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EFFECTS OF SLUDGE PELLET MULCH ON SOIL PHYSICOCHEMICAL PROPERTIES AND SOIL ENZYME ACTIVITIES

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Highlights:

- sludge pellet is appropriate for earth-friendly soil mulch;
- sludge pellet can significantly enhance soil moisture content, maintain soil temperature stability, increase soil organic matter and available nutrients, improve soil enzyme activity, and enhance soil quality;
- excessive thickness of sludge pellet mulch can increase soil bulk density and negatively impact the quality of soil;
- the recommended application rate for sludge pellet mulch in urban bare soil falls within the range of 9.6–28.8 kg/m^2.

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Abstract. The drinking-water treatment sludge (DWTS) possesses intricate characteristics, which restrict its broad applicability. To tackle this issue, we employed DWTS obtained from the Minhang District of Shanghai as the primary constituent, blending it with a low-alkaline curing material to produce pelletized mulch. This investigation primarily focuses on evaluating the environmental safety of sludge pellet mulch (SPM) and scrutinizing alterations in soil physicochemical properties at various mulch thicknesses. The outcomes affirm the durability of SPM and the compliance of eight heavy metals with prescribed standards concerning their concentration, pH, and EC values. After applying SPM, noteworthy enhancements were observed in soil moisture, organic matter content, available nutrients, and the activity of four enzymes. Furthermore, a reduction in soil temperature was observed. For urban landscape mulching, SPM within the range of 9.6–28.8 kg/m^2 emerged as the preferred choice, yielding the most favorable overall soil quality improvements.

Keywords: drinking-water treatment sludge, sludge pellet mulch, soil physicochemical properties, soil enzyme activities.

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1. Introduction

Mulching is recognized as an effective technique to enhance crop yield and product quality, commonly employed in the ecological revitalization of urban landscapes (Chakraborty et al., 2008; Chalker-Scott, 2007). Urban landscape mulches encompass three main categories: inorganic mulches (such as pebbles or gravel), organic mulches (including leaves, branches, or bark, either singly or in combination), and living mulches (such as herbs) (Ni et al., 2016). Both inorganic and organic mulches are cost-effective and widely accessible (Chalker-Scott, 2007; Ni et al., 2016). Inorganic mulches contribute to reducing soil water evaporation rates and elevating soil temperatures, thus indirectly fostering crop yield enhancement (Fairbourn, 1973). Organic and living mulches enrich the soil with nutrients, moderate soil temperatures, promote plant growth, and thereby augment yield and quality (Chalker-Scott, 2007; Koski & Jacobi, 2004; Sinkevičienė et al., 2009). However, each type of mulch also harbors certain limitations. Inorganic mulches have low nutrient content; for example, gravel mulching diminishes soil nutrient levels (Ni et al., 2016). Organic mulch is susceptible to dispersal during high-wind conditions and may pose fire hazards (Koski & Jacobi, 2004; Qu et al., 2018). In addition, living mulch frequently contends for water and nutrients, particularly in locales with comparatively high soil fertility (Ni et al., 2016). Each mulch type presents distinct attributes, and the selection of an appropriate mulching method hinges on local climate considerations and cost-effectiveness (Wang et al., 2015). In pursuit of economical solutions and enhanced soil environments, further investigation and the development of superior mulching approaches for urban landscape restoration are imperative.

In contrast to sewage sludge, drinking-water treatment sludge (DWTS) pertains to solid waste with elevated water content generated during the purification of drinking-water. Its components include suspended solids, clay, organic matter, and chemical agents, with variations contingent upon the water source (Ahmad et al., 2016). The escalating global population has driven an augmented demand for drinking-water, resulting in a surge in water treatment facilities and a substantial escalation in sludge production, a concern that cannot be overlooked (Zhao et al., 2021). Presently, China primarily employs sanitary landfilling and land use as the principal methods for sludge disposal (Lin et al., 2014; Yang et al., 2015). It raises concern that the landfill capacities in numerous Chinese cities, including Shanghai Laogang, Chengdu Chang'an, Shenzhen Xiaping, and Hangzhou Tianziling, among others–are alarmingly insufficient (T. L. Zhan et al., 2014; X.-J. Zhan et al., 2015). The pursuit of more ecologically sound and efficacious methods for sludge treatment holds paramount importance, both in terms of sludge reduction, transportation, and ultimate disposal.

In recent years, researchers have been dedicated to identifying environmentally friendly and sustainable methods for the disposal of sludge generated from drinking-water treatment. Due to its clean water source, drinking-water treatment sludge contains fewer harmful heavy metals and includes essential nutrients and trace elements crucial for plant growth. In sludge remediation, specific plant species play a dual role: efficiently absorbing heavy metals and enhancing production by assimilating trace and common elements in sludge (Antonkiewicz et al., 2019). This method not only reduces sludge disposal costs effectively but also fosters sludge restoration. In the realm of soil enhancement, promising scientific findings indicate that incorporating an appropriate quantity of DWTS can ameliorate soil physical attributes (Faisal et al., 2020; Oh et al., 2010), bolster soil fertility, and facilitate plant growth (Heil & Barbarick, 1989; Titshall & Hughes, 2005; Zhao et al., 2021). This transformation enables the conversion of waste into valuable resources. However, the broad implementation of this approach is hindered by the intricate nature of DWTS, characterized by its elevated moisture content and the challenges associated with pretreatment.

Sludge solidification effectively reduces sludge moisture content, enhances its strength and moldability, and facilitates the broader utilization of sludge resources. While research on traditional high-alkaline cementitious materials like cement and lime has achieved maturity, these materials entail high production energy consumption and significant pollution (Wan et al., 2022; Yuping et al., 2020). As a result, scholars worldwide have initiated efforts to diversify the selection of raw materials for Curing materials, employing varied combinations and formulations to develop agents suitable for distinct soil types (Yuping et al., 2020). In recent years, the utilization of red mud and phosphogypsum has emerged, representing green and low-alkaline alternatives for sludge conditioning and solidification (Yu et al., 2013; Zhang et al., 2014). This innovative approach not only contributes to sustainable development by repurposing industrial waste but also aligns with the principles of environmental preservation. Currently, the majority of pertinent research centers around conducting indoor sludge conditioning tests using one or more materials. The solidified sludge is predominantly incorporated into building materials, with less comprehensive exploration of its potential for soil improvement.

