid tester and a 6B-12 intelligent digester (Jiangsu Skyray Instrument Co., Ltd., China), and a PHS-25 pH meter (Shanghai INESA Scientific Instrument Co., Ltd., China).

SCOD was determined using the potassium dichromate method (GB 11914-89, Ministry of Ecology and Environment, China).[20] The pH was analyzed directly with a calibrated pH meter. Protein content was quantified using the Coomassie brilliant blue G-250 method,[21] and polysaccharide content was determined using the anthrone colorimetric method.[22] Chemical structures were analyzed using the Nicolet IR 200 Fourier transform IR spectrometer (Thermo Fisher Scientific, United States), and microstructural morphology was examined using a Sigma-500 scanning electron microscope with energy-dispersive spectroscopy (Bruker-AXS, Germany).

The water retention capacity was determined using the following method. First, 10 g of the dry sample was weighed and placed in a beaker. Subsequently, sufficient distilled water was added to the sample to achieve a semi-gel state. The sample was then screened through a 100-hole sieve to remove residual water and left to stand for 20 min. Finally, the mass of the gel after water absorption was weighed. The water retention capacity was calculated according to Equation (1):

$$\text{Water retention capacity} = (M_1 – M_0)/M_0 \quad (1)$$

Where M_1 is the mass of the gel after water absorption, and M_0 is the mass of the dry gel.

3. Results and discussion

3.1. Comparative analysis of different sludge SCOD extraction processes

SCOD indicates the concentration of soluble organic matter.[23] The higher the SCOD concentration, the more organic matter will be stabilized and converted into stable organic components rich in hydrophilic groups, which is beneficial for soil improvement and plant growth. As shown in Figure 1A, the raw sludge SCOD was 7,437 mg/L, indicating that the content of dissolved organic matter was limited without pretreatment. It was evident that UT alone led to an increase in SCOD concentration to 16,080 mg/L, which appears to be 2.16 times the value for the raw sludge, demonstrating that cavitation served to break down sludge particle agglomeration and release intracellular organic matter. The SCOD concentration for AUT was further increased to 25,334 mg/L, which appears to be 3.41 times higher than that of the raw sludge, indicating that alkaline conditions boosted the saponification and dissolution of sludge cell walls,[24] thereby improving the efficiency of ultrasonic sludge disintegration. The SCOD concentration of the HT sludge was 14,035 mg/L, which was higher than that of raw sludge but lower than that of UT sludge, possibly due to condensation or charring of some organics during thermal degradation, thereby restricting the formation of soluble organics. Notably, ATT exhibited a lower SCOD concentration than HT alone, possibly due to some thermal reaction products precipitating or transforming under alkaline conditions, restraining the accumulation of soluble organic matter. These results suggest that the combinatory effect of physical cavitation and chemical alkali solubilization can enhance sludge disintegration for improving organic matter solubilisation.[25]

3.2. Effects of AUT process parameters on sludge SCOD

Sludge moisture content, pH value, and ultrasonic time can influence SCOD. As illustrated in Figure 1B, the SCOD concentration significantly increased from 21,699 mg/L to 26,223 mg/L as the moisture content increased from 96% to 98%. Nonetheless, excessive moisture of 99% only raised the concentration of SCOD to 24,231 mg/L. This result may be associated with low water content, which increases sludge viscosity and hinders the occurrence of sufficient ultrasonic cavitation,[25] or excessive water dilution that reduces soluble organic content, resulting in a decrease in SCOD. Figure 1C presents the variation of SCOD concentration with pH using the AUT. The optimal SCOD was 31,767 mg/L at pH 10, and it dropped markedly at higher pH levels (11 and 12). This may be attributed to the fact that the cell walls were damaged under a moderate alkaline environment, and excessively high pH could result in chemical degradation or side reactions, which are not conducive to producing SCOD. Additionally, ultrasonication time can influence the release of SCOD, as shown in Figure 1D. The SCOD concentration gradually increased as the sonication time was prolonged, with a sudden increment at 2 h, and the maximum value of 32,103 mg/L was reached at 2.5 h. Longer ultrasonic durations can lead to more disrupted cells and the solubilization of organic matter, although the increase in SCOD is reduced with releasable materials approaching saturation.[26]

