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Investigation on Rapid Fermentation Technology of Seasonally Effective High-End Tobacco-Specific Organic Fertilizers

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ABSTRACT

While organic fertilizers enhance tobacco quality and economic value, their low maturity levels often limit their effectiveness when applied within the same growing season, discouraging farmer adoption. Conventional composting methods typically require over 90 days to achieve full maturity. This study aimed to optimize composting methods and material formulations for large-scale factory production to shorten the fermentation period, enabling same-season application and benefits. Two large-scale experiments (each exceeding 100 tons) compared molecular membrane forced aeration combined with static and windrow composting against traditional windrow composting. Different material ratios of cow dung, mushroom residue, and distillery waste were also evaluated. Results showed that the optimized method, utilizing molecular membrane technology and adjusted material ratios, reduced the composting time from over 90 days to 60 days. The optimal formula consisted of cow dung, mushroom residue, and distillery waste at a 4:3:3 dry weight ratio with a moisture content ≤ 63%. After 60 days, this optimized process yielded organic fertilizer meeting all quality standards, including humic acid content, nutrient levels, and absence of harmful organisms. This accelerated composting method facilitates same-season fertilizer application, benefiting farmers and enhancing the efficiency and cost-effectiveness of organic fertilizer production.

Keywords: high-end tobacco-specific organic fertilizer; composting method; optimization; rapid composting; cost reduction and efficiency enhancement.

INTRODUCTION

Tobacco, being a significant economic crop in China, plays a crucial role in driving economic growth and boosting farmers' incomes [1]. The yield and quality of flue-cured tobacco directly impact both farmer earnings and the industry's viability and competitiveness [1]. Soil, as a vital environmental factor, significantly influences tobacco growth and its nutritional status, ultimately affecting the quality of tobacco leaves [2, 3]. However, continuous tobacco cultivation leads to the "tobacco monoculture problem." Planting tobacco in the same field year after year results in stunted plant growth, increased susceptibility to diseases, and reduced yields, forcing farmers to rotate their contracted land [4]. High-quality soil is essential for producing superior tobacco leaves by providing optimal nutrients, directly impacting tobacco growth and leaf quality [5]. Fertilization is critical in tobacco cultivation [6]. Traditional practices often prioritize maximizing yield and quality by increasing fertilizer application, leading to excessive water and fertilizer use [7]. This long-term reliance on chemical fertilizers for flue-cured tobacco has detrimental consequences [8]. It leads to soil compaction, depletion of organic matter, and deterioration of soil physicochemical properties, ultimately harming tobacco leaf quality [9]. Organic fertilizers, rich in nutrients, hold immense potential for improving soil health and enhancing tobacco production [10]. While organic fertilizers enhance tobacco leaf quality [11] and reduce pest and disease incidence, poorly composted organic fertilizers may not show immediate improvements in the same growing season [6, 7]. The key factor determining farmer adoption of organic fertilizers is their ability to deliver tangible benefits within the same season, improving tobacco leaf quality and increasing profits [12–14]. Therefore, achieving rapid composting of organic fertilizers is paramount for ensuring their effectiveness in enhancing tobacco leaf quality within the same season [15]. This rapid decomposition is vital for the sustainable development of the tobacco industry [16, 17].

Currently, composting methods for organic fertilizer primarily focus on aerobic fermentation, requiring over three months to increase humic acid content for optimal utilization within the same tobacco growing season [18–20]. While this process improves leaf quality and farmer income, it suffers from lengthy fermentation cycles, low efficiency, and high costs [21]. Despite the recognized significance of properly applied organic fertilizer in soil improvement for flue-cured tobacco [22], investigation on accelerated composting methods utilizing forced aeration with molecular membranes, combined with static and windrow composting, remains unexplored.

This study investigates the impact of different composting methods, comparative trials of organic fertilizer materials, and optimal moisture content on various fertilizer quality indicators. The aim is to determine the optimal composting method and material formula for accelerating organic fertilizer maturation. Our investigation aims to achieve the following objectives: Enable the utilization of organic fertilizer within the same growing season. Enhance tobacco leaf quality and market competitiveness. Advance industrialized organic fertilizer fermentation technology and overall efficiency.

MATERIALS AND METHODS

Experimental design

Composting methods

Optimization of composting methods: The first 15 days utilize forced aeration with molecular membranes combined with static composting. After 15 days, the composting process transitions to windrow composting for the maturation stage. The control group employs windrow composting throughout the entire process.