The creation of cost-effective, superior-grade mulch from DWTS for urban landscapes presents an innovative avenue for the repurposing of DWTS resources. This approach not only harnesses the potential of DWTS resource utilization but also addresses issues like wind dispersal and rain runoff, which can impact traditional mulch. In tandem, it enhances urban soil quality, curtails conventional mulch-induced dust pollution, and reinforces resistance to strong winds and rainstorms.

This study employed sludge sourced from drinking-water treatment in Shanghai's Minhang District, China, as the primary material. A novel low-alkaline environmental protection Curing material was introduced, and the resulting mixture was granulated using a disc granulator to mulch bare soil. This research explores the physicochemical properties of sludge pellet mulch (SPM) and assesses the impact of various mulch thicknesses on the Soil micro-environment, available nutrients, and soil enzyme activities. It scrutinizes the potential of using pellets derived from sludge generated in drinking-water treatment processes to enhance soil quality. Furthermore, it seeks to identify the optimal thickness for the SPM coverage, offering valuable insights into the landscape utilization of DWTS.

2. Materials and methods

2.1. Materials

The source of the drinking-water treatment sludge (DWTS) was the Minhang District Drinking-water Treatment Plant in Shanghai, which possessed a natural moisture content of 95.4%. The materials for sludge solidification were furnished by Xingsheng Road Building Materials Co., Ltd. in the Pudong New Area of Shanghai. These materials mainly included low-alkaline industrial waste granite powder, which is mainly composed of SiO_2, phosphogypsum, and low-alkali sulphoaluminate cement (L-SAC). The DWTS was physically combined with the curing material in a mass ratio of 3:2. Subsequently, the mixture was processed in a disc granulator, resulting in the formation of dust-free, grayish-white particles with diameters ranging from 6 to 9 mm. All the materials were finely ground and sized below 1.18 mm. Dry the sludge particle mulch (SPM) at 50 °C until a constant weight is achieved over 12 hours.

The soil for the pot experiment was sourced from the botanical garden of the Shanghai Institute of Technology. It is characterized as brown-yellow alkaline loam (pH = 8.21), with sand, silt, and clay proportions of 38%, 48%, and 14%, respectively. Prior to use, the soil undergoes screening through a 20.25 mm nylon sieve to eliminate stones and foreign matter.

Collect samples of the test soil and SPM for the measurement of fundamental physicochemical properties (Table 1). The bulk density of soil was determined using the methods described by Bao (2005), while the bulk density and water absorption rate of SPM were assessed using the methods described by GB/T 17431.2-2010 (General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China [AQSIQ] & Standardization Administration of China [SAC], 2010). For the examined soil and SPM, pH, EC, and nutrient content indicators were determined according to Bao's (2005) methods. The Ba, Be, Cd, Cr, Cu, Ni, Pb, and Zn contents in the tested soil and SPM were determined following the method specifications (HJ 781-2016) for *Solid waste – Determination of 22 metal elements – Inductively coupled plasma optical emission spectrometry* (Ministry of Environmental Protection of the People's Republic of China [MEP], 2016). As per specifications, the test soil and SPM underwent grinding and sieving through a 100-mesh sieve. Subsequently, the sample underwent digestion with a mixed acid of HNO_3, HCl, HF, and 30% H_2O_2 (9:2:3:1). The content of trace elements in the digestion solution was assessed using inductively coupled plasma optical emission spectrometry (ICP-AES). As the SPM is primarily composed of sludge, quality control measures during testing involved the use of the soil standard sample GBW07403(GSS-3), a blank sample, and a duplicate sample to adhere to standard requirements.

Table 1. The physicochemical properties of soil and SPM, along with threshold values settled by the quality of sludge intended for gardens or parks in China (GB/T 23486-2009)

Attributes	Soil	The sludge pellet mulch (SPM)	GB/T 23486-2009 [d]
Water Absorption Rate, % [a b]	–	35.67	–
Bulk Density, g/cm^3 [a b]	1.22	0.96	–
pH [a]	8.21	7.6	5.5~7.8
EC, mS/cm [a]	1.27	1.04	salt-sensitive plants: <1.0 salt-tolerant plants: <2.0
Soil organic matter (SOM), g/kg [a]	12.7	22.34	–
Total Phosphorus (TA), g/kg [a]	0.51	8.42	–
Total Potassium (TK), g/kg [a]	12.26	38.18	–
Total Nitrogen (TN), g/kg [a]	12.11	10.89	–
Available Phosphorus (AP), mg/kg [a]	20.09	411.29	–
Available Potassium (AK), mg/kg [a]	89.94	856.07	–
Available Nitrogen (AN), mg/kg [a]	15.68	22.5	–
Ba, mg/kg [c]	ND	350.25	–
Be, mg/kg [c]	ND	ND	–
Cd, mg/kg [c]	ND	ND	<20
Cr, mg/kg [c]	ND	59.26	<1000
Cu, mg/kg [c]	5.22	37.34	<1500
Ni, mg/kg [c]	ND	ND	<200
Pb, mg/kg [c]	ND	13.75	<1000
Zn, mg/kg [c]	46.71	134.42	<4000

Notes: Values are means of four samples and standard errors are presented in parentheses. [a] Various indicators were determined using the methods described by Bao (2005). [b] The bulk density and water absorption rate of SPM were determined using the methods described by GB/T 17431.2-2010 (AQSIQ & SAC, 2010). [c] Various indicators were determined using the methods described by HJ 781-2016 (MEP, 2016). [d] Each indicator adopts the limit values for neutral and alkaline soil (pH ≥ 6.5).

The potted plant chosen for the experiment was Zinnia elegans Jacq., a common plant utilized for landscaping purposes in Shanghai, China. The grass seeds were procured from Jiangsu Qianhua Baimei Seed Industry Co., Ltd.