Figure 2A illustrates the recovery rate of supernatant organic matter at various centrifuge speeds and times. In general, the recovery rate increased with higher centrifugation speeds and longer centrifugation times. At the same centrifugation time, recovery increased by approximately 2–7% when the speed was increased

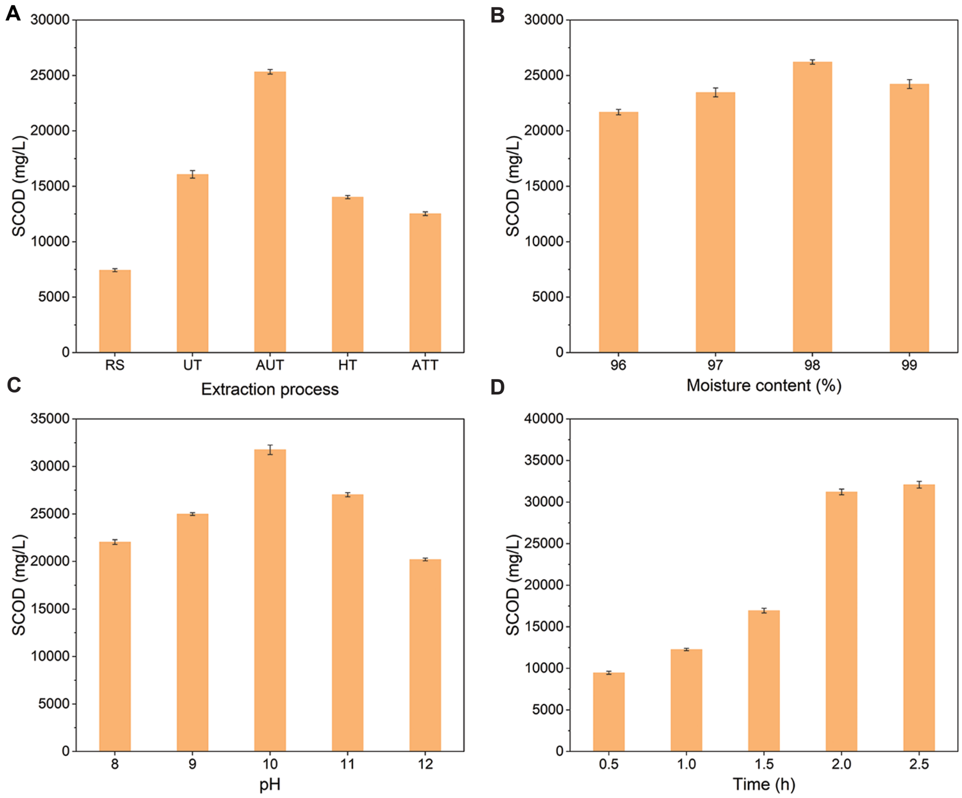

Figure 1. Effects of different treatment conditions on soluble chemical oxygen demand (SCOD). (A) Comparison of sludge extraction processes. (B) Effect of moisture content in the AUT process (pH of 9.0, 2 h. (C) Effect of pH in the AUT process (98% moisture content, 2 h). (D) Effect of ultrasonic time in the AUT process (pH of 10, 98% moisture content).

Abbreviations: ATT: Alkaline heat treatment; AUT: Alkaline ultrasonication treatment; HT: Heat treatment; RS: Raw sludge; UT: Ultrasonication treatment.