Comparative trial of different organic fertilizer materials (Experiment I)

Based on local resources in Zunyi, Guizhou, China, two formulations were designed. Formula 1: Cow dung and mushroom residue were mixed at a dry weight ratio of 6:4, supplemented with 0.4% composting inoculant, thoroughly mixed, and adjusted to a moisture content of approximately 70%. Formula 2: Cow dung and distillery waste were mixed at a dry weight ratio of 6:4, supplemented with 0.4% composting inoculant, thoroughly mixed, and adjusted to a moisture content of approximately 70%. Mushroom residue refers to the spent substrate after harvesting edible mushrooms like king oyster mushrooms and shiitake mushrooms.

Comparative trial of optimal moisture content for organic fertilizer composting (Experiment II)

Based on the results of Experiment I, the material formula was optimized for Experiment II. Cow dung, mushroom residue, and distillery waste were mixed at a dry weight ratio of 4:3:3, supplemented with 0.4% composting inoculant, and thoroughly mixed. Three moisture content levels were tested: 63%, 68%, and 73%.

Sample collection and measured parameters

Sample collection

Given the large volume of the molecular membrane composting system and the difficulty of collecting samples from the center, samples were collected from the four thicker corner areas for convenience. In each corner, samples were taken from the top, middle, and bottom layers at equal distances. The samples from the top layers of all four corners were combined, similarly for the middle and bottom layers. This resulted in three representative samples (top, middle, bottom), which were further mixed to obtain a composite sample for analysis (Figure 1). Temperature changes during the composting process were recorded using probes.

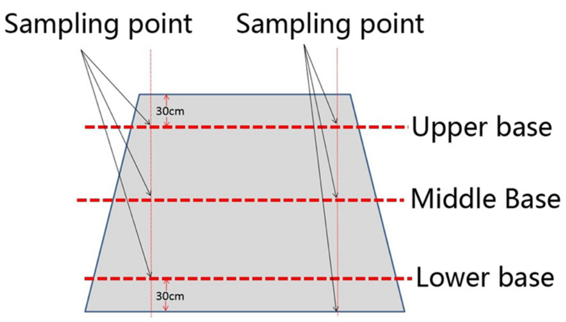

Figure 1. Schematic diagram of sampling points for molecular membrane fermentation

Sampling time

Experiment I: Samples were collected and analyzed on days 0, 10, 20, 30, 60, and 90 of composting (four samples per time point, divided into three biological replicates). Experiment II: Samples were collected and analyzed on days 0, 15, 30, 60, and 90 of composting (four samples per time point, divided into three biological replicates).

Measured parameters

1. Parameters measured at each sampling time point (reflecting maturity) – seed germination index, C/N ratio, humic acid (fulvic acid), absorbance change, moisture content.
2. Parameters measured before composting (microbial indicators) – cellulase activity, protease activity, viable microbial count.
3. Final product parameters (measured on days 60 and 90 – organic fertilizer quality indicators): Total N, P_2O_5, K_2O, viable microbial count, harmful organisms (*Escherichia coli* count, Ascaris egg count), pH, moisture content.

Measurement methods

Seed germination index was determined according to the NY/T525-2021 standard. Organic matter (OM) was measured using the potassium dichromate external heating method [23]. Total nitrogen was determined by the semi-micro Kjeldahl method [24]. Total phosphorus was measured using the acid-soluble molybdenum antimony colorimetric method [25]. Total potassium was determined by the NaOH fusion flame photometry method [26]. Humic acid (fulvic acid) was determined according to the NY/T 1971–2010 standard [27]. Absorbance changes were detected using a spectrophotometer [28]. Moisture content was measured using the oven drying method according to the GB/T 8567-2010 standard [29]. Soil enzyme activity was determined using colorimetric and volumetric methods. pH was measured using a pH meter [30]. Viable microbial count and *E. coli* count were determined using the plate counting method. Ascaris egg count was determined using the saturated sodium nitrate flotation method [31].