2.2. Experimental design

A potted experiment was conducted to investigate variations in the soil physicochemical properties resulting from different covering treatments. The experimental design flowchart is depicted in Figure 1. A total of 60 flowerpots, each with a diameter of 35 cm and an inner height of 45 cm, were filled with 60 kg of soil. Zinnia elegans Jacq. was cultivated through sowing, with 15 seeds uniformly sown at a depth of 1 cm in the pot's soil. These pots were subsequently placed in the greenhouse of the Plant Garden at the Shanghai Institute of Technology for seedling cultivation. After Zinnia elegans Jacq. emerged, five plants displaying consistent growth were selected for further analysis.

On February 13, 2023, sludge particles were employed as cover materials for the pots. Covering depths were designated as F1 (1–3 cm), F2 (3–6 cm), and F3 (6–9 cm). Pots without any coverings served as the control group, labeled as CK. The experiment encompassed a total of sixty sets of pots, with each treatment repeated fifteen times to achieve four treatment groups. Pots for each treatment were randomly positioned on the greenhouse seedbed and were watered once weekly with a volume of 1 L.

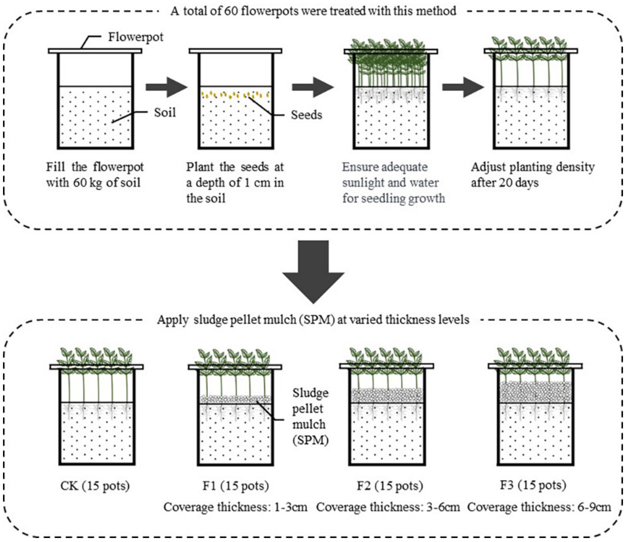


Figure 1. The experimental design flowchart

2.3. Soil sampling

Starting on February 15, 2023, every 30 days, three pots were randomly selected from each treatment group to assess the various physicochemical properties of the soils. Before sampling, both SPM and undecomposed debris were removed from the surface of the soil. Initially, soil temperature was gauged by inserting the instrument probe to a depth of 20 cm at the soil's center. Following this, the soil bulk density was measured using a ring cutter at a depth of 0–30 cm. Each pot was subjected to three repetitions. Subsequently, soil samples were obtained from the 0–30 cm depth utilizing the composite sampling technique.

The soil samples were separated into two parts. One part was stored within a constant temperature chamber at 4 °C to assess the enzyme activity of catalase (CAT), urease (Ure), alkaline phosphatase (ALP), and sucrase (Suc). The other part underwent grinding post-natural air drying for assessing diverse soil physicochemical indicators. These included soil water content (SWC), electrical conductivity (EC), pH, soil organic matter (SOM), alkaline nitrogen (AN), available potassium (AK), and available phosphorus (AP). The experiment consisted of three replicates for each group. Sampling was conducted from March 2023 to July 2023 to assess the changes in soil properties under different cover treatments.

2.4. Soil physicochemical analysis

All methods used for determining the soil physicochemical properties have previously been described in detail in Bao (2005). The soil underwent sieving through a 20.00 mm nylon sieve to eliminate impurities before measuring electrical conductivity (EC) and pH. The soil temperature (ST) was measured with an electronic geothermometer (Shanghai Siwei Instrument Manufacturing Co., Ltd., Shanghai, China) Briefly, soil water content (SWC) was assessed by oven drying to constant mass at 105 °C. Soil bulk density (SBD) was measured using the ring cutting method. Soil samples for assessing soil organic matter (SOM), alkaline nitrogen (AN), available potassium (AK), and available phosphorus (AP) must undergo sieving through a 0.149 mm nylon sieve. Soil organic matter (SOM) was measured using exothermic heating and oxidation with the potassium dichromate method. Alkaline nitrogen (AN) content was determined using the Kjeldahl method. Available phosphorus (AP) content was determined using the molybdenum antimony anti-colorimetric method. Available potassium (AK) content was measured using the flame photometer colorimetric method.

Soil enzyme activities were assayed according to detailed methods described by Guan (1986). The activity of urease (Ure) was assessed using the indophenol blue colorimetric method. The activity of alkaline phosphatase (ALP) was evaluated using the phosphorane diphenyl sodium colorimetric method, with a buffer solution pH of 11. The activity of catalase (CAT) was determined by employing the potassium permanganate titration method. The activity of sucrase (Suc) was determined using the 3,5-dinitrosalicylic acid colorimetric method.

2.5. Statistical analysis

All data were analyzed using SPSS 20.0 and Origin 2018. The effects of SPM on soil physicochemical properties and soil enzyme activities were assessed with one-way ANOVA by Fisher's least significant difference test (LSD) on SPSS 20.0, with a probability defined at 0.05.

Using Origin 2018 for correlation analysis and principal component analysis. Pearson correlation analysis was used to estimate relations between soil physicochemical properties and soil enzyme activities. Principal component analysis (PCA) was applied for using data of soil physicochemical properties and enzyme activities, to identify the important indicators for soil quality.

3. Results

3.1. Basic properties of SPM

At present, China has not established requirements for mulch and the relevant utilization of DWTS. Consequently, the safety assessment of SPM is conducted by referencing the GB/T 23486-2009 (AQSIQ & SAC, 2009) standard concerning the quality of sludge intended for gardens or parks (Table 1). This assessment aims to determine the suitability of these products for urban landscaping.

The assessment of sludge quality for application in gardens or parks, as outlined in GB/T 23486-2009, establishes key parameters (AQSIQ & SAC, 2009). These parameters indicate that an optimal pH range of 5.5 to 7.8 is conducive to plant growth in alkaline soil. It is advised that the electrical conductivity (EC) of the soil around the roots of salt-sensitive plants remains below 1.0 mS/cm. For salt-tolerant plants, this threshold can be extended to a maximum of 2.0 mS/cm. In the context of this standard, the pH and EC values of the SPM were measured at 7.6 and 0.98 mS/cm, respectively, meeting the stipulated criteria. Furthermore, the organic matter content in SPM is 22.34%, notably below the specified standard (organic matter index ≥ 25), indicating a disadvantage.