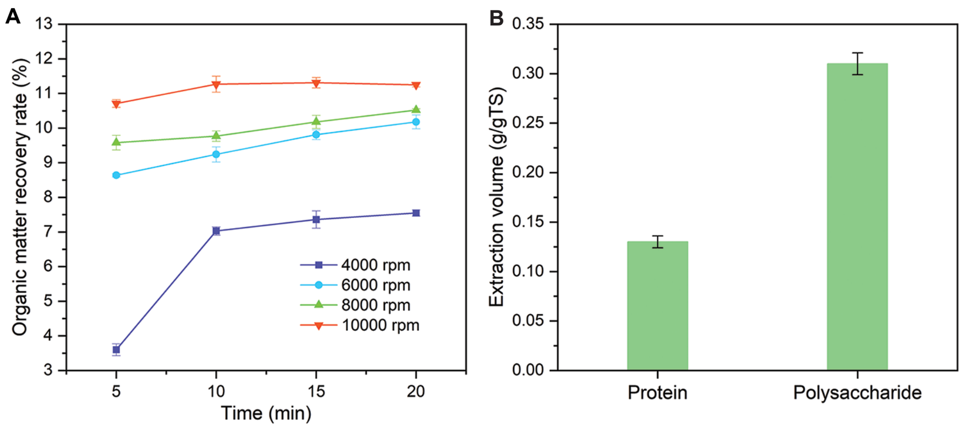

Figure 2. Extraction results of organic matter. Effects of (A) centrifugal speed and time on organic matter recovery rate, and (B) extraction volume of protein and polysaccharide from centrifugal solution under optimal process parameters.

Abbreviation: TS: Total solids.

from 4,000 to 10,000 rpm. At the same speed, a slight improvement in the effect was observed with prolonged centrifugation time, up to 20 min. The maximum recovery rate of 11.31% was achieved at 10,000 rpm for 15 min. Moreover, at optimal process conditions, the protein extraction amount was 0.13 g/g of total solids, with an extracted polysaccharide amount of 0.31 g/g of total solids (Figure 2B).

3.3. Characteristic analysis of the SBWRM

3.3.1. Comparison of water retention performance of sludge-based materials

As shown in Figure 3, the different sludge samples exhibited markedly different water absorption capacities. The raw sludge exhibited a water absorption ratio of only 4.1, which is relatively low in terms of water retention capacity. The extracted sludge material after the optimized AUT demonstrated a significantly higher water retention capacity of 14.5 g/g, compared to the raw sludge with an increase of around 3.54 times. The result indicates that the extraction process caused significant changes in the sludge structure and may have generated more porous structures and hydrophilic functional groups, thus improving the water absorption ability.[27] Moreover, the water retention capacity increased to 18.7 g/g when the sludge organic matter was combined with the polyvinyl alcohol additive in SBWRM. This implies that the porosity and hydrophilicity can be synergistically tuned by combined organic matter extraction and additive material compounding to achieve superior water retention. This can not only decrease irrigation frequency and water loss but also provide a high-value-added pathway for sludge utilization. In addition, as shown in Table 2, SBWRM contains extremely high nutrient concentrations, enabling it to provide an abundant nutrient supply during plant growth.

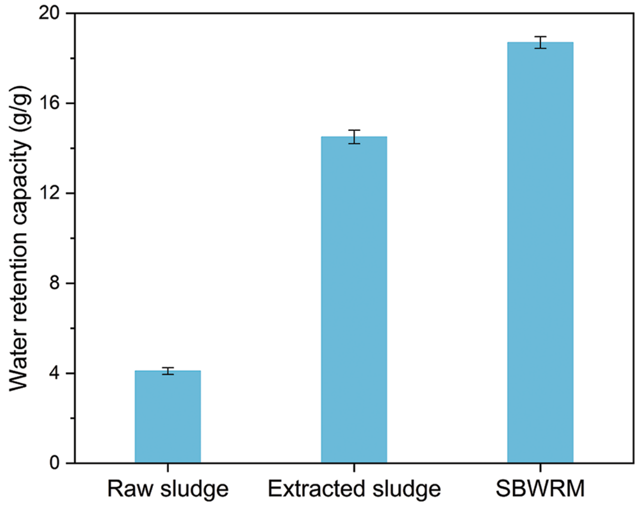

Figure 3. Water retention capacity of various sludge materials

Abbreviation: SBWRM: Sludge-based water-retaining material.

