

ORIGINAL RESEARCH ARTICLE

Phosphate-enhanced co-composting of
municipal sludge and forestry residues for low-
carbon topsoil improvementQiao Li¹, Jiuxian Yang¹, Ying Wang¹, Yipeng Wang¹, Wenyu Wu¹, Jiyuan Jin¹,
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(ddge1118@sjtu.edu.cn)**Citation:** Li Q, Yang J, Wang Y, *et al.* Phosphate-enhanced co-composting of municipal sludge and forestry residues for low-carbon topsoil improvement. *Asian J Water Environ Pollut.* 2026;23(3):026040018. doi: 10.36922/AJWEP026040018**Received:** January 23, 2026**Revised:** February 15, 2026**Accepted:** February 27, 2026**Published online:** April 22, 2026**Copyright:** © 2026 Author(s). This is an Open-Access article distributed under the terms of the Creative Commons Attribution License, permitting distribution, and reproduction in any medium, provided the original work is properly cited.**Publisher's Note:** AccScience Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.**Abstract**

The degradation of high-altitude hydropower reservoir slopes limits slope stability and ecological restoration. This work proposes phosphate-enhanced co-composting, which transforms municipal sludge and forestry residues (sawdust and fallen leaves) into a high-quality soil amendment suitable for degraded topsoils in the Shuangjiangkou reservoir area. The co-composting process was optimized by adjusting the carbon/nitrogen (C/N) ratio, bulking agent composition, and the phosphate dosage. A C/N ratio of 25 with a sawdust-leaves composite produced stable thermophilic conditions, increased microbial enzymatic activity, accelerated organic matter decomposition, and minimized ammonium loss. Moderate phosphate addition of 0.6 mmol P/g dry solid reduced composting time to 16 days and enhanced nutrient retention. Field application of the mature compost at a 9% addition rate significantly improved the treated soils, increasing organic matter from 5.20 to 44.53 g/kg and decreasing bulk density from 1.40 to 1.31 g/cm³, while nutrient contents and heavy metal concentrations met regulatory requirements. The phosphate-enhanced co-composting strategy provides an efficient and safe solution for soil amendment in high-altitude hydropower reservoir regions, particularly contributing to carbon neutrality by promoting organic carbon stabilization, reducing waste-related emissions, and enhancing soil carbon sequestration. These findings demonstrate a low-carbon pathway linking waste management, ecological restoration, and renewable energy infrastructure development.

Keywords: Co-composting strategy; Phosphate enhancement; Compost characteristics; Topsoil improvement; Low-carbon pathway

1. Introduction

In recent years, hydropower has provided more than 40% of the global renewable electricity supply. Large hydropower plants are considered critical for energy system optimization because they are stable and efficient.¹ However, large hydropower stations involve slope excavation and land reshaping, both of which have significant environmental impacts. Such projects can eliminate over 30% of vegetation in reservoir zones, and in some areas, water conservation capacity can be reduced by more than 20%.² The Shuangjiangkou hydropower station in Sichuan Province, China, has an annual generation capacity of 7,707 million kWh and is considered the world's highest dam. Its reservoir lies at an elevation of over 2,180 m and is surrounded by steep mountains and fragmented geology. The site experiences an alpine valley climate, with annual precipitation below 750 mm, mainly occurring in summer. This "dry winter, wet summer" pattern makes exposed slopes prone to erosion during rains, leading to severe soil loss and ecological degradation.³ Successive soils in the Shuangjiangkou reservoir area are loose, structurally unstable, low in organic matter (OM), and have poor water and nutrient retention—all factors that compromise slope stability and recovery.³ Engineering disturbances further degrade topsoil, leading to the loss of aggregate structure, soil nutrients, and microbes. Field experiments show that OM content in exposed slope soils is less than 6 g/kg, far below the 15 g/kg requirement specified by the Planting Soil for Greening standard (CJ/T 340–2016).⁴ These severe OM and aggregate deficiencies reduce erosion resistance and hinder vegetation recovery, which, in turn, cause slope instability and soil loss.⁵ Without artificial intervention, natural vegetation recovery in high-altitude regions can take 15–30 years.⁶ Given the specific climate, topographic, and edaphic conditions in the Shuangjiangkou reservoir area, both soil improvement and ecological slope restoration are needed for the sustainable operation of the hydropower station.

Traditional slope-protection methods, such as stone masonry revetments and concrete grid beams, stabilize slopes only in the short term and provide little improvement in soil properties or ecological conditions.⁶ Moreover, their construction produces large volumes of forestry residues (branches, leaves, and herbaceous remains) and excavated spoil, which could potentially be used as soil amendments. However, large-scale, efficient use is impeded by an unbalanced carbon-to-nitrogen (C/N) ratio, low composting efficiency, and a lack of integrated utilization technologies. For example, the C/N ratio of woody residues often exceeds 90, trunks and branches can reach 300–1,000,^{7,8} well above the optimal composting

C/N range of 20–30. This imbalance inhibits microbial activity and slows composting when woody material is used alone.^{9,10} Municipal sludge is rich in nitrogen, phosphorus, potassium, and trace elements, with a low C/N ratio of 6–10.¹¹ However, its high moisture content and viscous structure can hinder aeration, and if processed alone, it can prolong composting time.¹² Woody residues and sewage sludge share complementary properties, but the lack of systematic studies and process optimization has limited resource utilization, led to inconsistent soil improvement results, and increased costs in reservoir areas. Co-composting diverse organic wastes has recently shown promise for agricultural waste management and soil remediation. Research has shown that sludge recycling can improve soil structure and promote plant growth.^{13,14} Combining carbon-rich and nitrogen-rich wastes can shorten composting times by 30–50%, increase OM content by more than 20%, and improve nutrient availability.^{15,16} Based on these results, we propose a soil amendment strategy by co-composting forest residues with municipal sludge and phosphate additives to improve composting performance.^{17,18} Forestry residues improve aeration and moisture control in sludge, while sludge provides nitrogen and other nutrients to balance the C/N ratio, accelerate OM degradation, and encourage humification, resulting in high-quality humus in a shorter time.¹⁵

Hence, this study investigates whether resource-oriented co-composting of municipal sludge and forestry residues can support both soil restoration and low-carbon infrastructure development in hydropower reservoir areas. Specifically, it examines: (i) whether optimizing the C/N ratio enhances compost stabilization and OM degradation; (ii) whether phosphate addition improves process efficiency and nitrogen retention; and (iii) whether the resulting compost can significantly improve degraded topsoil properties without increasing environmental risks. We hypothesize that an optimal C/N ratio combined with moderate phosphate supplementation will accelerate compost maturity, enhance nutrient stabilization, and produce a safe and effective soil amendment. By testing these hypotheses, the study aims to establish a technically feasible, system-integrated pathway that links organic waste recycling to ecological restoration under carbon-neutral development strategies.