Although SPM offers less organic matter to the soil compared to sewage sludge, it exhibits advantages in terms of safety. This concern is particularly noteworthy when employing it as a surface mulch for urban bare soil. The primary constituent of SPM, known as DWTS, is typically devoid of harmful elements due to several factors, including the utilization of a relatively clean water source, disinfection during the water treatment process, and prolonged sludge storage in dedicated tanks. This characteristic sets it apart from sewage sludge (Dassanayake et al., 2015). Notably, previous studies have failed to identify toxicity to plants in the DWTS when utilized in soil (Ippolito et al., 1999; Xie et al., 2013). The introduction of a Curing material results in a modification of the initial material composition of DWTS. Upon comparison, the concentrations of hazardous heavy metals present in SPM were found to be beneath established standard thresholds, with no detectable levels of Be, Cd, and Ni. The presence of harmful heavy metals in SPM poses a reduced risk to terrestrial soil, rendering its application to the soil surface viable.

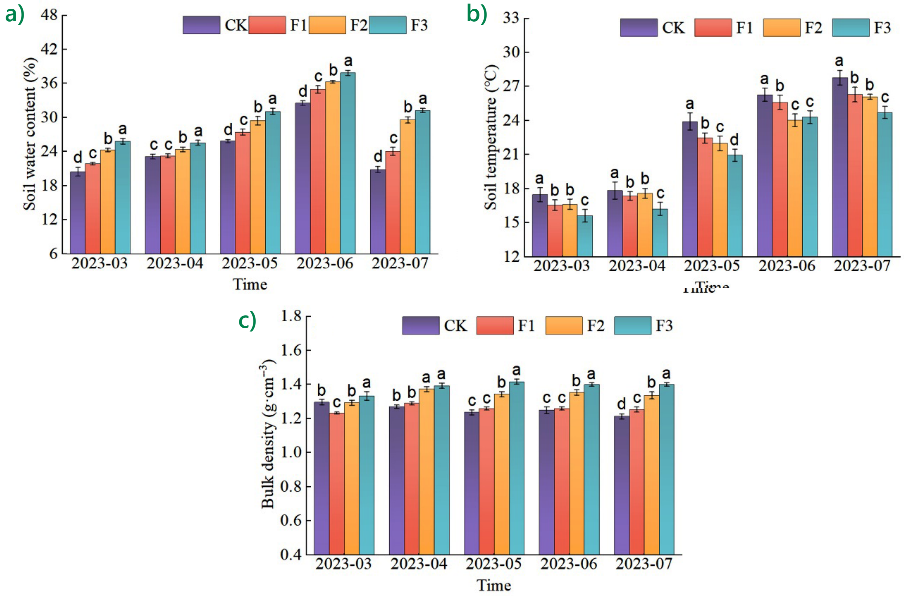
Table 1 presents the characteristics of SPM. Notably, the inclusion of a solidification agent results in a robust structure that resists damage, ensuring stability during transportation and utilization. The SPM exhibits a bulk density of 0.96 g/cm^3, rendering them lighter than conventional gravel and cobble coverings with densities ranging from 1.50 to 1.70 g/cm^3. It is noteworthy that SPM surpasses gravel and cobble in nutrient richness. This substantial nutrient content underscores the potential of SPM to enhance soil quality.

3.2. Effects of different mulch thicknesses on soil physical properties: moisture content, temperature, and soil bulk density

The dynamic changes of soil physical properties for three types of mulch thickness from March to July 2023 are shown in Figure 2. Except for April 2023, the soil water content (SWC) in treatment groups was consistently higher than CK, after SPM mulching (Figure 2a). The divergence among these treatments was most pronounced in July 2023. Notably, the soil water content of the F3 treatment increased by 10.39% when compared to the CK treatment. The elevated July temperatures in Shanghai led to an acceleration in soil evaporation. Consequently, the influence of SPM on soil water preservation became more conspicuous. For a comprehensive overview of soil physical property indices for each mulching treatment between March and July 2023, please refer to Table 2. Examining the period from March to July 2023, the average soil water content across treatments follows this order: F3 > F2 > F1 > CK. Furthermore, the soil water content of the F3, F2, and F1 treatments increased by 23.36%, 17.26%, and 7.12% respectively in comparison to the CK treatment. This underscores the affirmative role of SPM mulching in enhancing soil water content. Additionally, it is noteworthy that the water retention efficacy is most pronounced when the covering layer's thickness ranges from 6 to 9 cm.

In various temporal segments, the soil temperature (ST) associated with the SPM treatment consistently remained lower than that observed in CK. Furthermore, across all periods, F3 consistently exhibited significantly lower temperatures compared to the other treatment groups. Notably, a notable temperature discrepancy was observed between F3 and CK in each period (Figure 2b). The mean soil temperature for the period spanning March to July 2023 was as follows: CK > F1 >F2 > F3 (Table 2). These results underscore the efficacy of SPM in inducing a noteworthy reduction in soil temperature. Particularly, optimal effects are achieved when the protective covering layer attains a thickness ranging from 6 to 9 cm.

In different periods, the soil bulk density (SBD) of F2 and F3 was higher than that of CK, and there was a significant difference with CK (Figure 2c). F1 only had a significant difference with CK in March 2023 and July 2023. From March to July 2023, the average soil bulk density of each treatment showed as follows: F3 > F2 > F1 = CK, there was no significant difference between the soil bulk density of F1 and CK, and the soil bulk density of F2 and F3 treatments increased by 11.2% and 7.2% respectively compared with CK, with a small increase (Table 2). This indicates that mulching with SPM will increase the soil bulk density, which may be because the SPM are not light materials, and covering too thick easily exerts gravity on the soil surface, making the soil compact and increasing the soil bulk density.



Note: Different lowercase letters indicate significant differences among different treatments at 0.05 level, the same below.