RESULTS

Fulvic acid content

This study conducted two batches of large-scale organic fertilizer composting experiments, each exceeding 100 tons. The results of both experiments were combined for analysis. Figure 2 illustrates the changes in fulvic acid content. In Experiment I, the molecular membrane rapid composting method (MMM) resulted in significantly higher fulvic acid content in the organic fertilizer compared to the windrow composting method (WCM). Notably, on day 20 of composting, the highest fulvic acid content (7.90%) was observed in the mushroom residue-based organic fertilizer treated with MMM. The distillery waste-based organic fertilizer treated with the same method showed a slightly lower content (5.38%). In contrast, WCM resulted in fulvic acid contents of 2.46% and 4.88% for mushroom residue and distillery waste-based organic fertilizers, respectively. In Experiment II, a decreasing trend in fulvic acid content was observed throughout the composting process for all three treatments. No significant differences were observed between the different moisture content treatments, particularly after 15 days of composting (Figure 2). Overall, these results demonstrate that MMM accelerates the decomposition of organic matter in the fertilizer compared to WCM. This leads to a more rapid increase in fulvic acid content, shortening the composting cycle and enhancing composting efficiency. However, the water content ratio in the organic fertilizer did not significantly affect the final fulvic acid content in the composted product.

C/N ratio

In Experiment I, a significant increase in the C/N ratio of the organic fertilizer was observed after entering the composting phase. This increase remained relatively stable, with the overall C/N ratio maintained at approximately 13. Notably, on

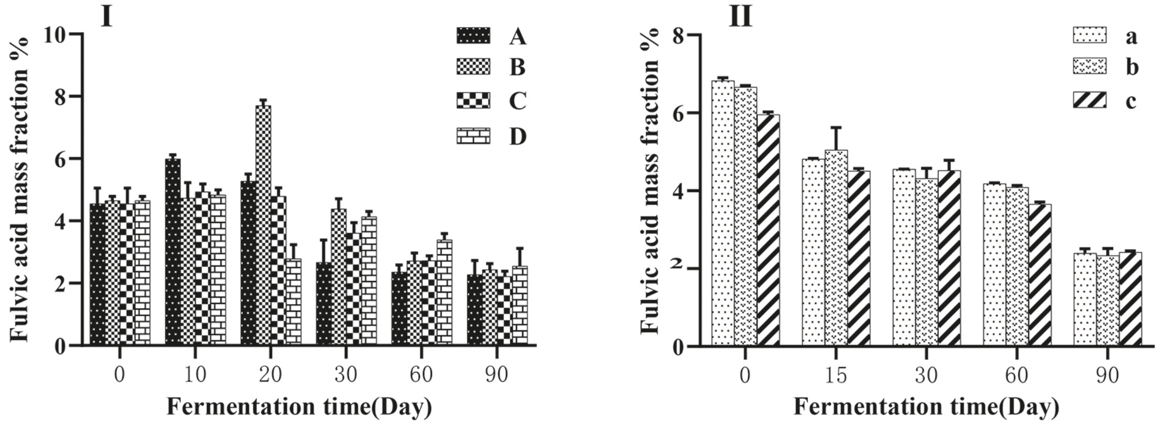

Figure 2. Content of humic acid; I – the influence of different ingredients and fermentation methods on the humic acid content in organic fertilizer; II – the influence of different moisture content treatments on the humic acid content in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

day 20 of composting, the organic fertilizer treated with MMM exhibited a higher C/N ratio compared to WCM (Figure 3). In Experiment II, the 63% moisture content treatment group showed minimal fluctuations in the C/N ratio. The highest C/N ratio of 13.2 was observed on day 60 of composting (Figure 3). These findings suggest that MMM effectively reduces the C/N ratio of organic fertilizer in a shorter timeframe compared to WCM. Moreover, a water content ratio of 63% in conjunction with MMM facilitated a faster decrease in the C/N ratio, which then stabilized over a period of time. This indicates that composting at lower moisture content enhances nitrogen content relative to carbon content in the organic fertilizer.

Seed germination index

In Experiment I, the seed germination index of organic fertilizer treated with both MMM and WCM showed an increasing trend (Figure 4). Overall, MMM resulted in a higher seed germination index compared to WCM. In Experiment II, the organic fertilizer treated with 63% moisture content exhibited a significantly higher seed germination index on day 60 compared to the 68% and 73% moisture content treatments. The highest germination index for the 63% moisture content treatment was observed on day 90. These findings demonstrate that MMM produces organic fertilizer with a higher seed germination index