2. Materials and methods

2.1. Materials

The forestry residues used in this study consisted of sawdust and leaves, mainly from coniferous trees and broad-leaved trees, collected from pruning and clearing activities at the construction site of the Shuangjiangkou water conservancy

project. The waste wood was first crushed to a particle size of <50 mm using a hammer mill (PC 1000 × 800, Shanghai Dingbo Heavy Industry Machinery Co., Ltd, China). The crushed material was sequentially sieved through 60-mesh (0.25 mm) and 100-mesh (0.15 mm) stainless-steel screens, and particles in the 0.15–0.25 mm size range, accounting for ≥90% of the mass, were retained. Fine powders and impurities were removed, and the selected fraction was air-dried to a moisture content ≤ 15% to prevent mildew. Leaves were manually cleaned to remove stones and plastics, and intact leaf samples were retained. These were milled to a particle size of 2–20 mm using a high-speed grinder (Model 400, 7.5 kW, Guangzhou Guoheng Machinery Equipment Co., Ltd., China). The leaf material was then mixed with sawdust at predetermined ratios and air-dried to a moisture content ≤ 20%.

Sludge was collected as deeply dewatered sludge cake from the sludge dewatering unit of a municipal wastewater treatment plant operating under the anaerobic–anoxic–aerobic process. The main physicochemical characteristics of the raw materials and the heavy metal contents of sludge are presented in Tables 1 and 2, respectively.

The topsoil used in the experiments was collected from the surface layer (0–20 cm) of the Shuangjiangkou project reservoir area. Its basic physicochemical properties are detailed in the results and discussion section.

2.2. Experimental design

The composting experiments were carried out in a self-assembled laboratory-scale system. Each unit consisted of a

cylindrical reactor (inner diameter of 10 cm, height 22 cm, and effective volume 1.2 L), an aeration disk, gas tubing, an aeration pump, a flow meter, and a thermostatic water bath shaker. The reactors were immersed in the water bath to ensure uniform external temperature conditions. After homogenization, the composting mixtures were placed into the reactors. Aeration was supplied continuously by a dual-channel pump at a flow rate of 0.6 L/min, regulated by a flow meter and valve. The external temperature of the reactors was stabilized at 35 ± 0.5 °C by the water bath system. Each experiment was performed in triplicate.

Process monitoring was performed daily and included measurements of temperature, pH, OM, and ammonium nitrogen, using a multi-point sampling strategy. Compost maturity was evaluated according to the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918–2002), the Standard for Sludge Stabilization Treatment of Municipal Wastewater Treatment Plant (CJ/T 510–2017), and the Technical Specification for Sludge Compost of Municipal Wastewater Treatment Plant (T/CECS 536–2018), where an OM degradation rate ≥ 40% was regarded as the maturity threshold.

To investigate the effect of material composition and phosphate addition on composting performance, three treatment groups were established by adjusting the C/N ratio through varying proportions of raw materials. Monopotassium phosphate of analytical grade was purchased from Aladdin Chemical Reagent Co., Ltd. (China). The detailed experimental setup is summarized in Tables 3 and 4.

Table 1. The main physicochemical characteristics of sawdust, leaves, and sludge used in the composting experiment

Material	Moisture content (%)	Organic matter (%)	Total carbon (C, %)	Total nitrogen (N, %)	C/N ratio	pH
Sawdust	12.11	86.54	47.18	0.117	403.2	6.29
Leaves	18.36	78.79	48.32	2.23	23.25	6.36
Sludge	61.41	52.13	21.15	2.16	9.79	6.98

Table 2. Heavy metal contents of sludge used in the composting experiment (mg/kg)

Item	As	Cd	Cr	Hg	Cu	Ni	Pb	Zn
Sludge	13.17	0.75	12.19	0.62	64.16	11.47	9.06	271.53
GB 4284–2018 A level	<30	<3	<500	<3	<500	<100	<300	<1,200

Note: “GB 4284–2018 A level” refers to the strictest pollutant control grade specified in the Chinese national standard of “Control standards of pollutants in sludge for agricultural use (GB 4284–2018)”, which sets maximum allowable limits for heavy metals (e.g., Cd, Pb, Hg) in sludge intended for land application (such as farmland, gardens, and grasslands), ensuring minimal environmental risk. The “A level” designation indicates compliance with the most stringent criteria under this standard, typically required for sensitive agricultural uses.

Abbreviations: As: Arsenic; Cd: Cadmium; Cr: Chromium; Cu: Copper; Hg: Mercury; Ni: Nickel; Pb: Lead; Zn: Zinc.

Table 3. Experimental design for composting treatments

Treatment group	Carbon-to-nitrogen ratio in the mixed matrix	Added phosphate dosage (mmol P/g DS ^a)
Sawdust–sludge	20, 25, 30	0
(Sawdust + leaves)–sludge	20, 25, 30	0
(Sawdust + leaves)–sludge–phosphate	25	0, 0.3, 0.6, 0.9

Note: ^aDS: Dry solids.

Table 4. Material ratios for composting experiments with various C/N ratios

Mass ratio	Carbon/nitrogen (C/N) of 20	C/N of 25	C/N of 30
Sawdust: sludge	0.22:1	0.32:1	0.44:1
(Sawdust + leaves):sludge ^a	0.4:1	0.77:1	1.45:1

Note: ^a For the experimental group of mixed sludge of sawdust and leaves, the mass ratio of sawdust to leaves is 1:1.

2.3. Physicochemical analysis

A digital temperature recorder (JC-TW, Qingdao Juchuang Environmental Protection Co., Ltd., China) equipped with an internal probe was used to continuously monitor compost temperature, with measurements recorded every 24 h. Moisture content was determined by drying 3.0 g of the fresh sample at 105 °C and measuring the weight loss. For pH measurement, the sample was mixed with deionized water at a mass-to-volume ratio of 1:10, shaken at 120 rpm for 4 h, and the pH of the suspension was measured using a pH meter (S500-Basic, Mettler Toledo, Switzerland) in accordance with the Determination of pH in Soil (NY/T 1377–2007). OM content was determined according to the Method for Determination of Soil Organic Matter (NY/T 1121.6–2006). Dried samples were ignited in a muffle furnace at 600 °C for 6 h, and OM content was calculated based on mass loss before and after combustion. Ammonium nitrogen (NH₄⁺–N) concentration was measured spectrophotometrically using the Nessler reagent method. In brief, a 5.00 g sample was extracted with 50 mL of 2 mol/L potassium chloride solution (Shanghai McLean Biochemical Technology Co., Ltd., China) by shaking for 30 min. After settling, the supernatant was collected, mixed with 1 mL Nessler reagent (Shanghai McLean Biochemical Technology Co., Ltd., China), and allowed to develop color for 10–15 min at room temperature in the dark. Absorbance was then measured at 400 nm using a ultraviolet (UV)–Vis spectrophotometer (Genesys 30, Thermo Fisher Scientific, Inc., USA). The contents of heavy metals were analyzed with an inductively coupled plasma-optical emission spectrometer (Agilent 5110 ICP-OES, Agilent Technologies, Inc., USA).