Figure 2. The dynamic changes of soil physical properties under three types of mulch thickness treatments

Table 2. The average soil physical properties values for three types of mulch thickness from March to July 2023

Treatment	Soil water content (SWC), %	Soil temperature (ST), °C	Soil bulk density (SBD), g/cm^3
CK	24.57±0.11d	22.66±0.17a	1.25±0.04c
F1 (1–3 cm)	26.32±0.09c	21.66±0.10b	1.26±0.03c
F2 (3–6 cm)	28.81±0.27b	21.26±0.23b	1.34±0.07b
F3 (6–9 cm)	30.31±0.17a	20.37±0.15c	1.39±0.06a

Note: Values with different letters in the same column indicate significant differences between treatments ($p < 0.05$, $n = 3$). Data are means ± standard deviation.

3.3. Effects of different mulch thicknesses on soil available nutrients

The dynamic changes of soil available nutrient for three types of mulch thickness from March to July 2023 is shown in Figure 3. Throughout these periods, the soil available nutrient concentration in the SPM treatment consistently exceeded that of the CK treatment. Additionally, varied degrees of improvement were seen in the content of soil organic matter (SOM), alkaline nitrogen (AN), available potassium (AK), and available phosphorus (AP). The soil organic matter content in F1, F2, and F3 soils showed an early increase followed by stabilization from March to July 2023, while the alkaline nitrogen content showed an ongoing increase. For each treatment, the available potassium and available phosphorus patterns were particularly complex. Specifically, the available potassium content in F1, F2, and F3 soils decreased from March to April before increasing from April to June. In July, the available potassium content within F2 and F3 soils mirrored that of June, whereas a substantial decrease was observed in F1. Regarding available phosphorus, there was a gradual rise in F1, F2, and F3 from March to April, followed by a decline in May. Subsequently, the available phosphorus content for F1 and F2 experienced a recovery from June to July, while F3's available phosphorus content continued to decline. F2 kept the highest ranking across all indicator data during the dynamic changes in soil available nutrients under various mulch treatments from March to July 2023.

The average soil available nutrient values for three types of mulch thickness from March to July 2023 are presented in Table 3. Notably, during this period, treatment F2 exhibited the highest average soil available nutrient content. A comparison with the CK reveals a substantial increase in its

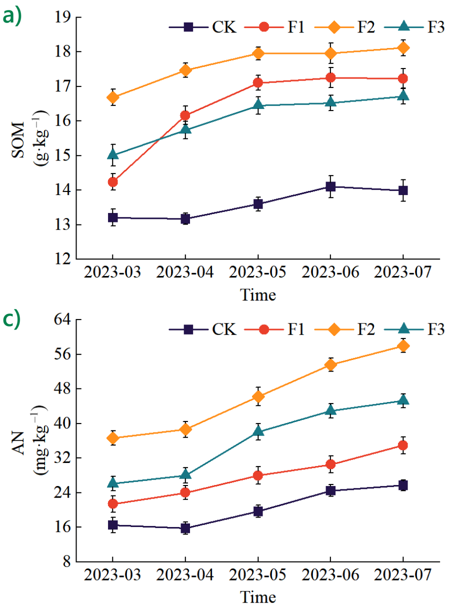


Figure 3. The dynamic changes of soil available nutrients under three types of mulch thickness treatments

Table 3. The average soil available nutrient values for three types of mulch thickness from March to July 2023

Treatment	Soil organic matter (SOM), g/kg	Alkaline nitrogen (AN), g/kg	Available potassium (AK), g/kg	Available phosphorus (AP), g/kg
CK	13.62±0.10d	20.43±0.82d	114.64±1.35d	100.76±0.78d
F1 (1–3 cm)	16.40±0.25b	27.77±0.68c	141.78±1.15c	135.23±0.89b
F2 (3–6 cm)	17.64±0.11a	46.63±0.61a	155.50±0.33a	144.83±1.29a
F3 (6–9 cm)	15.95±0.10c	36.07±0.70b	148.52±0.55b	127.98±1.09c

Note: Values with different letters in the same column indicate significant differences between treatments ($p < 0.05$, $n = 3$). Data are means ± standard deviation.

soil organic matter, alkaline nitrogen, available potassium, and available phosphorus content by 29.52%, 128.24%, 35.64%, and 43.74%, respectively. Meanwhile, treatment F3 displayed slightly higher average alkaline nitrogen and available potassium content than CK, registering increases of 17.11% and 27.01%, respectively. Similarly, treatment F1 showed marginally higher average alkaline nitrogen and available potassium content compared to CK, with increments of 35.93% and 23.67%, respectively. Notably, the application of SPM significantly enhanced the content of available nutrients in the soil, with the 3–6 cm thickness treatment yielding the most remarkable results.

3.4. Effects of different mulch thicknesses on soil enzyme activities

The dynamic changes of soil enzyme activities for three types of mulch thickness from March to July 2023 are shown in Figure 4. There were very minor changes in the activity of catalase (CAT) and urease (Ure) over the range of mulching treatments from March to April 2023. The following period, from May to June, saw a noticeable difference in catalase, with F1 showing noticeably higher activities than F2, F3, and CK (Figure 4a). Similarly, the activity of urease displayed a significant variation, with both F1 and F2 showing substantially greater activity than F3 and CK (Figure 4b). The variation in the activity of alkaline phosphatase (ALP) and sucrase (Suc) among several mulching treatments was minimal from March to July 2023. The activity of alkaline phosphatase and sucrase followed the pattern: F1 > F2 > F3 > CK (Figure 4c, 4d).

The average soil enzyme activity values for three types of mulch thickness from March to July 2023 are presented in Table 4. F1 had the highest average activity levels for catalase and sucrase throughout this period. Compared with CK, the activity of catalase and sucrase in F1 increased by 54.55% and 36.69% respectively. Simultaneously, the highest average activity levels for urease and alkaline phosphatase were observed in F2, with significant increases of 38.67% and 88.89%, respectively, over CK. It is evident that SPM has a significant positive impact on the activity of all four soil enzymes. Specifically, F1 demonstrates the most pronounced improvement in the activity of catalase and sucrase, while F2 emerges as the superior treatment for enhancing the activity of urease and alkaline phosphatase.