Table 2. Nutrient content of the sludge-based water-retaining material

Element	Content
Nitrogen (mg/kg)	463.5
Phosphorus (mg/kg)	1,243.8
Potassium (mg/kg)	1,385.7

3.3.2. Scanning electron microscopy analysis

The differences in the microstructure of the sample are visible in the scanning electron microscopy images (Figure 4). The sludge structure from the optimal EPS extraction process is relatively loose, consisting of aggregated blocks. In contrast, the structure of the prepared SBWRM is tight and highly stable, which is beneficial for enhancing the soil's long-term water retention capacity.

3.3.3. Fourier transform IR spectroscopy analysis

Fourier transform IR spectroscopy was used to further characterize the chemical functional groups in the different sludge samples. As depicted in Figure 5, the peak at 3,429 cm^{-1} corresponds to the stretching vibration of O-H, while the peaks at 2,923 cm^{-1} and 1,386 cm^{-1} are caused by the stretching and bending vibrations of C-H in lipids. The peak at 1,648 cm^{-1} represents the stretching vibration of C=O, while the peak at 1,543 cm^{-1} originates from the stretching vibration of C-N, indicating the presence of protein-like substances. The peak at 1,027 cm^{-1} is related to the C-O stretching of polysaccharide-like substances, while the peak at 695 cm^{-1} is associated with the out-of-plane bending of aromatic C-H.[28] Notably, the characteristic peak intensities of these hydrophilic groups in SBWRM were more pronounced, indicating a significantly higher water retention capacity in SBWRM.

3.4. Application of the SBWRM in plant growth

The practical application of SBWRM was further evaluated through a plant growth experiment. As depicted in Figure 6A, the influences of differing dosages of SBWRM on seed germination were significant. The 0% supplement group presented only three seeds that germinated by day 3, showing a low germination rate.

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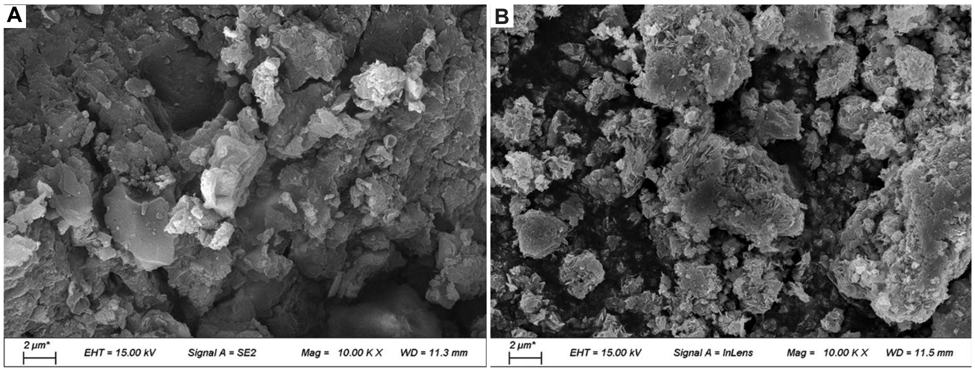

Figure 4. Scanning electron microscopy images. (A) Sludge extracellular polymeric substances and (B) the sludge-based water-retaining material. Scale bar: 2 µm; magnification: ×10,000.

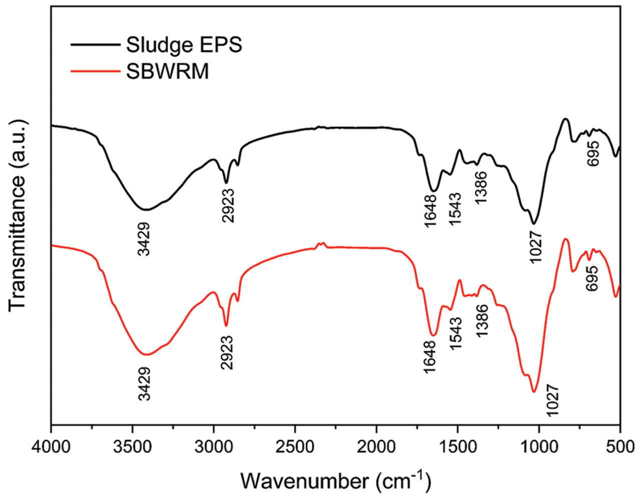

Figure 5. Fourier transform infrared spectra of sludge extracellular polymeric substances and the sludge-based water-retaining material