2.4. Bioactive analysis

The activities of microbial enzymes, including cellulase, protease, urease, and peroxidase, were measured

at specific sampling intervals. Cellulase and urease activities were assayed simultaneously using a UV–Vis spectrophotometer with commercial test kits (Nanjing Jiancheng Bioengineering Institute, China), according to the 3,5-dinitrosalicylic acid method (540 nm) and the indophenol blue method (578 nm), respectively.¹⁹ Protease activity was measured colorimetrically using ninhydrin, while peroxidase was measured according to a previously reported method.²⁰

3. Results and discussion

3.1. Characteristics of woody wastes and sludge

Table 1 summarizes the main properties of woody wastes used in this study. Sawdust had a low moisture content of 12.11% with a high OM proportion of 86.54%, but low nitrogen and phosphorus content, resulting in a high C/N ratio. Fallen leaves had a high OM content of 78.79% and a slightly higher nitrogen concentration than wood chips, which moderated the feedstock C/N ratio. Sewage sludge had a much higher moisture content of 61.41%, with 52.13% OM and abundant nitrogen and phosphorus. Its low C/N ratio makes it unsuitable for composting alone. Together, sawdust and leaves provide carbon and physical structure, while sludge contributes nitrogen and phosphorus.

Excessive levels of heavy metals in sludge may pose a hazard to the environment,²¹ and the main heavy metals in the sludge are shown in Table 2. All measured levels of arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) were below the limits specified in the Control Standards of Pollutants in Sludge for Agricultural Use (GB 4284–2018), indicating that the sludge is suitable as compost feedstock. Zn and Cu concentrations were significantly higher in this sludge, probably due to inputs from domestic wastewater and some industrial discharges. Pb, Cd, and Cr levels were

relatively low and posed no apparent environmental risk. Overall, the heavy metal concentrations in the sludge used in this study were acceptable and did not pose significant risks to the agricultural safety of the compost.

3.2. Physicochemical properties in composting

3.2.1. Temperature

Temperature variation during composting reflects microbial activity and substrate degradation rates to a certain extent.²² As shown in Figure 1, feedstock composition and external conditions influenced the heating rate, peak temperature, and duration of the thermophilic phase. For the sawdust–sludge (S–S) treatment (Figure 1A), all three C/N ratios (20, 25, and 30) exhibited typical heating, thermophilic, and cooling stages. The initial temperature was approximately 25 °C, and all treatments entered the thermophilic phase within 3 days. At a C/N ratio of 20, heating was the fastest, reaching a maximum temperature of 63.4 °C on day 7; however, cooling occurred rapidly, with temperatures declining by day 14. At a C/N ratio of 25, the temperature peaked at 64.5 °C on day 10, maintaining the longest thermophilic period (7 days) and slower cooling. At a C/N ratio of 30, the temperature rose with a lower peak temperature (56.1 °C) and thermophilic duration shorter than 5 days, suggesting that excessive carbon inhibited microbial growth and OM degradation. The superior thermal profile at a C/N ratio of 25 suggests that this ratio provided a balanced carbon-to-nitrogen supply, supporting optimal microbial growth and respiratory heat production.²³ In contrast, nitrogen limitation at higher C/N ratios likely constrained microbial protein synthesis, while excessive nitrogen at lower C/N ratios may have promoted rapid early metabolism but shortened thermophilic stability due to substrate depletion.²⁴ Overall, a C/N ratio of 25 provided the most favorable temperature profile, with high peak temperature and thermophilic stability for pathogen inactivation and OM stabilization.

The addition of leaves increased the initial system temperature to approximately 36 °C, higher than that of the sawdust-only controls, and significantly accelerated the heating phase (Figure 1B). At a C/N ratio of 20, the temperature reached its maximum at 63.1 °C on day 5 and remained in a thermophilic phase for approximately 8 days before declining rapidly. At a C/N ratio of 25, the temperature peaked at 63.4 °C on day 7 and remained in a thermophilic phase for more than 10 days, producing the most stable and prolonged thermal profile. At a C/N ratio of 30, the peak temperature was reached at 61.2 °C on day 9, after which it declined more rapidly. The incorporation of leaves increased the proportion of readily degradable carbohydrates and soluble organic compounds, stimulating rapid microbial colonization and respiration. Simultaneously, the heterogeneous particle structure of leaves improved inter-particle porosity and oxygen diffusion efficiency, facilitating aerobic metabolism.²⁵ The combined enhancement of substrate bioavailability and oxygen transfer kinetics likely accelerated microbial heat production and OM transformation. Overall, a C/N ratio of 25 showed the best performance.

Phosphate supplementation in the (sawdust + leaves)–sludge (SL–S) treatment was further investigated at a C/N ratio of 25 (Figure 1C). In the control group without phosphate addition, the temperature reached 62.8 °C on day 6. The addition of 0.3 and 0.6 mmol P/g dry solid (DS) increased the peak temperature to 64.5 °C and 65.4 °C, respectively, and extended the thermophilic period to 10 days. In contrast, the addition of 0.9 mmol P/g DS did not improve composting performance; the peak temperature reached only 62.7 °C, lower than that of the control group, and the thermophilic duration was shortened, possibly due to acidification or nutrient imbalance.²⁶

In summary, compost temperature responded strongly to C/N ratio, leaf addition, and phosphate management. Across all treatments, a C/N ratio of 25 resulted in the

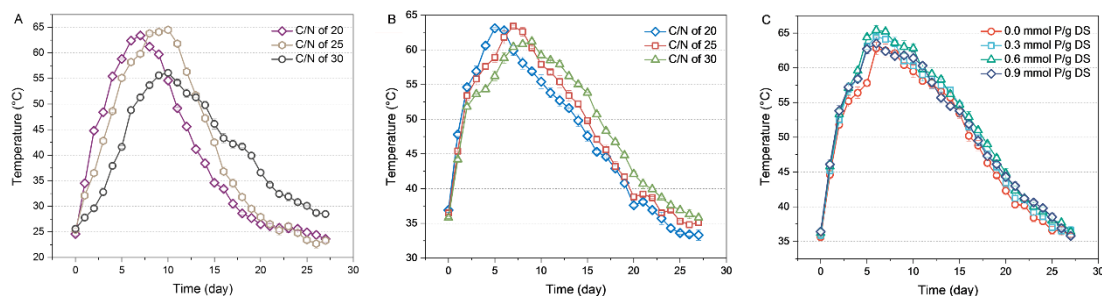


Figure 1. Changes in temperature during composting under different treatments: (A) S–S and (B) SL–S treatments with various C/N ratios, and (C) SL–S–P treatments with various phosphate dosages based on SL–S at a C/N ratio of 25

Abbreviations: C: Carbon; DS: Dry solid; N: Nitrogen; SL–S: (Sawdust + leaves)–sludge; SL–S–P: (Sawdust + leaves)–sludge–phosphate; S–S: Sawdust–sludge.

most favorable thermal profile. During the thermophilic phase, a rapid transition to thermophilic conditions and temperatures above 55 °C sustained for more than 7 days satisfied the criteria for pathogen inactivation and stabilization. Leaf addition and moderate phosphate supplementation (0–0.6 mmol P/g DS) further improved the thermal regime and promoted OM degradation and humification.

