Effects of Expanded Polytetrafluoroethylene Porous Membrane Covering and Biochar on Nitrogen, Phosphorus, and Potassium Contents in Aerobic Composting

Jie Cao, Ruirong Li,* Haoli Qu,* Pengjun Wang, Jingjing Fu, Yan Gong, and Mingjiang Chen

The effects of covering technology and the combined membrane covering with biochar on nutritional elements content during the aerobic composting process of agricultural waste were studied. The results showed that the concentration effect of organic matter degradation during composting increased the nitrogen, phosphorus, and potassium contents in all treatment groups. The proportion of available phosphorus and available potassium also increased to varying degrees. Compared with composting without an expanded poly(tetrafluoroethylene) (PTFE) covering with 0.2 to 0.4 μm pores, the covered composting increased the total nitrogen, total phosphorus, total potassium, available phosphorus, and available potassium contents by 13.1%, 12.6%, 7.4%, 21.5%, and 16.6%, respectively, while the addition of biochar to polymer membrane-covered composting increased the total nitrogen, total phosphorus, total potassium, available phosphorus, and available potassium contents by 19.7%, 13.7%, 8.3%, 18.0%, and 20.2%, respectively. This study indicated that membrane covering technology can effectively increase the nutrient element contents in compost products and the availability of phosphorus and potassium and that the addition of biochar enhances these effects.

DOI: 10.15376/biores.20.1.25-41

Keywords: Biochar; Membrane covering; Potassium; Phosphorus; Aerobic composting; Nitrogen

Contact information: Ministry of Agriculture and Rural Affairs, Nanjing Institute of Agricultural Mechanization, Nanjing 210014, China;
** Corresponding authors: lrr006@163.com; 308658480@qq.com*

INTRODUCTION

Nitrogen, phosphorus, and potassium are essential components that underpin soil productivity (Islam *et al.* 2023). Increasing the soil nutrient reservoir capacity is an important aspect of soil fertility improvement (Palacino *et al.* 2024). Recycling and reuse of nutrients in agricultural ecosystems is a traditional practice in China’s agricultural fertilization process, playing a crucial part in preserving soil nutrients and improving soil fertility (Yang *et al.* 2022). Maintaining the recycling and reuse of nutrients based on appropriate fertilization strategies not only can meet the nutrient demands of high-yield crops and balance the soil nutrient needs, but it also can reduce the excess nutrients entering the environment, thereby mitigating the environmental risks caused by irrational fertilization (Kwadjo *et al*. 2018; Xing *et al.* 2022). This is of great significance for maintaining basic soil fertility, improving cultivated land quality, and promoting green and sustainable agricultural development (Reddy *et al.* 2024).

Agricultural waste consists of organic materials discarded during the agricultural production process. It typically contains a high concentration of nitrogen, phosphorus, and potassium, which are essential components that the soil critically requires (Ren *et al.* 2022). Mo *et al*. (2009) analyzed the nutritional components of tomato, cucumber, chili, and headed cabbage wastes and demonstrated that the nitrogen, phosphorus, and potassium contents of the wastes ranged from 3.2% to 8.6%, the organic matter content ranged from 42.8% to 67.4%, and the trace element contents, including calcium, iron, and zinc, ranged from 1.62% to 8.71%. Cai (2015) researched vegetables in the Yuzhong area of Gansu and found that the nitrogen, phosphorus, and potassium contents in greenhouse-cultivated Solanaceae plants were higher than those in land-cultivated plants. Additionally, the nitrogen and potassium contents were higher than the phosphorus content. The total carbon and lignin contents were the highest in open-field eggplants, and the highest cellulose content (54 %) was found in greenhouse chili peppers.

Rational and efficient resource utilization of agricultural waste has significant ecological and social benefits (Cao *et al.* 2024a). Composting and returning to the field are the most widely used methods for resource utilization of agricultural waste (Wei *et al.* 2021). Chinese farmers have used compost for thousands of years (Li *et al.* 2023). Different from the relatively stable phosphorus and potassium elements, during the composting process, nitrogen can be excreted by its transformation into gases such as ammonia and nitrous oxide. This can lead to the loss of nutrient elements in the compost and simultaneously cause odor pollution. Recently, with advancements in technology, the polymer membrane-covered composting method has been widely researched and applied because of its economic efficiency and effective deodorization capabilities (Ma *et al*. 2017; Li *et al*. 2021a; Cui *et al*. 2024; Lin *et al.* 2024). The main functional structure of the polymer film is expanded polytetrafluoroethylene (e-PTFE), which has uniformly distributed pores that generally have an aperture of 0.2 to 0.4 micrometers. Such tiny pores can effectively reduce the emission of ammonia and other malodorous gases during the composting process. Qin *et al*. (2022) found that at a sludge, garden waste, and corn straw ratio of 7:3:1 and an aeration rate of 0.125 $m^3/min \cdot m^3$, the polymer film composting method achieved the best maturity and nitrogen fixation effect. Sun *et al*. (2014) explored the application of membrane-covering technology in the sludge composting process on the Qinghai-Tibet Plateau and found that membrane-covering technology could reduce the emission of nitrous oxide and ammonia during composting. Gonzalez *et al*. (2016) analyzed physicochemical properties and microorganisms during the sludge composting process under membrane-covering conditions and discovered that the membrane could reduce the odor emission rate approximately 90% during composting. Cao *et al.* (2022, 2024b) found that membrane-covered composting had a better effect on reducing ammonia emissions than traditional methods, such as adding superphosphate or biochar.

Research on polymer membrane-covered composting technology has mainly focused on improving composting efficiency and reducing ammonia emissions. However, the impact of membrane-covered composting technology on nutrient elements, such as nitrogen, phosphorus, and potassium, in compost materials has rarely been reported. In this study, the authors aimed to investigate the impact of polymer membrane-covered composting and the simultaneous addition of biochar on nitrogen, phosphorus, and potassium contents during the aerobic composting of agricultural waste to provide technical support for promoting nutrient recycling in the utilization of agricultural waste for fertilization purposes and reducing the application of chemical fertilizers in agricultural production.

EXPERIMENTAL

Materials

The tomato straw and mushroom residue used in this study were sourced from a large vegetable cultivation garden in Nanjing, China. The tomato straw was cut to less than 3 cm. Biochar was purchased from Nanjing Qinfeng Straw Technology Co., Ltd., and rice straw was used as the raw material. The cation exchange capacity and specific surface area of the biochar were 9.4 cmol/kg^{-1} and 53.5 m^2/g^{-1}, respectively. The nutrient element contents and basic physicochemical properties of the composting materials are shown in Table 1.