At SBWEM dosages of 20% and 40%, germination was significantly faster during the first period of the early stage (days 1–3) compared to the control. The 40% addition group achieved the highest germination rate, with nine sprouts, by day 7, after which it remained stable. The 60% addition group started germinating on day 2, and germination counts were much lower than those of the 20% and 40% addition groups. The 80% addition group was also characterized by inhibited germination, as only one seed germinated by day 5, which may be due to the decrease in substrate aeration and oxygen availability resulting from the excessive proportion of water-retaining material. In the meantime, as shown in Figure 6B, the changes in plant height generally corresponded to the germination results. The group with a dosage of 40% had the highest growth rate at all stages, reaching a height of 17.1 cm on day 25 and a maximum of 17.8 cm on day 27. The 20% addition group came second with the final height of 14.6 cm at day 27, while the 0% addition group only reached 13.5 cm. Both the 60% and 80% addition groups showed significantly reduced plant heights, demonstrating that an overdose of SBWRM inhibits plant growth. Hence, an appropriate amount of SBWRM can markedly promote seed germination and plant growth, with 40% identified as the optimal dosage that balances moisture retention and aeration.

3.5. Effects of the SBWRM on soil

3.5.1. Effects of the SBWRM on soil properties

According to Figure 7, the soil moisture content was significantly improved with a higher ratio of SBWRM. Upon application of a 20% addition, the soil moisture changed from a control value of 31.3% to 42.8%, representing a 36.7% increase. Increasing the addition up to 80% promoted the soil moisture content to 55.4%, confirming a remarkable water retention capacity when dosing SBWRM in soil. This is primarily due to the high content of organic matter and the porous structure of the SBWRM, which can adsorb and retain a significant amount of water, thereby suppressing evaporation and leaching losses and continuously supplying water to the soil under natural conditions.[29] The EC also increased after SBWRM application, reaching a maximum of 1,256 µS/cm with a 60% addition, and then decreasing slightly at an 80% addition. This trend is likely caused by ion leaching, nutrient loss, and salt accumulation. A moderate increase in EC can improve nutrient supply, but an excessive rise in EC may lead to salt stress. Excessive salinity has a negative impact on plant growth, and dosage optimization should be performed in field applications to mitigate this effect.[30,31]

The soil pH increased from neutral to slightly alkaline with a 20–60% addition, and this was likely caused by the neutralization of the alkaline materials

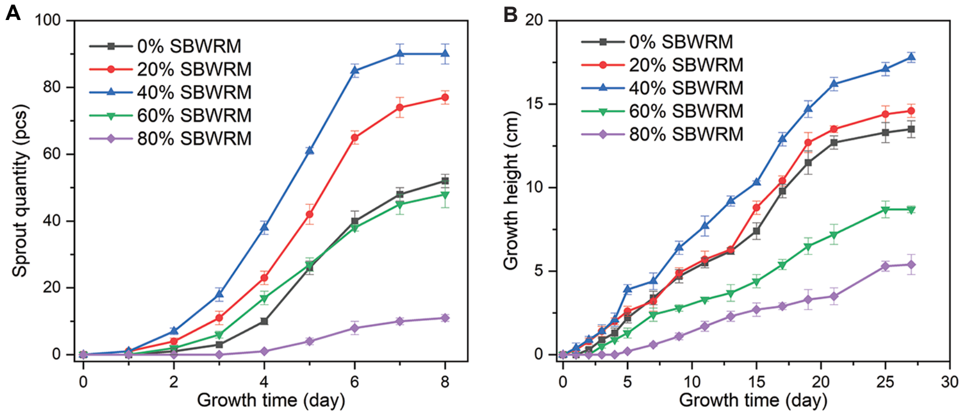

Figure 6. Effects of various sludge-based water-retaining material (SBWRM) additions. (A) Sprout quantity and (B) growth height.