Table 4. The average soil enzyme activities values for three types of mulch thickness from March to July 2023

Treatment	Activity of catalase (CAT), $mg \cdot kg^{-1} \cdot d^{-1}$	Activity of urease (Ure), $mg \cdot kg^{-1} \cdot d^{-1}$	Activity of alkaline phosphatase (ALP), $mg \cdot kg^{-1} \cdot d^{-1}$	Activity of sucrase (Suc), $mg \cdot kg^{-1} \cdot d^{-1}$
CK	0.11±0.01d	1.50±0.02d	0.09±0.05d	40.48±0.34d
F1 (1–3 cm)	0.17±0.04a	2.02±0.02b	0.14±0.02b	55.33±0.48a
F2 (3–6 cm)	0.15±0.04b	2.08±0.02a	0.17±0.03a	50.30±0.57b
F3 (6–9 cm)	0.14±0.03c	1.78±0.01c	0.12±0.03c	46.60±0.49c

Note: Values with different letters in the same column indicate significant differences between treatments ($p < 0.05$, $n = 3$). Data are means ± standard deviation.

3.5. Correlation analysis and principal component analysis of soil enzyme activities and soil indexes

3.5.1. Correlation analysis

The relationship between soil physicochemical characteristics and soil enzyme activities is depicted in Figure 5. Specifically, the activities of four soil enzymes exhibited positive correlations with soil nutrient levels. Notably,

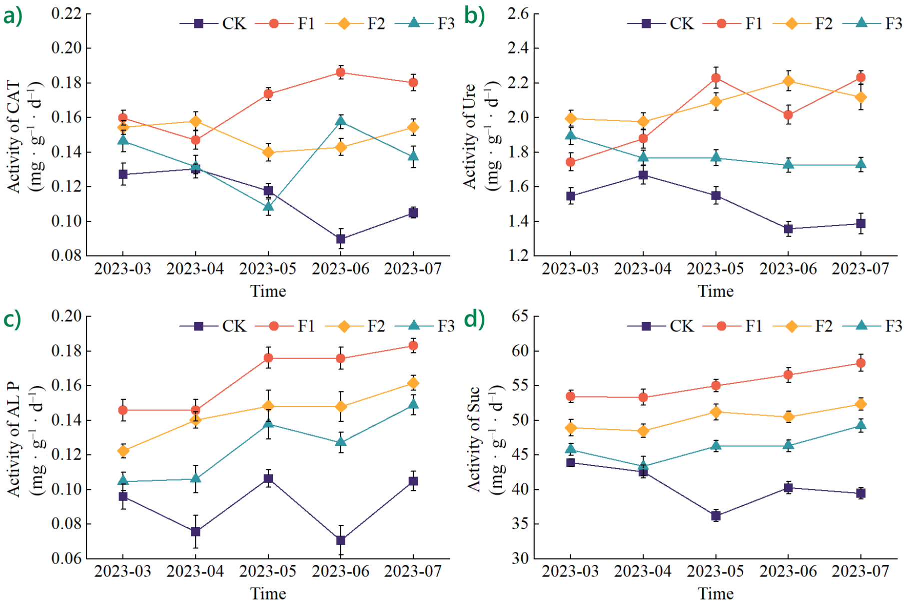


Figure 4. The dynamic changes of soil enzyme activities under three types of mulch thickness treatments

the activity of alkaline phosphatase (ALP) demonstrated significant positive correlations with soil organic matter (SOM) and available phosphorus (AP). The activity of Ure demonstrated significant positive correlations with soil organic matter (SOM). In contrast, no significant correlation emerged between the activities of these four enzymes and the soil physical properties. Furthermore, all four enzymes showed negative correlations with soil temperature (ST), while the activity of catalase (CAT) and sucrase (Suc) exhibited no correlation with soil bulk density (SBD).

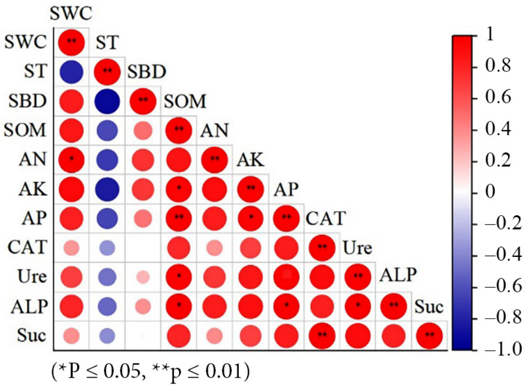


Figure 5. The correlation analysis between soil physicochemical characteristics and soil enzyme activities

3.5.2. Principal Component Analysis

To further investigate the impact of mulching treatments on soil physicochemical properties and enzyme activities, we conducted a Principal Component Analysis (PCA) on eleven indicators, including soil water content (SWC), soil temperature (ST), soil bulk density (SBD), soil organic matter (SOM), alkaline nitrogen (AN), available potassium (AK), available phosphorus (AP), and the four enzyme activities (Figure 6). The cumulative contribution rate of the two principal components amounted to 95.7% (PC1: 75.1%, PC2: 19.6%), which effectively reflects the essential information from the original dataset. Notably, In PC1, the first five indicators with the most significant load are available phosphorus (AP), soil organic matter (SOM), available potassium (AK), alkaline phosphatase (ALP), and urease (Ure). In PC2, catalase (CAT), sucrase (Suc), soil temperature (ST), urease (Ure), and alkaline phosphatase (ALP) are the top five indicators with the most significant load. Moreover, except sucrase (Suc) and catalase (CAT), different treatment groups can be distinctly discerned, signifying significant variations among the treatments, barring sucrase (Suc) and catalase (CAT).