Table 1. Physicochemical Properties of Composting Materials

Parameters	TC (%)	TN (%)	C/N	MC (%)	TK (%)	TP (%)
Tomato stalks	46.31 ± 1.76	1.40 ± 0.05	33.08 ± 1.03	20.7 ± 1.22	2.37 ± 0.09	1.25 ± 0.06
Mushroom residue	20.42 ± 1.23	1.07 ± 0.02	19.08 ± 0.56	49.4 ± 0.39	1.62 ± 0.06	0.43 ± 0.04
Biochar	46.84 ± 0.75	0.59 ± 0.06	79.39 ± 0.25	2.7 ± 0.09	0.53 ± 0.04	0.51 ± 0.02
Mixture	38.17 ± 0.45	1.30 ± 0.04	29.36 ± 0.25	62.8 ± 1.98	2.13 ± 0.09	0.99 ± 0.07

TC, total carbon; TN, total nitrogen; C/N. carbon/nitrogen ratio; MC, matter content; TP, total phosphorus; TK, total potassium

Experimental Design

The composting apparatus used in this study, as shown in Fig. 1, primarily consisted of a 500-L fermentation container, container control system, and an aeration system. Air was pumped into the bottom of the material through a pipeline at a fixed flow rate of 0.1 m^3·min^{-1}·m^{-3} (Cao *et al.* 2022).

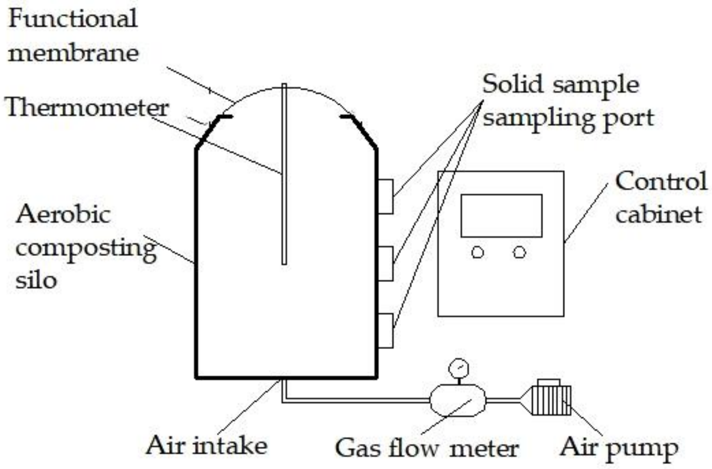

Fig. 1. Structure diagram of aerobic composting device

Well-mixed materials of the same weight were placed into three fermentation units and labeled as CK, T1, and T2. In the T2 group, an additional 10% biochar was added to the composting material. The upper part of the fermentation container of the CK group was left uncovered, whereas the top parts of the fermentation containers in the T1 and T2 groups were covered with a polymer membrane composed of expanded polytetrafluoroethylene (e-PTFE) porous membrane material.

Sample Collection and Analysis

The composting experiment lasted 36 days. Samples were taken from different parts of the compost pile using the 3-point method on days 0, 6, 12, 18, 24, 30, and 36 of the experiment. After evenly mixing the samples, three separate samples were taken and immediately tested for nutritional elements such as nitrogen, phosphorus, and potassium. Total carbon (TC) and total nitrogen (TN) were determined using an elemental analyzer (Vario MACRO cube, Germany). For the determination of ammonium nitrogen and nitrate nitrogen, a 2 M potassium chloride solution was used for extraction for 60 min with a solid-to-liquid ratio of 1:10 (m/V, based on dry weight). After the mixture was allowed to stand for 30 min, it was centrifuged and filtered. The filtrate was analyzed using a flow analyzer (iFIA7; Beijing Titian Instrument Co., Ltd, Beijing, China). Total potassium (TK) and total phosphorus (TP) content were measured using flame photometry (HD-20; Shandong Horde Electronic Technology Co., Ltd, Shandong, China) and the alkali fusion-molybdenum antimony anti-spectrophotometric method (HD-UV60; Shandong Horde Electronic Technology Co., Ltd, Shandong, China), respectively. Available phosphorus content (AP) was determined using the sodium bicarbonate extraction-molybdenum-antimony anti-colorimetric method (Liu *et al.* 2014). Available potassium (AK) was measured using an ammonium acetate extraction-flame photometer (HD-20; Shandong Horde Electronic Technology Co., Ltd, Shandong, China). Organic matter content was measured using the potassium dichromate volumetric method (NY/T 525 (2021)). All test samples were set in three parallels. The compost pile temperature was measured automatically using a continuous temperature-monitoring probe built into the fermentation device. The average value was taken as the daily compost temperature, and the ambient temperature was measured simultaneously.

Data and Statistical Analyses

The test data were processed using Excel 2016 (Microsoft Corp., Redmond, WA, USA) and statistically analyzed using SPSS 22.0 (IBM Corp., Armonk, NY, USA). Graphs were created using Origin 9.1 (OriginLab Corp., Northampton, MA, USA). Data Analysis of Variance (ANOVA) was conducted using Statistical Analysis System (SAS) version 9.4 (SAS Institute Inc., Cary, NC, USA). The mean comparison was conducted using Tukey’s test at a significance level of 0.05.

RESULTS AND DISCUSSION

Temperature Changes

Temperature is one of the most important factors affecting microbial activity and the aerobic composting process of organic solid waste and reflects microbial activity in the composting system. The temperature changes of the materials in the three experimental groups are shown in Fig. 2, all exhibiting a sharp rise, followed by a brief period of stability and gradual decline.

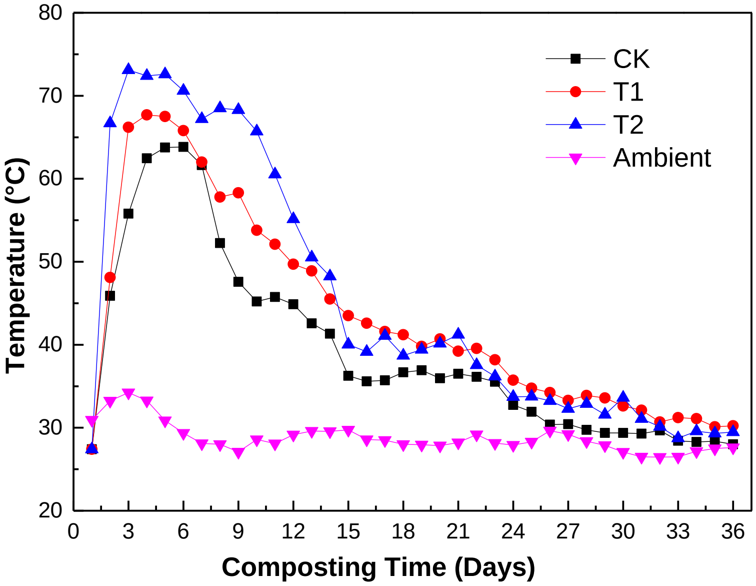

Fig. 2. Temperature profiles of the three groups. Run CK: control; Run T1, membrane covering; Run T2, membrane covering + biochar addition