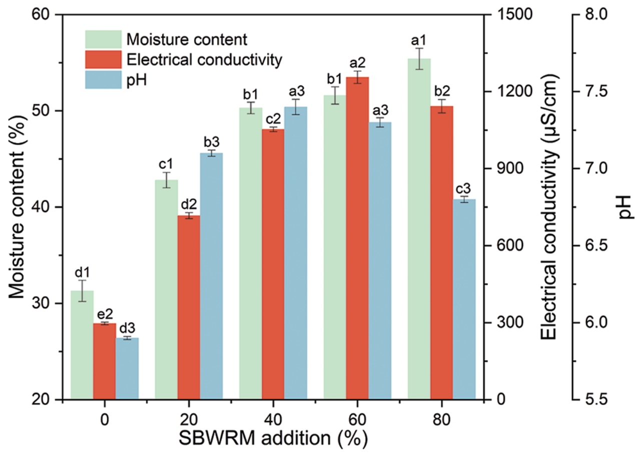

Figure 7. Effects of the sludge-based water-retaining material addition on soil moisture content, electrical conductivity, and pH

Notes: a1, b1, c1, and d1 represent the significant differences in the data on moisture content. The a2, b2, c2, d2, and e2 represent the significant differences in the data on electrical conductivity. The a3, b3, c3, and d3 represent the significant differences in data on pH. The numbers 1, 2, and 3 represent the various indexes of moisture content, electrical conductivity, and pH, respectively. Each set of data is labeled from high to low as a, b, c, d, and e, and if there is no significant difference between two data points, the same markers are used.

present in SBWRM. However, at 80% addition, soil pH reduced slightly to 6.86, which may be attributed to the production of acids from the degradation of organic matter or the accumulation of salts. It is hypothesized that SBWRM can effectively enhance soil water retention capacity and modify the soil pH to a suitable range for plant growth; however, its effect on EC suggests that the application dosage should be adjusted based on crop salt tolerance.

3.5.2. Effects of the SBWRM on soil nutrients

As shown in Figure 8, the addition of SBWRM greatly improved soil nitrogen, phosphorus, and potassium contents. The nitrogen content increased from 23 mg/kg in the control to 111 mg/kg at a 20% addition, then to 181 mg/kg and ultimately to 223 mg/kg at additions of 40% and 60%, respectively. However, the nitrogen content slightly declined to 200 mg/kg with an increasing proportion up to 80%. A similar trend was noted for phosphorus content, which increased from the initial 100 mg/kg to 563 mg/kg and 508 mg/kg at 60% and 80% additions, respectively. The potassium content also increased with the addition rate, peaking at 559 mg/kg with a 60% addition and then slightly decreasing to 504 mg/kg at an 80% addition. These findings suggest that SBWRM contributes to remarkable enhancements in soil nutrient balance. These findings could be attributed to the fact that the SBWRM contains abundant organic matter and valuable plant nutrients (nitrogen, phosphorus, and potassium), which were released into the soil slowly to increase nutrient availability. Additionally, the robust water retention strengthened soil moisture, thereby boosting microbial activity and nutrient mineralization, which further augmented the nutrient supply. Notably, excessive dosage caused a slightly lowered level of nutrients that may be indicative of poor matrix structure, restricting contact between the nutrients and the soil, and suppressing the activity of microorganisms.[32] Therefore, an appropriate amount of SBWRM can be used as a soil conditioner to promote plant growth by regularly providing nutrients and water to the plants.[33]