3.2.2. pH variation

The dynamic changes in pH during composting reflected the combined effects of nitrogen transformation and organic acid production. As shown in Figure 2, substrate composition and phosphate addition influenced pH evolution. In the S–S treatments (Figure 2A), the initial pH ranged between 6.8 and 7.0, indicating a neutral to slightly acidic environment. During the first two days, pH declined slightly, probably due to the rapid release of organic acids. Thereafter, pH increased sharply, particularly at a C/N ratio of 20, where pH rose above 8.6 on day 6, suggesting that ammonia production and volatilization drove system alkalization. The treatment with a C/N ratio of 30 showed a smaller pH increase and stabilized at 7.3–7.7, suggesting that higher carbon input buffered against excessive alkalization.

In the SL–S treatment, alkalization was more pronounced. At a C/N ratio of 20, pH reached 9.1 on day 8, then declined and stabilized near 8.2 (Figure 2B). The presence of leaves accelerated OM degradation and nitrogen mineralization, resulting in greater ammonia production than in sawdust-only treatments. By contrast, at a C/N ratio of 30, pH fluctuated between 6.7 and 7.9, indicating that higher C/N ratios limited nitrogen transformations and maintained relatively stable pH. At a constant C/N ratio of 25, phosphate addition moderated pH dynamics (Figure 2C). Without phosphate supplementation, pH rose rapidly and exceeded 8.5 by day 10. With the highest

phosphate dose (0.9 mmol P/g DS), the peak pH was constrained to approximately 8.2, and the decline during the later stage was more pronounced. These observations indicate that phosphate partially neutralized ammonia-driven alkalization, thereby dampening excessive pH increases and improving composting stability.²⁷

In summary, pH evolution depended strongly on raw material composition and phosphate level. At lower C/N ratios, enhanced proteolysis and ammonification increased the release of ammonium ion (NH_4^+) from organic nitrogen pools. Under thermophilic and alkaline conditions, a portion of NH_4^+ shifted toward gaseous NH_3 , which volatilized, displacing the equilibrium and promoting pH elevation. The presence of leaves further intensified early-stage nitrogen mineralization, thereby amplifying ammoniacal accumulation and subsequent alkalization dynamics.²⁸ In contrast, higher C/N ratios and phosphate addition mitigated excessive alkalinity and improved overall composting conditions.

3.2.3. Organic matter degradation

Changes in OM during composting directly reflects the extent of substrate decomposition and transformation and is therefore a key indicator of compost maturity and stability. As shown in Figure 3, OM content decreased over time in all treatments, including both sawdust alone and sawdust–leaves mixtures. All treatments showed a rapid initial decomposition phase, followed by slower degradation during the middle and late stages. In the S–S treatment, the initial OM content increased with increasing C/N ratios. By day 27, OM contents had decreased to 32.5%, 37.3%, and 41.2%, respectively. These results showed that higher C/N ratios provided larger OM reserves and retarded the decomposition rate, prolonging the stabilization phase.

Organic matter levels were generally higher in SL–S treatments than in the S–S treatments, with initial values ranging from 62.3% to 72.5%. By the end of composting,

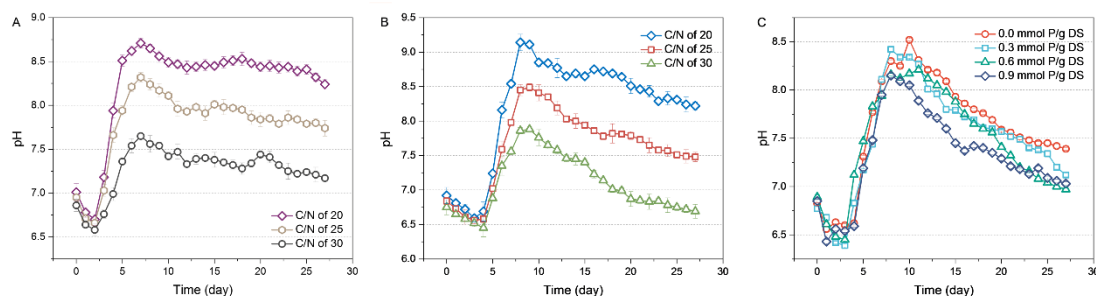


Figure 2. Changes in pH during composting under different treatments: (A) S–S and (B) SL–S treatments with various C/N ratios, and (C) SL–S–P treatments with various phosphate dosages based on SL–S at a C/N ratio of 25
Abbreviations: C: Carbon; DS: Dry solid; N: Nitrogen; SL–S: (Sawdust + leaves)–sludge; SL–S–P: (Sawdust + leaves)–sludge–phosphate; S–S: Sawdust–sludge.

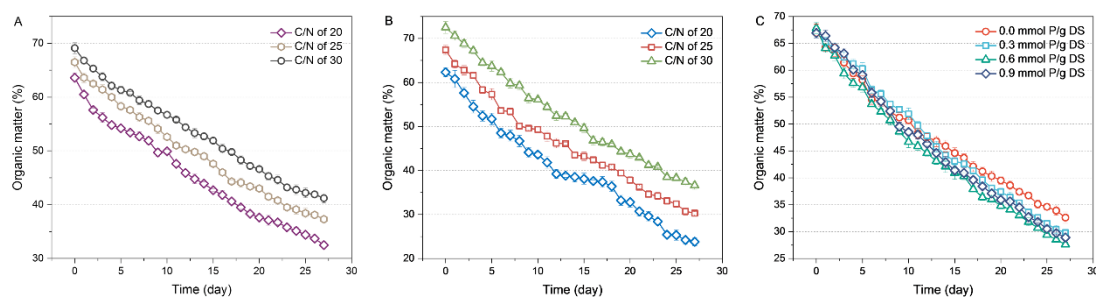


Figure 3. Changes in OM content during composting under different treatments: (A) S-S and (B) SL-S treatments with various C/N ratios, and (C) SL-S-P treatments with various phosphate dosages based on SL-S at a C/N ratio of 25

Abbreviations: C: Carbon; DS: Dry solid; N: Nitrogen; SL-S: (Sawdust + leaves)–sludge; SL-S-P: (Sawdust + leaves)–sludge–phosphate; S-S: Sawdust–sludge.

OM content decreased to 23.8%, 30.3%, and 36.6% at C/N ratios of 20, 25, and 30, respectively. At a C/N ratio of 20, OM degradation was fastest, likely because readily degradable components (e.g., leaves) increased microbial activity, leading to greater OM loss during later stages.²⁹ In the (sawdust + leaves)–sludge–phosphate (SL-S-P) treatment, OM content decreased continuously but showed clear dependence on phosphate dosage. In the control group (0 mmol P/g DS), OM decreased from 67.5% to 32.6%, whereas at a high phosphate dosage (0.9 mmol P/g DS), OM decreased from 66.9% to 28.9%, showing a greater overall reduction. Moderate phosphate addition (0.3 mmol P/g DS) enhanced early-stage decomposition, whereas excessive phosphate seemed to increase microbial utilization of organic substrates and accelerate OM depletion. Overall, all composting treatments followed a pattern of rapid OM decline followed by gradual stabilization. The biphasic degradation pattern reflects sequential substrate utilization dynamics. Easily degradable fractions, such as soluble sugars, proteins, and hemicellulose, were rapidly mineralized during the early thermophilic stage, resulting in a sharp decrease in OM content.³⁰ As composting progressed, the remaining OM consisted predominantly of lignocellulosic and humified compounds, whose oxidative depolymerization and structural reorganization proceeded more slowly,³¹ leading to gradual stabilization. The C/N ratio, bulking agent type, and phosphate supplementation all played significant roles in regulating OM degradation. A moderate C/N ratio combined with adequate phosphate addition balanced OM degradation and stabilization, thereby improving compost quality.