The temperature in the CK, T1, and T2 groups peaked at 63.8, 67.7, and 73.6 °C on the 6th, 4th, and 3rd days, respectively, after the start of the experiment. Throughout the composting cycle, the high-temperature periods (≥ 55 °C) lasted for 5, 8, and 9 days, respectively. The changes in temperature during aerobic composting mainly depend on material conditions, microbial growth and metabolism, and insulation effects. Compared with the CK group, the T1 group covered with a polymer film exhibited higher compost temperatures ($p < 0.05$) and longer high-temperature periods ($p < 0.05$). This was attributed mainly to the good insulation effects of the polymer film, creating a relatively closed and stable composting environment and enhancing microbial activity. This result is consistent with those of Cao *et al*. (2022). Regarding temperature increase and performance maintenance, the T2 group, in which both membrane covering and biochar addition were applied, showed the best results. This is consistent with the porous structure of the biochar, which provided an excellent area for microbial growth and metabolism. The biochar also made the whole bed more evenly permeable, allowing the pumped air to be distributed better throughout the compost pile, accelerating the degradation of organic matter, and increasing the compost temperature. Continuous high temperatures can more effectively kill harmful microorganisms in the material, and the composting inoculants contain heat-resistant strains; therefore, it will not restrict the progress of the composting reaction. Wang *et al*. (2024) reported similar findings when biochar was added to an animal manure composting process.

Changes in the Organic Matter Content

Composting is a process in which unstable organic matter in a mixture undergoes microbial degradation, transformation, and humic acid synthesis. Therefore, changes in the organic matter content of the mixture reflect, to a great extent, the microbial metabolic processes, and the progress of the composting reaction. The changes in the organic matter content in the three experimental groups are shown in Fig. 3.

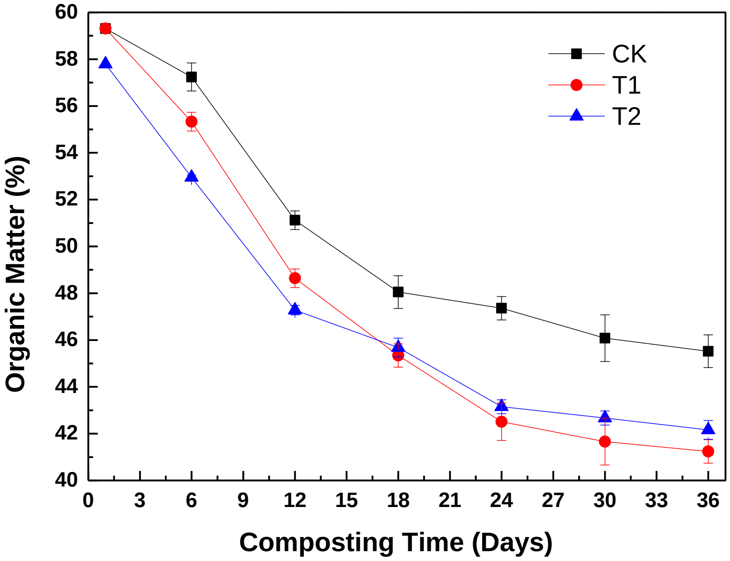

Fig. 3. Organic matter content variation profiles of the three experimental groups

As the composting reaction continued, the organic matter content in each composting group exhibited a gradually declining trend, with higher and lower declining rates in the early and later stages, respectively. At the end of the experiment, the organic matter content of the materials in the CK, T1, and T2 experimental groups decreased from the initial composting levels of 59.3%, 59.3%, and 57.8% to 45.5%, 41.2%, and 42.2%, respectively, with reductions of 23.2%, 30.5%, and 27.0%, respectively. The degradation percentages (T1 > T2 > CK) indicated that the polymer membrane-covered technology effectively increased the degradation rate of organic matter during the composting process. This was mainly because the membrane covering formed a relatively enclosed micro-positive-pressure composting environment, which was beneficial for microbial growth and metabolism (Li *et al.* 2023). This corresponds to the higher material temperature in the T1 group. The micro-positive pressure composting environment promoted oxygen distribution within the material, resulting in better decomposition effects. The extent of organic matter degradation in the T2 treatment material, which had biochar added, was lower than that in T1, primarily because the organic matter in biochar was more difficult to degrade (Wang *et al.* 2020).

Changes in the Total Nitrogen Content

Nitrogen is an essential nutrient for plant growth and a component of proteins, nucleic acids, and chlorophyll in plants. Nitrogen has a significant impact on plant growth and development. The nitrogen transformation process in aerobic composting mainly includes the mineralization of organic nitrogen, nitrification and denitrification, ammonia adsorption and volatilization, and the synthesis of organic nitrogen. The changes in the TN content of the materials in the three experimental groups are illustrated in Fig. 4.

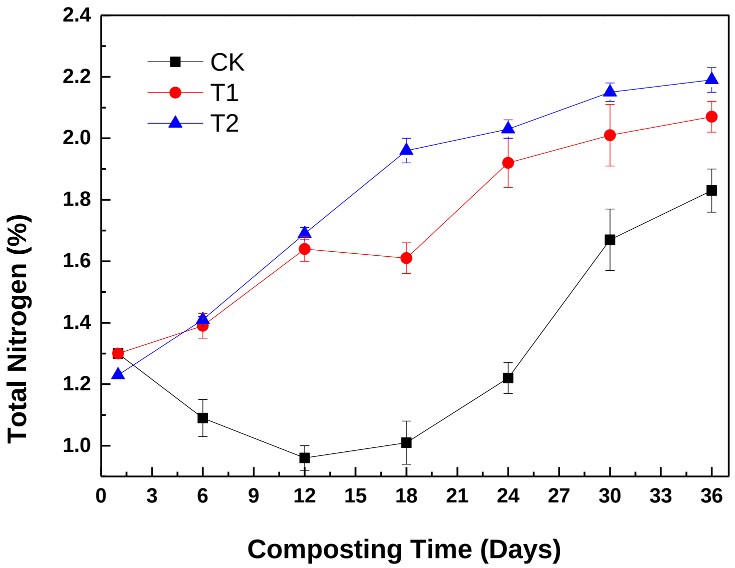

Fig. 4. Total nitrogen content variation profiles of the three experimental groups