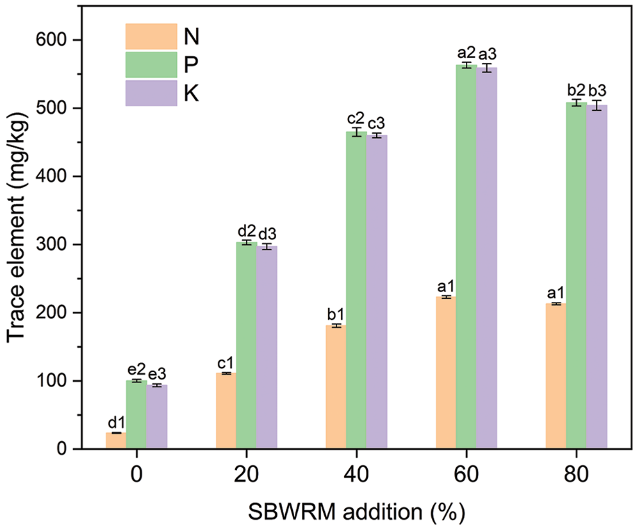

Figure 8. Effects of sludge-based water-retaining material (SBWRM) addition on the nitrogen (N), phosphorus (P), and potassium (K) soil content

Notes: a1, b1, c1, and d1 represent the significant differences in the data on N. The a2, b2, c2, d2, and e2 represent the significant differences in the data on P. The a3, b3, c3, d3, and e3 represent the significant differences in the data on K. The numbers 1, 2, and 3 represent the various indexes of N, P, and K, respectively. Each set of data is labeled from high to low as a, b, c, d, and e, and if there is no significant difference between two data points, the same markers are used.

3.6. Technological feasibility

In this study, organic matter was extracted from urban sludge and, after pretreatment and stabilization, was used as a water-retaining material for soil in arid areas. Our results verify that SBWRM can improve soil structure and nutrient supply, promoting plant germination and growth. The cost of SBWRM is calculated at 4,919 CNY/ton, which is significantly lower than that of common water-retaining materials (approximately 8,000 CNY/ton). In addition, SBWRM is rich in plant nutrients, including nitrogen, phosphorus, and potassium, with no secondary organic pollution. In practical applications, the preferred source of sludge water-retaining materials is urban sludge, which has a lower pollution potential. It is necessary to analyze soil EC, nutrient characteristics, ambient humidity, and temperature, and to verify that the properties of the amended soil meet relevant standards such as "Planting soil for greening" (CJ/T 340–2016).[34] The selection of locally adapted plant species is also recommended.

4. Conclusion

In this work, EPS were extracted from municipal sludge using an alkaline-ultrasonic synergistic method, and SBWRM was prepared with polyvinyl alcohol. The water retention capacity and its application to vegetative substrates were systematically evaluated. Breaking through the traditional sludge treatment paradigm, which is centered solely on pollutant removal, priority was given to the high-value conversion of nutrient-rich EPS components into multifunctional matrix materials. The results indicated that a 40% addition of SBWRM remarkably accelerated seed germination and plant growth, while also improving the soil moisture content, pH, and contents of nitrogen, phosphorus, and potassium, thereby achieving a synergistic effect that enhanced both soil environmental quality and nutrient supply. Compared to common natural or synthetic water-retaining agents, sludge-based materials have shown significant advantages in terms of cost, environmental friendliness, and multifunctionality, making SBWRM a green material for sustainable land management. This study demonstrates that sludge reutilization can help address the challenge of residual sludge disposal and serve as a viable strategy for developing green materials for agricultural production, ecological restoration, and soil–water conservation in arid and semi-arid areas. Future research should focus on field pilot experiments to explore the impact of different types of soil and natural environments on SBWRM, with the goal of validating both large-scale ecological security and economic feasibility. These explorations will accelerate the transition of SBWRM from laboratory innovation to real-world deployment.

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Conflict of interest

The authors declare that they have no competing interests. Six authors are employees of POWERCHINA Chengdu Engineering Corporation Limited, and one author is affiliated with academic institutions. No commercial or financial relationships influenced the conduct of this research.

Author contributions

Conceptualization: Dongdong Ge
Formal analysis: Yanfeng He, Jiuxian Yang
Investigation: Yanfeng He, Yipeng Wang, Dongdong Ge
Methodology: Qiao Li, Wenyou Wu
Writing–original draft: Yanfeng He, Jiyuan Jin, Yipeng Wang
Writing–review & editing: Qiao Li, Jiuxian Yang, Dongdong Ge

Availability of data

The data presented in this study are available from the corresponding author upon reasonable request.

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