3.2.4. Variations in ammonium nitrogen

Ammonium nitrogen is an important intermediate in nitrogen transformations during composting, and its concentration varies over time in response

to mineralization, ammonia volatilization, pile pH, temperature, and C/N ratios. As shown in Figure 4, all treatments exhibited a characteristic pattern of an initial increase followed by a subsequent decline in $\text{NH}_4^+\text{-N}$.

In the S-S treatment, the initial $\text{NH}_4^+\text{-N}$ content was relatively low, ranging from 0.043% to 0.057%. With rising temperature and accelerated nitrogen mineralization, $\text{NH}_4^+\text{-N}$ peaked on day 6 at a C/N ratio of 20, reaching a maximum of 0.072%, whereas a C/N ratio of 30 showed a lower peak of 0.059%. Thereafter, $\text{NH}_4^+\text{-N}$ content gradually declined and stabilized, likely due to ammonia volatilization, nitrification, or microbial assimilation. In general, higher C/N ratios reduced the risk of ammonia volatilization.

In the SL-S treatment, $\text{NH}_4^+\text{-N}$ increased and then declined gradually, with peak values occurring slightly earlier (around day 7). The maximum $\text{NH}_4^+\text{-N}$ contents at the C/N ratios of 20, 25, and 30 were 0.065%, 0.059%, and 0.051%, respectively. Adding leaves provided readily degradable carbon, which stimulated the microbial activity and accelerated the production of $\text{NH}_4^+\text{-N}$. However, the subsequent decline was more pronounced, with concentrations dropping below 0.03% after day 13, particularly at a C/N ratio of 30. This suggests that leaf addition promoted early nitrogen mineralization but favoured nitrogen stabilization at later composting stages.

In the SL-S-P treatment, $\text{NH}_4^+\text{-N}$ also increased initially, but its concentrations were consistently lower than those in the phosphate-free control. With increasing phosphate dosage, the $\text{NH}_4^+\text{-N}$ peak decreased to 0.053% at 0.9 mmol P/g DS, after which the decline became more gradual. These observations suggested that phosphate addition reduced ammonia volatilization by moderating pH and enhancing microbial nitrogen assimilation, thereby improving nitrogen retention. Overall, $\text{NH}_4^+\text{-N}$ dynamics were regulated by both C/N ratio and phosphate addition.

Higher C/N ratios provided sufficient carbon skeletons for microbial immobilization of ammonium into biomass, reducing the accumulation of free NH_4^+ susceptible to volatilization. Moderate phosphate supplementation likely enhanced adenosine triphosphate (ATP)-dependent biosynthetic processes and microbial growth efficiency, promoting nitrogen incorporation into stable organic forms.³² This coordinated carbon–nitrogen–phosphorus coupling improved nitrogen retention and contributed to compost maturation quality.

In summary, NH_4^+ -N dynamics were driven mainly by the C/N ratio and phosphate addition. A higher C/N ratio combined with moderate phosphate supplementation reduced ammonia volatilization, increased nitrogen use efficiency, and ultimately improved compost quality.

3.3. Enzymatic activity in composting

Composting is a biochemical process in which microorganisms produce enzymes that decompose and transform OM.³³ Therefore, measuring key mineralization enzymes, such as cellulase, protease, urease, and peroxidase, provides effective indicators of microbial abundance and activity dynamics during composting.

3.3.1. Cellulase

Cellulase activity generally increases during the thermophilic phase and declines as composting progresses. This is due to changes in the microbial communities and substrate availability. Activity typically peaks when microbial biomass and OM degradation rates are high. Figure 5A shows the changes in cellulase activity during composting. Cellulase activity was relatively low during the initial stage of composting. The initial cellulase activity values for S–S (C/N = 25), SL–S (C/N = 25), and SL–S–P (C/N = 25, 0.6 mmol P/g DS) were 2.396, 2.579, and 2.531 mg glucose/g/dw/h, respectively. A brief decrease in cellulase activity was observed during the early stage in

both the S–S and SL–S treatments. This phenomenon may be attributed to the rapid increase in temperature preceding the substantial growth of thermophilic and mesophilic microbial populations, while low-temperature cellulase-producing microorganisms were suppressed by heat. As a result, enzyme secretion was temporarily reduced, leading to low initial cellulase activity. Cellulase activity in SL–S–P continued to increase and reached a peak value of 8.005 mg glucose/g/dw/h, while the high concentration of cellulase was maintained for a longer duration. These results suggest that phosphorus supplementation stimulated microbial activity during composting, probably because phosphorus is an essential element for cellular metabolism—including ATP synthesis and enzyme structural maintenance—which contributed to growth and enzyme production.^{34,35}

3.3.2. Protease and urease

Proteases mediate the initial steps of mineralization, which are often considered the rate-limiting steps in the nitrogen cycle. Thus, protease and urease are key functional enzymes driving nitrogen transformation during composting.³⁶ As shown in Figure 5B, S–S (C/N = 25), SL–S (C/N = 25), and SL–S–P (C/N = 25, 0.6 mmol P/g DS) treatments followed similar protease activity curves, characterized by a rapid increase during the early stage of composting, peaking on day 7 at 351.6, 374.3, and 395.7 $\mu\text{g/g/dw/h}$, respectively, followed by a sharp decline. This pattern reflected the high amount of readily degradable OMs (proteins) in the starting materials, which promoted microbial growth and enhanced protease secretion for protein hydrolysis. As composting entered the thermophilic phase, most easily degradable substrates were depleted, and microbial metabolism shifted toward more recalcitrant polymers such as cellulose and lignin, leading to a decline in protease activity. Meanwhile, urease activity (Figure 5C) showed a trend similar to that of protease, rising rapidly during the thermophilic phase, peaking on day 9, and then declining

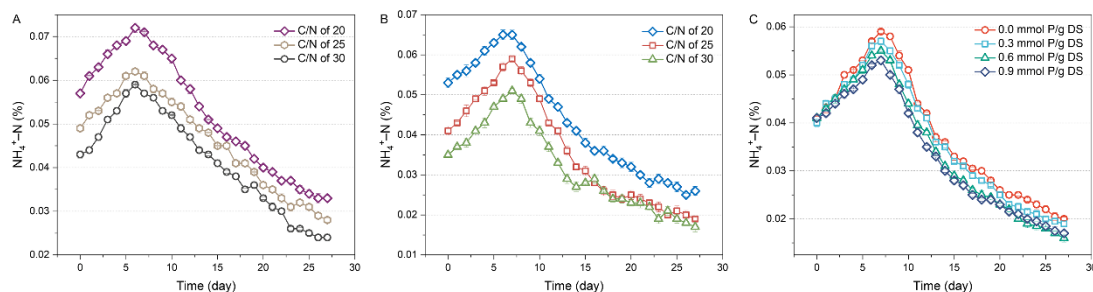


Figure 4. Changes in NH_4^+ -N content during composting under different treatments: (A) S–S and (B) SL–S treatments with various C/N ratios, and (C) SL–S–P treatments with various phosphate dosages based on SL–S at a C/N ratio of 25

Abbreviations: C: Carbon; DS: Dry solid; N: Nitrogen; NH_4^+ -N: Ammonium nitrogen; SL–S: (Sawdust + leaves)–sludge; SL–S–P: (Sawdust + leaves)–sludge–phosphate; S–S: Sawdust–sludge.