The TN content in the CK group first decreased and then gradually increased. This was mainly due to the rapid decomposition of organic materials during the early stages of composting, during which significant quantities of organic nitrogen were transformed into ammonium nitrogen and diffused outward as ammonia gas (Zhou *et al*. 2024). However, Liu *et al*. (2024) found that during the composting of pig manure, the nitrogen content in the material maintained a continuous upward trend without showing a downward trend. This may mainly be due to the high nitrogen content in the pig manure. The carbon-to-nitrogen ratio of its raw material was 20:1, which was much lower than the 29:1 in this study. The TN contents in the T1 and T2 groups gradually increased, which was mainly because the polymer membrane formed a water film on its inner wall during the composting process, absorbing a large amount of ammonia gas and reducing the nitrogen loss caused by ammonia emissions (Cao *et al*. 2022). At the same time, during the composting process, the organic components were continuously mineralized, causing the total dry matter of the compost to continuously decrease at a rate greater than the decrease in nitrogen content caused by ammonia volatilization, resulting in a “concentration effect” in the TN content of the compost pile (Li *et al*. 2021b). In other words, the mineralized nitrogen accumulated and was enriched due to progressive degradation and volatilization of other organic compounds. The addition of biochar in the T2 group further increased the adsorption of ammonia gas, leading to even lower ammonia emissions and a higher TN content in the compost pile (Huang *et al*. 2024). At the end of the experiment, the TN content in the CK, T1, and T2 experimental groups increased by 40.8%, 59.2%, and 78.0%, respectively, indicating that aerobic composting enhanced the TN content in the materials. Furthermore, the use of membrane-covering technology and the addition of biochar are conducive to reducing nitrogen loss during the composting process.

Changes in the Ammonium Nitrogen Content

Ammonium nitrogen in composting materials primarily originates from the microbial decomposition and utilization of organic nitrogen in the compost. Ammonium-nitrogen can be directly used by microorganisms to synthesize components of their life forms and is also a major component of nitrogen loss in compost. The changes in ammonium-nitrogen content in the three experimental groups are shown in Fig. 5.

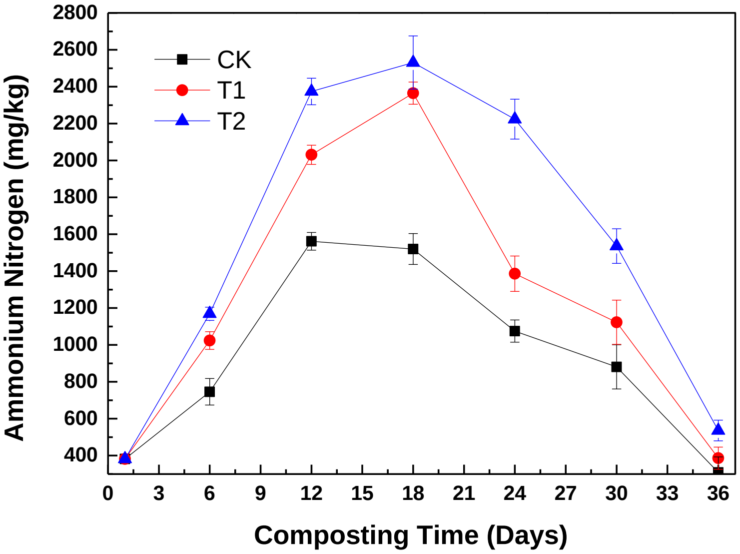

Fig. 5. Ammonium nitrogen content variation profiles of the three experimental groups

After the experiment began, the ammonium-nitrogen content increased rapidly. The ammonium nitrogen content in the CK, T1, and T2 groups peaked at 1562 mg/kg on the 12th day, 2365 mg/kg on the 18th day, and 2531 mg/kg on the 18th day, respectively. In the early stages of composting, the nitrogen-containing substances in the material were rapidly decomposed and transformed into ammonium-nitrogen by microorganisms, causing a rapid increase in water-soluble ammonium-nitrogen content. Subsequently, as the compost pile's temperature slowly fell, the activity of nitrifying bacteria intensified, nitrification intensified, and the proportion of ammonium-nitrogen converted into nitrate nitrogen continued to increase (Gao *et al*. 2018). Additionally, some ammonium-nitrogen contents were assimilated as a nitrogen source required for microbial growth, leading to a continuous decline in the concentration of ammonium-nitrogen in the compost pile. At the end of the experiment, the ammonium-nitrogen contents in the materials of the three experimental groups were 309 mg/kg, 386, and 536 mg/kg, respectively. Compared with the CK group, Membrane-covered composting had little effect on the ammonium-nitrogen content of the compost product. However, the addition of biochar to the membrane significantly increased the ammonium-nitrogen content of the product to a greater extent ($p < 0.05$). This was attributed mainly to the vast specific surface area of biochar, which gave it a strong adsorption capacity for ammonium-nitrogen (Huang *et al*. 2024).

Changes in the Nitrate Nitrogen Content

The nitrate nitrogen in compost materials mainly originates from the transformation of ammonium nitrogen by nitrifying bacteria. The main factor influencing nitrification in the aerobic composting process is the compost temperature, with the most suitable temperature generally ranging between 20 and 40 °C. High and low temperatures inhibit nitrification. Compared with ammonium nitrogen, the nitrate-nitrogen content in the materials of the three groups was lower during the initial stage of composting. During this period, the activity of the ammonifying bacteria was high, and nitrogen was primarily metabolized to ammonia gas, forming ammonium-nitrogen. Moreover, the compost temperature was high during the same period, which suppressed the nitrification activity of nitrifying bacteria. As the compost pile temperature gradually decreased, the activity of nitrifying bacteria within the pile increased, and the concentration of ammonium nitrogen, which is the raw material required for nitrification, increased significantly.