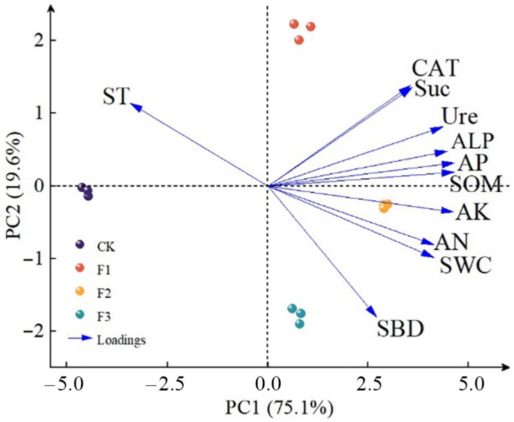


Figure 6. The Principal Component Analysis on soil physicochemical characteristics and soil enzyme activities

The comprehensive soil quality scores for each treatment are presented in Table 5. The comprehensive soil quality scores for all three mulching treatments surpass those of CK. Specifically, the F1 treatment achieved the highest comprehensive score at 2.98, securing the top position, while the F2 treatment earned a score of 2.65, placing it second. These results indicate that mulch layers of both 1–3 cm and 3–6 cm thickness contribute to enhanced soil quality, with the 1–3 cm thickness layer exhibiting superior performance.

Table 5. The comprehensive soil quality scores for four treatments

Treatment	FC1 (73.7%)	FC2 (22.0%)	Comprehensive scores	Ranking
CK	–4.52	0.08	–4.60	4
F1 (1–3 cm)	0.84	2.14	2.98	1
F2 (3–6 cm)	2.93	–0.28	2.65	2
F3 (6–9 cm)	0.75	–1.76	–1.04	3

4. Discussions

4.1. Effect of mulching on soil physical properties

Mulching has a significant impact on the soil microenvironment, influencing factors such as soil moisture content, temperature, and soil bulk density, while its effects vary depending on factors such as soil type, mulching method, and the material used for mulching (Ahmad et al., 2022; Chalker-Scott, 2007). In our study, SPM played a crucial role in enhancing soil water content and maintaining soil temperature stability. Mulch can reduce evaporation loss from the soil surface, resulting in increased soil water content compared to uncovered soil (Safari et al., 2021; Stelli et al., 2018). The spaces between SPM particles are sizable, enhancing permeability and facilitating water infiltration, thereby improving soil moisture content. Moreover, mulching with SPM creates a gray-white physical barrier on the soil surface, reflecting a portion of the heat energy from solar radiation. This reduces heat absorption and effectively inhibits soil water evaporation, which is particularly advantageous in hot weather conditions, ultimately enhancing water use efficiency.

Soil bulk density serves as a vital indicator of soil structure, providing insight into soil porosity and aeration to a certain extent (Håkansson & Lipiec, 2000). In this study, the SPM did not lead to a reduction in soil bulk density; rather, soil bulk density increased significantly when the mulch thickness exceeded 3 cm. When saturated with water, the soil bulk density's weight further escalated, primarily due to the added gravitational force introduced by the SPM, which may lead to soil compaction, hence elevating soil bulk density. Consequently, it is advisable that when employing SPM as a soil mulch, the thickness should not exceed 3 cm.

4.2. Effect of mulching on soil available nutrients

Mulching can promote material circulation and energy flow in the soil to some extent, facilitating the absorption and utilization of nutrients by plants. It is worth noting that different types of mulch have varying effects on soil nutrient levels (Iqbal et al., 2020; Kader et al., 2017). Inorganic mulches, such as pebbles or gravel, do contribute to improved soil moisture and heat retention but fall short of significantly enriching soil nutrients, as they lack the necessary nutrients for plant growth (Thakur & Kumar, 2021). In contrast, organic mulches, such as leaves, branches, or bark, decompose over time, releasing nutrients into the soil and augmenting its nutrient content (Chalker-Scott, 2007). Living mulch, as an organic mulch, when combined with mechanical treatment, effectively diminishes weed abundance and biomass. Concurrently, the nutrient absorption by living mulch is lower compared to weeds, thereby enhancing crop yield (Kołodziejczyk et al., 2017). The results demonstrate that using SPM significantly increases SOM and available nutrients compared to the control group. SPM contains a wealth of nutrients essential for plant growth. When SPM, applied as a mulch, is exposed to rain, the water-soluble nutrients within SPM readily dissolve and are transported into the soil, consequently bolstering soil organic matter and increasing the available nutrients.

In this research, the experimental group employing mulch with a thickness of 3–6 cm exhibited the highest levels of organic matter and available nutrients, followed by the group using mulch with a thickness of 1–3 cm. Surprisingly, as the thickness of the SPM mulch increased, there was no corresponding increase in soil-available nutrients. This phenomenon can be attributed to the fact that an increase in mulch thickness negatively impacts soil aeration, thereby compromising the survival of soil microorganisms. Consequently, the decomposition and mineralization processes of soil organic matter slow down, resulting in a reduced supply of soil-available nutrients.

4.3. Effect of mulching on soil enzyme activities

Soil enzymes play a pivotal role in a multitude of biochemical reactions within the soil, significantly influencing soil nutrient cycling, the decomposition of organic matter, and the transfer of energy (Bierza et al., 2023; Dick, 1994, 1997). Sucrases participate in converting soil carbohydrates, hydrolyzing organic matter into glucose and sucrose for plant growth and microbial activity (Ge et al., 2011; Xie et al., 2017). Phosphatases constitute a group of enzymes catalyzing the hydrolysis of esters and anhydrides of phosphoric acid (Condron et al., 2005). Urease acts on carbon–nitrogen bonds, producing carbon dioxide and water through the hydrolysis of ammonia or amino salts, while catalase is associated with the soil's redox ability (Baddam et al., 2016; Nowak et al., 2004). Mulching can enhance enzyme activity within the soil, thereby creating a favorable environment for plant metabolism, suppressing weed invasion, and reducing weed density and biomass (Masciandaro et al., 2004; Splawski et al., 2016). The obtained results demonstrate that mulching with SPM significantly enhances the activity of four key soil enzymes. This enhancement can be attributed primarily to the fact that, in comparison to the control group, SPM mulching reduces soil temperature, and improves soil water content, thus facilitating optimal conditions for the thriving of soil microorganisms, and subsequently, enhancing the activities of diverse soil enzymes.