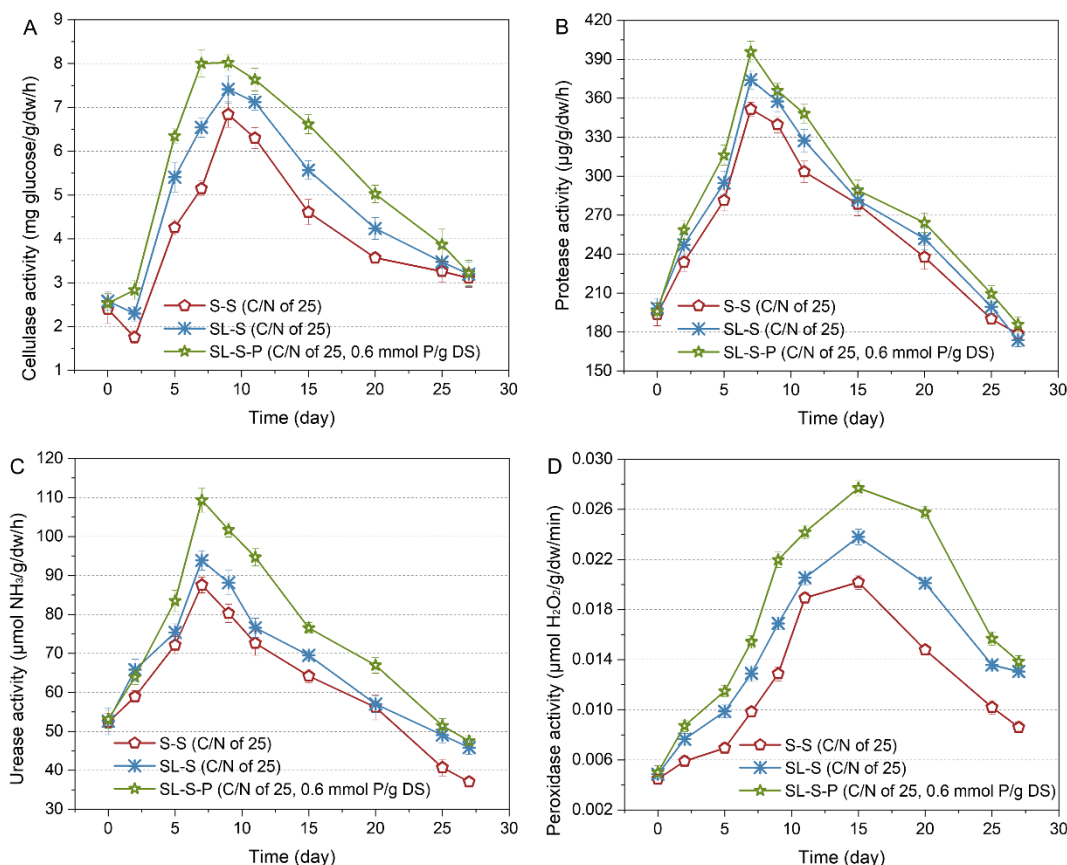


Figure 5. Changes in (A) cellulase, (B) protease, (C) urease, and (D) peroxidase activities in S-S (C/N ratio of 25), SL-S (C/N ratio of 25), and SL-S-P (C/N ratio of 25, 0.6 mmol P/g DS) treatments

Abbreviations: C: Carbon; DS: Dry solid; N: Nitrogen; SL-S: (Sawdust + leaves)–sludge; SL-S-P: (Sawdust + leaves)–sludge–phosphate; S-S: Sawdust–sludge.

gradually. Consistent with the cellulase results, both SL-S (C/N = 25) and SL-S-P (C/N = 25, 0.6 mmol P/g DS) treatments exhibited higher enzyme activities, suggesting that leaf and phosphorus additions stimulated growth and metabolism and accelerated the composting process.

3.3.3. Peroxidase

The slow degradation of structurally complex lignin in OM limits composting efficiency.³⁷ Lignin breakdown is a multifaceted biochemical process dependent on oxidative enzymes, such as peroxidases. The measured peroxidase activity during composting is presented in Figure 5D. The initial peroxidase activities in S-S (C/N = 25), SL-S (C/N = 25), and SL-S-P (C/N = 25, 0.6 mmol P/g DS) treatments were 0.0045, 0.0049, and 0.0050 μmol hydrogen peroxide (H₂O₂)/g/dw/min, respectively. Enzyme activity increased in all treatments, peaked on day 15 at 0.0201, 0.0238, and 0.0277 μmol H₂O₂/g/dw/min, respectively, and

subsequently declined.

The time profile indicated that lignin degradation occurred predominantly during the later stages of composting. Under a C/N ratio of 25, SL-S showed higher peroxidase activity than the S-S treatment. Phosphorus supplementation appeared to stimulate ligninolytic activity by supporting microbial energy metabolism and enzyme synthesis. As phosphorus is integral to nucleic acid formation and ATP generation, its availability likely enhanced microbial biomass production and sustained peroxidase secretion.³⁸ The prolonged enzyme activity suggests the improved oxidative degradation of recalcitrant lignin fractions, facilitating deeper OM transformation. Together, the results suggest that both leaf addition and phosphorus amendment enhanced peroxidase activity during composting, likely by stimulating microbial metabolism and accelerating the breakdown of recalcitrant organic compounds such as lignin.

3.4. Application in topsoil improvement

3.4.1. Compost duration and product

Table 5 shows that the time required for different compost mixtures to reach 40% OM degradation varied substantially across compost mixtures. In the S-S treatment, the time to reach 40% OM degradation was 27 days at a C/N ratio of 30 and 20 days at a C/N ratio of 20, indicating that a higher proportion of sawdust slowed OM mineralization. The SL-S treatment exhibited faster OM degradation. At a C/N ratio of 30, only 21 days were required to reach 40% degradation, indicating that the presence of readily degradable leaves promoted early-stage mineralization. The degradation process was further accelerated in SL-S-P system, where the addition of phosphate (0.6 mmol P/g DS) reduced the required time to 16 days, indicating that phosphate alleviated potential nutrient limitations on microbial metabolism. By enhancing microbial growth kinetics and enzymatic activity, phosphate addition likely increased the rate constants of OM mineralization,³⁹ thereby shortening the stabilization period compared with non-amended systems. As shown in Figure 6, the final compost contained 412 g OM/kg. Meanwhile, hydrolyzable nitrogen, available phosphorus, and available potassium all exceeded the minimum standardized limits, indicating improved nutrient availability. The compost also exhibited a low bulk density of 0.45 g/cm³ and a moderate pH of 6.89. Collectively, these properties indicate that the compost product can effectively compensate for deficiencies in nutrient composition and physicochemical properties of topsoil, supporting its application for topsoil improvement.