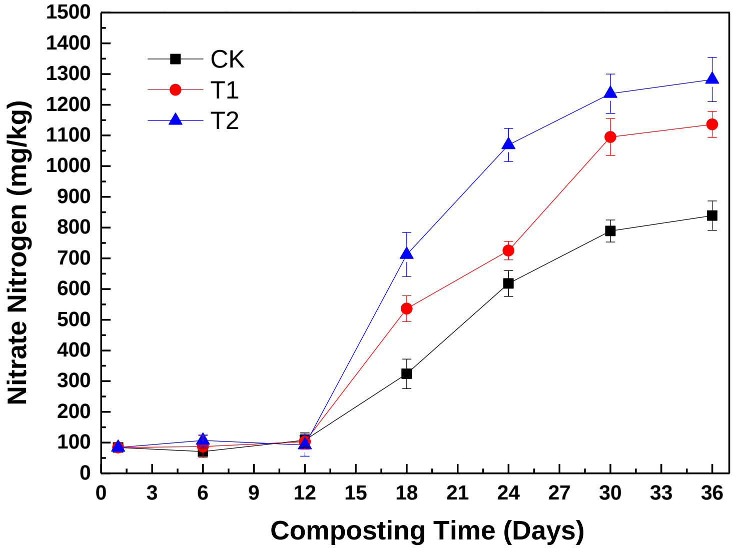

Fig. 6. Nitrate nitrogen content variation profiles of the three experimental groups

During nitrification, a significant quantity of ammonium nitrogen is transformed into nitrate nitrogen, which accumulates within the pile (Gao *et al*. 2018). Nitrate nitrogen increased rapidly on the 12th day after composting. Thirty days after the start of the experiment, as ammonium-nitrogen had been largely consumed, the nitrification process weakened, and nitrate-nitrogen content in the compost pile gradually stabilized. At the end of composting, the nitrate nitrogen content was the lowest in the CK group (839 mg/kg), followed by the T1 (1136 mg/kg) and T2 groups (1282 mg/kg). The ammonium-nitrogen content in the T1 and T2 groups increased 35.4% and 52.8% respectively, compared with that in the CK group, both of which were generally higher than the CK group ($p < 0.05$). However, no significant difference was observed between the T1 and T2 groups, indicating that biochar did not effectively increase the nitrate nitrogen content in the compost products. This was mainly attributed to the effect of the membrane covering and the addition of biochar in reducing ammonia emissions (Ma *et al*. 2017; Cao *et al*. 2022), which increased the ammonium nitrogen content required for nitrification in the compost pile.

Changes in the Total Phosphorus Content

Phosphorus is the third most abundant element in plants after nitrogen and potassium and is usually found in higher concentrations in seeds. It is a component of many important plant compounds, including nucleic acids, proteins, and enzymes. It plays a significant role in plant nutrition. During aerobic composting, phosphorus is more stable than nitrogen. Although different forms of phosphorus can be converted into each other, they do not volatilize or get lost; therefore, the absolute TP content remains almost unchanged (Yun *et al*. 2023). However, due to the decomposition and transformation of a large amount of organic matter during the composting process, as well as the volatilization of carbon dioxide and ammonia, the total dry matter in the compost pile continuously decreases, resulting in an increase in the TP content due to the concentration effect (Wang *et al*. 2019). The changes in the TP content of the materials in the three experimental groups are shown in Fig. 7.

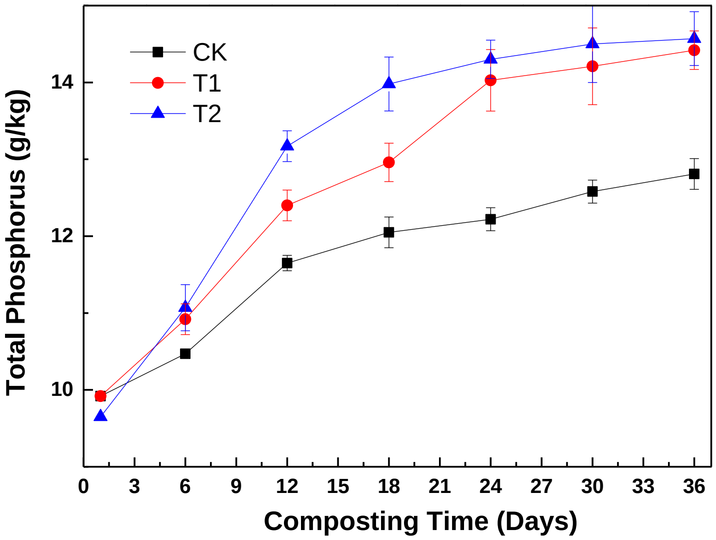

Fig. 7. Total phosphorus content variation profiles of the three experimental groups

The TP content of the materials in the CK, T1, and T2 groups increased from 9.92, 9.92, and 9.65 g/kg at the beginning of composting to 12.8, 14.4, and 14.6 g/kg at the end of composting, respectively, with increases of 29.1, 45.4, and 52.0%, respectively. Statistics analysis showed that compared to the CK group, both the T1 and T2 groups were generally improved ($p < 0.05$). This indicates that the membrane covering technology could effectively enhance the degradation rate of materials in the composting process, and simultaneously adding biochar to the covered membrane further promoted material degradation. That was mainly because the porous structure of biochar could provide a favorable living space for microorganisms, and its larger cation exchange capacity might also have some significance for the enhancement of microbial activity (Wang *et al*. 2024). This result is consistent with the degradation rate of organic matter in the material, as shown in Fig. 3.

Changes in the Available Phosphorus Content

The AP is the collective term for phosphorus that plants can absorb and utilize directly. In chemistry, AP is defined as phosphorus that can participate in isotope exchange and is easily extracted by certain chemical reagents or phosphates in solution. The changes in the AP content of the materials in the three experimental groups are shown in Fig. 8, all decreasing at first, then rapidly increasing, and finally stabilizing. This was mainly because, in the early stages of fermentation, the organic acid content in the material was relatively low, with limited ability to dissolve phosphorus.

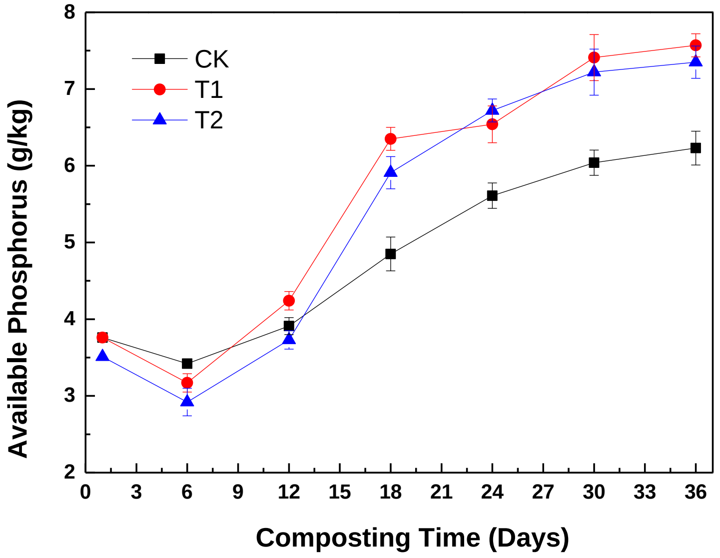

Fig. 8. Available phosphorus content variation profiles of the three experimental groups