The data analysis has revealed a positive correlation between soil enzyme activities and the presence of SPM. Soil enzymes, such as urease and phosphatase, play crucial roles in nitrogen (N) and phosphorus (P) cycling, respectively (García-Ruiz et al., 2008). In phosphorus-deficient soils, plant roots and microorganisms increase phosphatase secretion to enhance the solubilization and remobilization of phosphate. Thus, phosphatase activity serves as an indicator of inorganic phosphorus availability for plants and microorganisms (Kai et al., 2002; Piotrowska-Długosz & Charzynski, 2015). The research data revealed a significant positive correlation between alkaline phosphatase and available phosphorus. Therefore, SPM coverage can enhance alkaline phosphatase enzyme activity, promoting available phosphorus formation and providing available inorganic phosphorus for plants. Additionally, a positive correlation exists between ure and an, with a significant positive correlation with som, mainly due to Urease enzyme's role in regulating soil nitrogen transformation (Zhao et al., 2012). Under stable organic nutrient conditions, soil enzyme activity is typically higher, fostering increased mineralization and creating a more favorable environment for nutrient cycling (Roldán et al., 2005). Although catalase and suc show a positive correlation with soil organic matter and other available nutrients, the correlation is not deemed significant. Overall, these findings suggest that the use of SPM can enhance the activities of four kinds of soil enzymes in different degrees, and ultimately enhance soil fertility. Furthermore, correlations were identified between catalase and sucrase, alkaline phosphatase, and urease, indicating intricate interactions among soil enzymes.

In the comprehensive assessment of soil quality for each treatment, the highest score was achieved by the treatment involving a mulch thickness of 1–3 cm, followed by the 3–6 cm thickness treatment. Conversely, the treatment with a mulch thickness of 6–9 cm yielded a negative impact on soil quality. These results indicate that a mulch thickness of 1–3 cm with SPM had the most positive effect on improving soil quality. It is noteworthy that when compared to the control group, the use of SPM demonstrated an overall enhancement in soil quality.

4.4. Environmental effect

With the growing population, there is an increasingly urgent demand for water resources, and the scale of water treatment plants is also expanding (Caniani et al., 2013; Nayeri & Mousavi, 2022). In this context, converting sludge into soil mulch can facilitate the resource utilization of waste, mitigate the adverse effects of conventional disposal methods such as landfills on the environment, and offer a range of environmental benefits.

Common organic mulch (such as leaves, branches, and bark) is easy to decompose. When encountering severe weather conditions such as strong storms and heavy rainfall, it is prone to be carried away and drifting onto roads, consequently obstructing urban road drainage channels and becoming a source of ground dust (BingPeng et al., 2018; Jodaugienė et al., 2010). In contrast, inorganic mulches, such as sand and gravel, remain stable but do not provide nutrients to the soil (Thakur & Kumar, 2021). SPM complies with the landscaping requirements for GB/T 23486-2009 and, therefore, serves as a viable green mulch option. SPM contains ample organic matter and essential nutrients. Experimental results demonstrate that SPM mulching significantly increases soil organic matter content, boosts available nutrients, enhances soil enzyme activities, and elevates overall soil quality. Furthermore, due to the inclusion of a curing agent, SPM enhances particle hardness and quality, maintaining pellet shape over an extended period without susceptibility to damage or displacement. This durability results in reduced maintenance costs. The longer SPM remains on the soil surface, the more pronounced its positive impact on soil improvement becomes. Additionally, SPM exhibits exceptional water retention capabilities, reducing irrigation requirements and facilitating water resource conservation.

Traditional sludge treatment typically involves preliminary processes such as thickening and stable dehydration before considering land use, sanitary landfill, or incineration. Nonetheless, these methods incur substantial investment and operational costs, accounting for approximately 40% to 65% of the total operational expenses of sewage plants (Meng et al., 2013; Zan et al., 2009). In this investigation, the DWTS is transported to a designated storage yard for solidification and granulation. Once it has passed the necessary maintenance tests, this processed sludge can be used as an urban landscape mulch. This methodology not only streamlines sludge disposal within water treatment plants and addresses transportation challenges but also offers a clear path for resource utilization, ultimately enhancing economic benefits. Consequently, the utilization of these refined sludge particles not only augments urban greening and ecological advantages but also contributes significantly to the sustainable development of urban ecological environments, aligning with both Chinese and global environmental conservation objectives.

After thoughtful deliberation, the optimal strategy is to restrict the thickness of the Sludge Particle Mulch (SPM) cover to a range of 1–3 cm. This specific range has been determined to minimize adverse effects on soil bulk density while simultaneously maximizing the positive impact on soil quality enhancement. It is crucial to highlight that this experiment, primarily conducted within a greenhouse pot setting, has yet to be implemented in an actual urban green space. Considering the experiment's context and the identified SPM bulk density of 0.96 g/cm^3, coupled with the recommended coverage thickness falling within the 1–3 cm range, a meticulous calculation leads to the proposed SPM dosage for urban bare soil–ranging from 9.6 to 28.8 kg/m^2. In future experiments, particularly for the application of SPM in urban green spaces, further research can be conducted based on the recommended dose. This will allow for a more comprehensive understanding of SPM's impact on soil quality and its potential benefits. Moreover, the utilization of water purification sludge in urban landscaping can pave the way for a sustainable and eco-friendly approach, leading to reduced waste and enhanced resource utilization.

5. Conclusions

The primary objective of this research is to investigate the safety and substantial benefits associated with SPM for soil mulch. Firstly, the research results indicate that the physicochemical properties of SPM comply with Chinese regulations, rendering it suitable for environmentally friendly soil mulch. Secondly, SPM exhibits the capability to significantly enhance soil water content, maintain soil temperature stability, increase soil organic matter and available nutrients, improve soil enzyme activity, and overall enhance soil quality. After careful consideration, the suggested application rate of SPM for urban bare soil is estimated to be in the range of 9.6–28.8 kg/m^2. The controlled experiment conditions validate the potential benefits of SPM. However, further research is advised to ensure the reliability of these findings in the soil greening process.

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Author contributions

Conceptualization, Haiyan SUN; investigation and experiment, Qian MO, Yuying WANG, Shuying SONG, Xue ZHANG, Ting HE and Chengrui ZHUO; writing original draft preparation, Qian MO; writing–review and editing, Haiyan SUN and Qian MO; project administration, Qian MO, Yuying WANG, Shuying SONG, Xue ZHANG, Ting HE and Chengrui ZHUO. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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