3.4.2. Topsoil improvement formula

As shown in Figure 6, compost addition rates of 3.5%, 6%, and 9% significantly increased soil OM, available phosphorus, available potassium, and hydrolyzable

nitrogen, while decreasing bulk density and maintaining soil pH within the range of 6.98–7.55. Notably, at an addition rate of 9%, OM content increased from 5.20 to 44.53 g/kg, while bulk density decreased from 1.40 to 1.31 g/cm³. The substantial increase in soil OM reflects the incorporation of stabilized humic substances, which act as binding agents promoting aggregate formation.⁴⁰ The development of stable aggregates enhanced pore space and reduced soil compaction, thereby lowering bulk density and improving water-holding capacity and aeration. Meanwhile, all measured soil quality indicators satisfied the standard requirements for planting soils, indicating that the amended soil was well-suited for topsoil improvement for slope revegetation/greening in the reservoir area. Figure 7 shows that the mechanical compositions of soil modified with compost product at 9% included 45.61% sand, 36.41% silt, and 17.98% clay. Compared with raw topsoil, the proportions of sand and clay decreased, suggesting that compost addition improved soil aggregation and contributed to enhanced water retention and aeration.

3.4.3. Risk analysis of heavy metals

Figure 8 shows that heavy metal concentrations in both the compost product and amended soil were well below the limits for landscaping soils. In amended soil, As, Cd, Cr, Hg, Cu, Ni, Pb, and Zn were measured at 1.33, 0.08, 1.21, 0.07, 10.1, 1.23, 1.04, and 46.7 mg/kg, respectively, all lower than the grade I soil quality criteria. These results indicate that the compost did not introduce heavy metal contamination and effectively improved soil physical and chemical properties by increasing OM and nutrient content while ensuring heavy metal safety. Soil improvement depended heavily on compost feedstock ratio, amendment rate, and compost maturity. Higher compost proportions increased OM and nutrient concentrations, but excessive addition could compromise soil structural stability.⁴¹

Table 5. Time required for different compost treatments to reach 40% OM degradation

Composting treatment		Initial OM content (%)	OM _t ^a (%)	Duration (days)
S-S	C/N of 20	63.6	37.6	20
	C/N of 25	66.5	39.5	23
	C/N of 30	69.1	41.2	27
SL-S	C/N of 20	62.3	36.4	18
	C/N of 25	67.4	39.4	19
	C/N of 30	72.5	42.9	21
SL-S-P (0.6 mmol P/g DS)	C/N of 25	67.8	40.3	16

Note: ^aOM_t represents the organic matter content when its degradation reaches 40%. Abbreviations: C: Carbon; DS: Dry solid; N: Nitrogen; OM: Organic matter; SL-S: (Sawdust + leaves)–sludge; SL-S-P: (Sawdust + leaves)–sludge–phosphate; S-S: Sawdust–sludge.

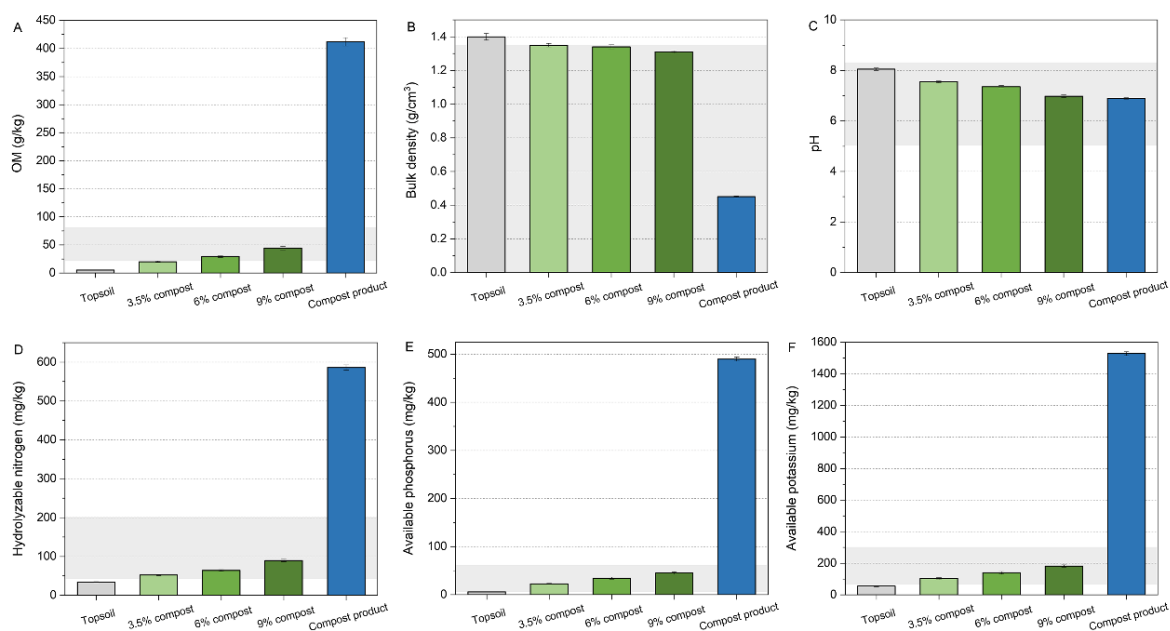


Figure 6. The (A) OM, (B) bulk density, (C) pH, (D) hydrolyzable nitrogen, (E) available phosphorus, and (F) available potassium of topsoil, compost product, and compost-amended soils compared with the standardized ranges (gray areas) of Planting Soil for Greening (CJ/T 340-2016)
Abbreviation: OM: Organic matter.