The massive rate of microbial reproduction requires the consumption of AP in the material, which leads to a decrease in AP at the initial stage of composting (Yang *et al*. 2012). As the experiment progressed, the number of microorganisms and their activity increased. A large amount of phosphorus is transformed into forms that are more easily absorbed by plants through the decomposition of organic matter. Moreover, due to the concentration effect produced by the extensive degradation of organic matter (Wang *et al*. 2019), the AP content in the materials of the three experimental groups rapidly increased after the 6th day following the start of the experiment. At the end of the experiment, the AP content in the CK, T1, and T2 groups increased from 3.76, 3.76, and 3.51 g/kg at the beginning of composting to 6.23, 7.57, and 7.35 g/kg at the end of composting, respectively, with increases of 67.7, 101.3, and 109.4%, respectively. This indicated that the membrane-covering technology could effectively increase the AP content in compost products, and the addition of biochar while covering the membrane had an even better effect on increasing the available phosphorus content. This may be related to the enhancement of microbial activity during composting (Liu *et al*. 2014). However, Li *et al*. (2020) reported that the AP content could only be increased by 30% during composting process, which was much lower than the related results of this study. This might be due to the lower temperature of their composting pile, with the highest temperature reaching only 55℃ (compared to the highest temperature of 73℃ in this study). High temperatures are beneficial for the dissolution of phosphates, thereby increasing the content of AP.

Changes in the Total Potassium Content

Potassium is a major plant nutrient and one of the primary elements that often limits crop yield because of insufficient supply in the soil. To date, no organic compounds containing potassium have been identified in the plant tissues. Potassium exists in an ionic form dissolved in the plant sap, and its main functions are related to plant metabolism. Similar to phosphorus, potassium does not leach during composting (Pan *et al*. 2023). Therefore, the increase in TK content in the material is also due to the concentration effect caused by the degradation of organic matter (Liu *et al*. 2015). The change in the TK content directly reflects the degradation rate of organic materials in the compost. At the end of the experiment, the TK content in the CK, T1, and T2 groups increased from 21.3, 21.3, and 21.0 g/kg at the beginning of composting to 26.0, 27.1, and 28.1 g/kg, respectively, with increases of 21.9, 30.9, and 33.9%, respectively. Similar to the impact on the phosphorus content in the products, both the T1 and T2 groups exhibited a favorable enhancement compared to the CK group ($p < 0.05$). This indicates that the membrane covering technology could effectively enhance the degradation rate of materials in the composting process, and simultaneously adding biochar to the covered membrane further promoted material degradation. This result is consistent with the TP content of the material, as shown in Fig. 7.

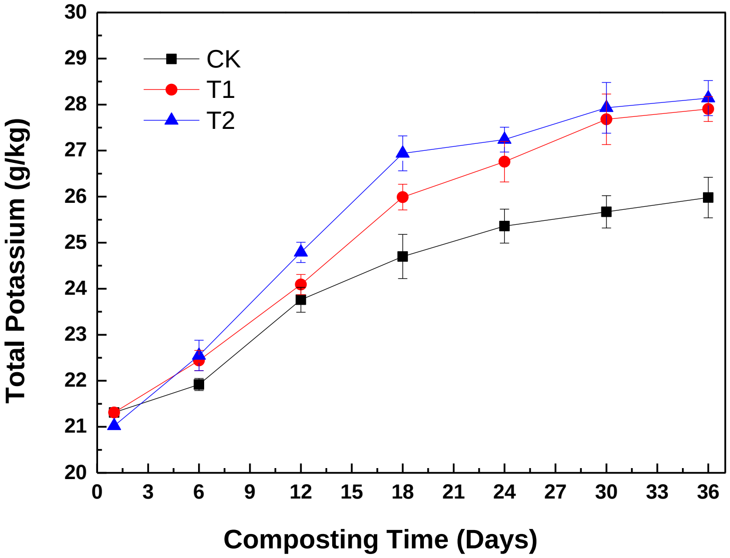

Fig. 9. Total potassium content variation profiles of the three experimental groups

Changes in the Available Potassium Content

The AK refers to potassium that can be easily absorbed and utilized by crops, mainly water-soluble and exchangeable potassium. The changes in the AK content of the materials in the three experimental groups are shown in Fig. 10, all of which exhibited a steadily increasing trend. This was mainly due to microbial activity during the composting process, leading to the activation of the potassium retained in the organic materials and promoting the conversion of TK to AK, as well as the concentration effect caused by the reduction in the mass of compost materials (Liu *et al*. 2015).

At the end of the experiment, the AK content of the materials in the CK, T1, and T2 increased from 7.12, 7.12, and 7.10 g/kg at the start of composting to 11.6, 13.5, and 13.9 g/kg, respectively, with increases of 62.8, 89.9, and 96.2%, respectively. The ratio of AK to TK increased from 33.4% to 44.6%, 48.4%, and 49.5% in the CK, T1, and T2 groups, respectively. Statistical analysis revealed a general difference among the three experimental groups ($p < 0.05$). Similar to its effect on the AP content in the compost pile, membrane-covering technology also was able to effectively increase the available potassium content in compost products. The addition of biochar to the membrane covering also increased the AK content. This was mainly because the favorable physicochemical properties of biochar promoted the growth and metabolism of microorganisms (Wang *et al*. 2024), thereby enhancing the activation and transformation of potassium elements.

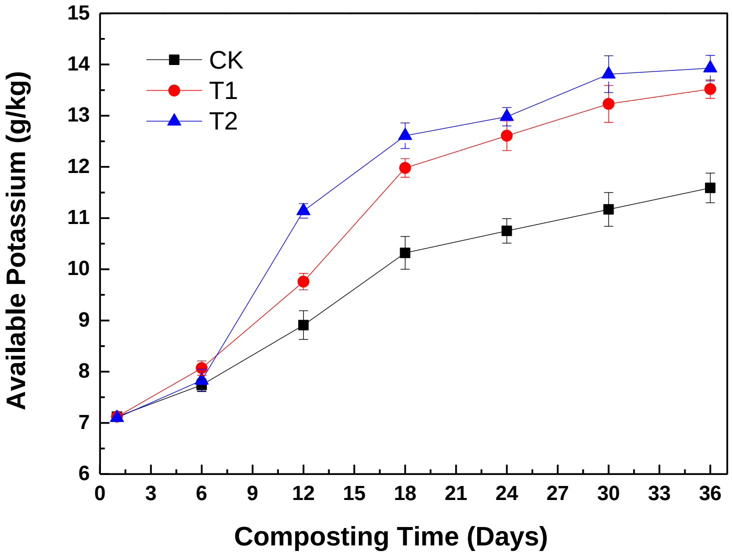

Fig. 10. Available potassium content variation profiles of the three experimental groups

CONCLUSIONS

1. The membrane covering technology effectively increased the temperature and the duration of high temperatures (≥ 55 ℃) during the composting process, which was conducive to effectively killing harmful pathogenic bacteria in the compost pile and enhancing the biological safety of the compost product. After the membrane covering was applied, the degradation rate of organic matter increased, which increased the phosphorus and potassium contents of the compost product due to the concentration effect.
2. Membrane-covering technology effectively increased the content of nutrient elements, predominantly nitrogen, phosphorus, and potassium, in the compost products and promoted a major increase in the availability of phosphorus and potassium. The addition of biochar with the membrane covering yielded better outcomes. Compared with that in the control (CK) group, the total nitrogen (TN), total phosphorus (TP), total potassium (TK), available phosphorus (AP), and available potassium (AK) contents increased 13.1%, 12.6%, 7.4%, 21.5%, and 16.6%, respectively, in the compost products in the T1 group that were covered with a polymer film, and by 19.7%, 13.7%, 8.3%, 18.0%, and 20.2%, respectively in the T2 group, in which membrane coverage was combined with biochar.
3. Benefiting from its large specific surface area and favorable pore structure, biochar provided an excellent growth and metabolic area for microorganisms. Biochar also made the whole bed more evenly permeable, allowing the pumped air to be distributed more effectively across the entire compost pile. These favorable conditions accelerated the degradation of organic matter and increased the content of nitrogen, phosphorus, and potassium in the compost product.

ACKNOWLEDGMENTS

This work was supported by the National Key Research and Development Program of China (Grant No. 2022YFD2002105).

REFERENCES CITED

Cai, J. (2015). "Waste resources nutrient research on solanaceous vegetable," *Northern Horticulture* 07, 20-23. DOI: 10.11937/bfyy.201507006

Cao, J., Li, R. R., Qu, H. L., Weng, P. J., Fu, J. J., Chen, M. J., and Chen, Y. S. (2022). "Effects of the membrane-covered technology and superphosphate on the compost quality and nitrogen-containing gas emissions during aerobic composting," *BioResources* 17(1), 1781-1793. DOI: 10.15376/biores.17.1.1781-1793

Cao, J., Chen, M. J., Li, R. R., Qu, H. L., and Weng, P. J. (2024a). "Effect of molecular membrane cover coupled with biocarbon on ammonia emission reduction and maturation in aerobic fermentation," *Journal of Chinese Agricultural Mechanization* 45(4), 175-179. DOI: 10.13733/j.jcam.issn.2095-5553.2024.04.025

Cao, J., Qu, H. L., Li, R. R., Weng, P. J., Fu, J. J., and Chen, M. J. (2024b). "Effects of membrane-covered and biochar on compost quality and greenhouse gas reduction in aerobic composting," *BioResources* 19(2), 3475-3488. DOI: 10.15376/biores.19.2.3475-3488

Cui, D., Wei, H., Li, Y. H., and Chen, X. M. (2024). "Semipermeable membrane aerobic composting of Chinese medicine residues: Performance and functional microbial community structure," *Microbiology China* 51(6), 1917-1933. DOI: 10.13344/j.microbiol.china.231020

Gao, B. B., Wang, X., Chang, R. X., and Chen, Q. (2018). "Effects of clay and chemical additives on nitrogen retention during cow manure composting," *Transactions of the Chinese Society of Agricultural Engineering* 34(20), 250-257. DOI: 10.11975/j.issn.1002-6819.2018.20.032

Gonzalez, I., Robledo-Mahon, T., Silva-Castro, G. A., Rodríguez-Calvo, A., Gutierrez, M. C., Martín, M. A., Chica, A. F., and Calvo, C. (2016). "Evolution of the composting process with semi-permeable film technology at industrial scale," *Journal of Clean Production* 115, 245-254. DOI: 10.1016/j.jclepro.2015.12.033

Huang, Y. C., Dong, C. X., Yuan, J., Zhang, W., and He, L. W. (2024). "Effects of biochar on the maturity, degradation of lignocellulose and odor emissions of aerobic composting of grazing cashmere goat manure," *Journal of China Agricultural University* 29(8), 157-168. DOI: 10.11841/j.issn.1007-4333.2024.08.13

Islam, M. R., Oliullah, K., Kabir, M. M., Alom, M., and Mridha, M. F. (2023). "Machine learning enabled IoT system for soil nutrients monitoring and crop recommendation," *Journal of Agriculture and Food Research* 14, 100880-100892. DOI: 10.1016/j.jafr.2023.100880

Kwadjo, K. E., Kra, K. D., Douan, B. G., Angoua, K. H., and Doumbia, M. (2018). "Insects from the Voandzou and Vigna Subterranean (L.) verdc populations. Fabaceae is located in the Abidjan district of Cote d'Ivoire," *REB–PASRES* 2(3), 32-41.

Li, R. R., Cai, L., Cao, J., Weng, P. J., Qu, H. L., Chen, M. J., and Chen, Y. S. (2023). "Effect of different multichannel ventilation methods on aerobic composting and vegetable waste gas emissions," *Environmental Science and Pollution Research* DOI: 10.1007/s11356-023-30017-6

Li, Y., Qiu, H. Z., Zhang, J. B., Su, Y. Q., Wei, Q. Y., and Chen, Z. Y. (2021a). "Effects of superphosphate and furfural residue addition on NH_3 emissions and nitrogen conversion during the aerobic composting," *Chinese Journal of Environmental Engineering* 15(12), 3992-4000. DOI: 10.12030/j.cjee.202110008

Li, Y. S., Sun, B., Peng, X. W., Bai, Z. H., and Zhuan, X. L. (2021b). "Effects of nano-membrane on aerobic composting process and odor emission of livestock manure," *Environmental Science* 42(11), 5554-5562. DOI: 10.13227/j.hjkx.202103109

Li, R. H., Tu, Z. N., Jin, X. D., Li, S. L., and Zhao, X. B. (2020). "Biochar carried microbial solution promotes compost maturity and nitrogen, phosphorus conservation," *China Environmental Science* 40(8), 3449-3457. DOI: 10.19674/j.cnki.issn1000-6923.2020.0387

Lin, J. C., Han, Z. Y., Wang, D. M., and Mai, L. W. (2024). "Effects of different coverings on the simplified static composting and humification process of cheery-tomato straw," *Transactions of the Chinese Society of Agricultural Engineering* 40(4), 273-283. DOI: 10.11975/j.issn.1002-6819.202310126

Liu, W., Zhang, J., Li, B. W., and Wang, S. T. (2014). "Effect of microorganism agents on tomato straw compost and changes of the NPK element forms," *Chinese Soil and Fertilizer* 24(3) 88-92. DOI: 10.11838/sfsc.20140318