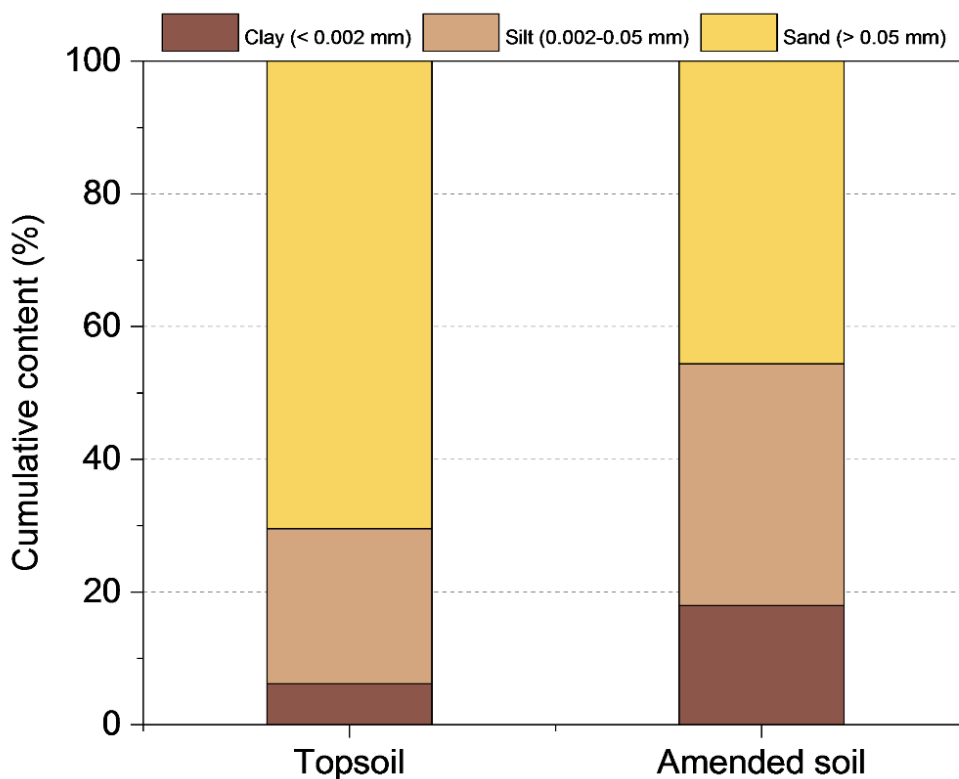


Figure 7. Mechanical compositions of topsoil and amended soil with 9% compost product

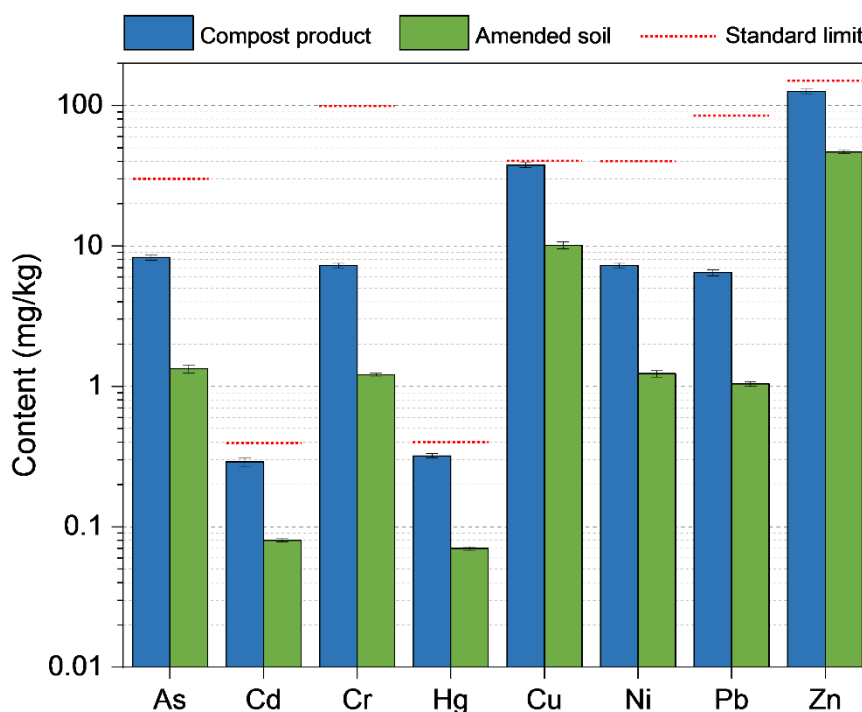


Figure 8. Heavy metal contents in compost product and amended soil with 9% compost product compared with soil standard (Planting Soil for Greening [CJ/T 340–2016], Grade I)

Abbreviations: As: Arsenic; Cd: Cadmium; Cr: Chromium; Cu: Copper; Hg: Mercury; Ni: Nickel; Pb: Lead; Zn: Zinc.

Conversely, insufficient or immature compost could lead to ammonia volatilization or leave OM incompletely decomposed, limiting the improvement effect. Therefore, the use of appropriate amendment rates and fully mature compost is required to achieve optimal soil enhancement.

3.5. Implications for carbon neutrality

Achieving carbon neutrality requires coordinated reductions in emissions across energy production, waste management, and land-use systems.⁴² Beyond energy-sector decarbonization, resource-oriented treatment of organic wastes and enhancement of terrestrial carbon sinks represent complementary pathways.⁴³ The phosphate-enhanced co-composting strategy proposed in this study establishes a functional linkage between municipal sludge management, forestry residue utilization, and ecological restoration in hydropower reservoir areas. By converting locally generated organic wastes into stabilized soil amendments, the system provides a potential alternative to disposal routes such as landfilling and incineration. The optimized C/N ratio and phosphate supplementation improved humification efficiency and nitrogen stabilization, enhancing material utilization and reducing nutrient losses. Application to degraded reservoir

topsoils improved soil structure and fertility, which may support vegetation recovery and soil carbon accumulation over time.

It should be noted that this study did not directly quantify greenhouse gas emissions, carbon balances, or life-cycle impacts. Therefore, the relevance of carbon neutrality discussed here is conceptually based on process characteristics rather than measured emission reductions. Nevertheless, the integrated waste-to-soil framework illustrates how ecological restoration measures can be aligned with low-carbon development strategies in renewable energy infrastructure regions.

3.6. Technical application and prospects

Building upon the system-level implications discussed above, practical implementation requires careful consideration of scalability and environmental performance. The optimized compost formulation (C/N ratio of 25 with phosphate addition of 0.6 mmol P/g DS) provides a technically feasible configuration for producing stable soil amendments. Application of mature compost at a 9% addition rate improved soil properties without exceeding heavy metal standards, indicating suitability for slope restoration in hydropower reservoir areas.

However, this study was conducted under laboratory-controlled conditions, and field-scale performance may vary. Importantly, greenhouse gas emissions during composting and long-term soil carbon sequestration were not directly monitored, and no life-cycle assessment was performed. Future research should therefore include pilot-scale validation, quantitative carbon accounting, and life-cycle evaluation to determine the net mitigation potential relative to conventional sludge disposal pathways.

For decision-makers, on-site composting systems may support local resource utilization and reduce waste transport requirements. Nevertheless, large-scale adoption should be accompanied by carbon performance assessment, environmental monitoring, and standardized management protocols to ensure both ecological safety and alignment with broader carbon-neutral development objectives.⁴⁴

4. Conclusion

This study developed a phosphate-enhanced co-composting approach using municipal sludge, sawdust, and fallen leaves to produce a high-quality soil amendment for degraded reservoir topsoils. The optimal C/N ratio was 25, with a sawdust-leaves mixture serving as a bulking agent. With phosphate added at 0.6 mmol P/g DS, composting improved microbiological activity and OM degradation rate. Moreover, nitrogen loss was reduced, and composting time was shortened. The final compost enhanced OM content, improved nutrient availability, decreased bulk density, and optimized particle size distribution, while maintaining heavy metal concentrations within safe limits. Together, this solid waste-based composting strategy provides a technically feasible and environmentally sustainable low-carbon solution for soil improvement and ecological restoration in high-altitude hydropower project areas.

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Conflict of interest

The authors declare that they have no competing interests.

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Writing – review & editing: Jiuxian Yang, Ying Wang, Yalin Yu, Dongdong Ge

Availability of data

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

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