Liu, W., Huo, R., Zhang, J., Li, B. W., Liu, Y. N., Yu, M. N., and Hou, J. (2015). "Effect of biochar on N, P and K transformation of tomato straw and chicken manure composting and mechanisms," *Journal of Soil and Water Conservation* 29(3), 289-294. DOI: 10.13870/j.cnki.stbcxb.2015.03.052

Liu, D. X., Chen, G. S., Lu, X. X., Xie, M. H., Li, C., and Liang, Y. H. (2024). "Greenhouse gas emission and nutrient changes during aerobic composting with different manure sources," *Northen Horticulture* 2024(11), 70-78. DOI: 10.11937/BFYY.20240018

Ma, S. S., Sun, X. X., Han, N. J., Li, R. Q., Schlick, U. W. E., and Huang, G. Q. (2017). "Reduction of ammonia emission during membrane-covered aerobic composting," *Transactions of The Chinese Society of Agricultural Machinery* 48(11), 344-349. DOI: 10.6041/j.issn.1000-1298.2017.11.042

Mo, S. Y., Zhang, Z. G., Shang, M. Q., and Wu, F. Z. (2018). "Analysis on chemical components of vegetable stumps," *China Vegetables* 12, 21-26. DOI: 10.19928/j.cnki.1000-6346.2018.12.009

NY/T 525 (2021). "Organic fertilizer," Ministry of Agriculture and Rural Affairs of the People's Republic of China, Beijing, China.

Palacino, B., Ascaso, S., Valero, A., and Valero, A. (2024). "Regeneration costs of topsoil fertility: An exergy indicator of agricultural impacts," *Journal of Environmental Management* 369, 12297-12307. DOI: 10.1016/j.jenvman.2024.122297

Pan, Y. J., Chang, H. Q., and Song, P. P. (2023). "Nutrients characteristics of pig manure in lager-scale farms and effect of filler addition during composting," *Acta Agriculture Zhejiangensis* 35(7) 1690-1698. DOI: 10.3969/j.issn.1004-1524.20226909

Qin, W., Jiang, X. R., Liu, M. G., Liu, Y., Wang, J. L., Ji, G. S., Xu, L. S., and Yan, Z. Y. (2022). "Effects of the additive ratio and aeration rate on sludge composting with airflow film," *Journal of Agro-Environment Science* 41(6), 1357-1367. DOI: 10.11654/jaes.2021-1231

Reddy, D. D., Rao, A. S., and Rupa, T. R. (2024). "Effects of continuous use of cattle manure and fertilizer phosphorus on crop yields and soil organic phosphorus in a Vertisol," *Bioresource Technology* 75(2), 113-118. DOI: 10.1016/S0960-8524(00)00050-X

Ren, L. H., Kong, X. L., Su, J., Zhao, D. Y., Dong, W. J., and Liu, C. M. (2022). "Oriented conversion of agricultural bio-waste to value-added products - A schematic review towards key nutrient circulation," *Bioresource Technology* 346, 126578-126588. DOI: 10.1016/j.biortech.2021.126578

Sun, X. P., Lu, P., Jiang, T., Schuchardt, F., and Li, G. X. (2014). "Influence of bulking agents on CH_4, N_2O, and NH_3 emissions during rapid composting of pig manure from the Chinese Ganqinfen system," *Zhejiang University of Sciences B* 15(4), 353-364. DIO: 10.1631/jzus.B13a0271

Wang, Y., Li, L. L., Zhu, D. W., Zhou, W. B., Chen, Y. X., and Wu, Y. P. (2019). "Influence of straw pretreatment on phosphorus forms during the process of pig manure thermophilic composting," *Journal of Plant Nutrition and Fertilizers* 25(6), 963-971. DOI: 10.11674/zwyf.18279

Wang, H. H., Han, Q. L., Liu, Z. Z., Jin, M. J., Shi, L. L., Shen, M. X., and Gu, H. D. (2020). "Effects of biochar at different pyrolysis temperatures on reduction and control of nitrogen loss in sheep manure composting process," *Transactions of the Chinese Society of Agricultural Engineering* 36(19), 184-191. DOI: 10.11975/j.issn.1002-6819.2020.19.021

Wang, H. H., Lv, Z. W., Jin, M. J., Shen, Y., and Tao, Y. Y. (2024). "Effects of rice husk biochar pyrolyzed at different temperatures on compost maturity and greenhouse gas emissions of sheep manure," *Journal of Agro-Environment Science* 43(3), 696-703. DOI: 10.11654/jaes.2023-0632

Wei, Y. Q., Wang, N., Liu, Y. F., Zhan, Y. B., Ding, X. Y., and Liu, Y. D. (2021). "Recycling of nutrients from organic waste by advanced compost technology – A case study," *Bioresource Technology* 337, 125411-125419. DOI: 10.1016/j.biortech.2021.125411

Xing, L., Zhang, Y. M., Hu, C. S., Dong, W. X., Li, X. X., Liu, X. P., Zhang, L. J., and Wen, H. D. (2022). "Effects of long-term nutrient recycling pathways on soil nutrient dynamics and fertility in farmland," *Chinese Journal of Eco-Agriculture* 30(6), 937-951. DOI: 10.12357/cjea.20220306

Yang, X., Lian, B., Zhu, X. L., An, Y. L., Chen, J., and Zhu, L. J. (2012). "Effect of adding potassium-bearing mineral powder on nitrogen potassium and potassium contents of chicken manure compost," *Earth and Environment* 40(2), 286-292. DOI: 10.14050/j.cnki.1672-9250.2012.02.018

Yang, Z., Li, H. Q., Zhai, J. L., Zhang, L. H., and Nan, Q. (2022). "Review on the assessment model of nutrient recycling with agricultural residues treatment technologies," *Chinese Journal of Applied Ecology* 33(12), 3213-3219. DOI: 10.13287/j.1001-9332.202212.022

Yun, P., Ma, Q., Huang, M. H., Yan, Y. X., Yan, Z. J., and Wang, X. L. (2023). "Carbon and phosphorus characteristics of different urban and rural organic waste composts," *Southwest China Journal of Agricultural Sciences* 36(7), 1455-1464. DOI: 10.16213/J.CNKI.SCJAS.2023.7.013

Zhou, S., Li, Y., Zhang, G. Z., Xu, P., Lin, A. Y., Wu, Y. J., and Yang, Z. C. (2024). "Effects of additives on the fermentation process and nitrogen loss of tomato stem aerobic composting," *Journal of China Agricultural University* 29(3), 79-86. DOI: 10.11841/j.issn.1007-4333.2024.03.07

Article submitted: September 21, 2024; Peer review completed: October 19, 2024; Revised version received and accepted: October 25, 2024; Published: November 4, 2024.
DOI: 10.15376/biores.20.1.25-41