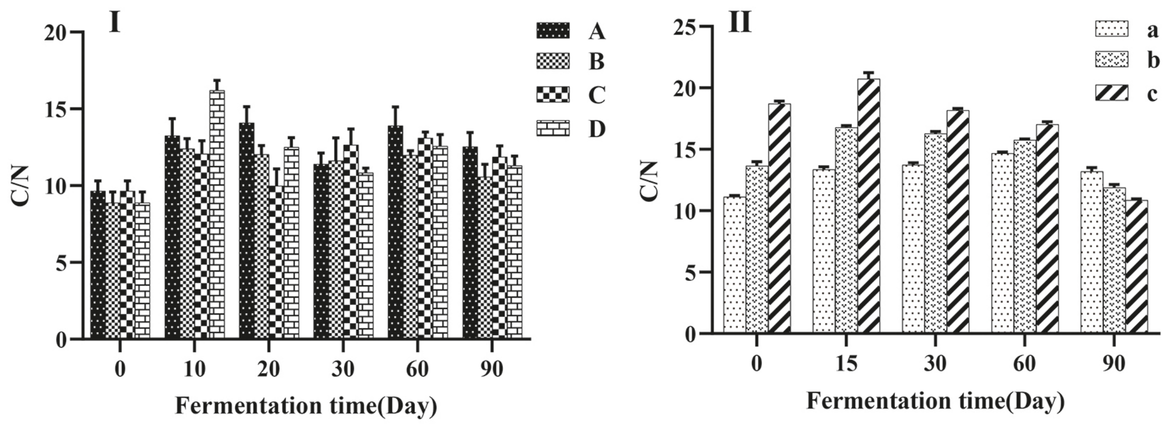

Figure 3. Carbon to nitrogen ratio; I – the influence of different ingredients and fermentation methods on the carbon to nitrogen ratio in organic fertilizer; II – the influence of different moisture content treatments on the carbon to nitrogen ratio in organic fertilizer; A – molecular membrane distiller's dregs; B – molecular membrane mycelial residue; C – strip pile distiller's dregs; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

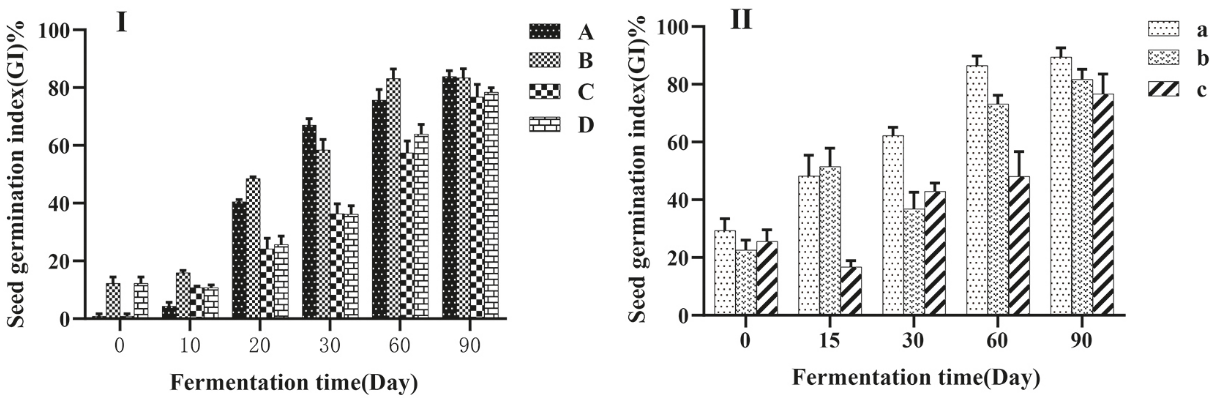

Figure 4. Seed germination index; I – the influence of different ingredients and fermentation methods on the seed germination index in organic fertilizer; II – the influence of different moisture content treatments on the seed germination index in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane fungal residue; C – strip pile distiller's grains; D – strip pile fungal residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

compared to WCM. Additionally, a moisture content of 63% during composting yielded a higher germination index compared to higher moisture contents. Importantly, the germination index observed on day 60 was already very close to the value obtained on day 90, indicating a faster maturation process at the optimal moisture content.

Moisture content

In Experiment I, different composting treatments had slight effects on the fresh weight moisture content of the organic fertilizer. However, the air-dried moisture content remained relatively consistent in the early stages of composting, increased during the middle stages, then decreased, and finally stabilized towards the end of the composting period. Notably, WCM resulted in a consistent fresh weight moisture content throughout the composting period, while the air-dried moisture content showed a relatively steady increase (Figure 5).

In Experiment II, all three treatments exhibited a general downward trend in air-dried moisture content. The 63% moisture content treatment showed a continuous decrease, while the 68% and 73% moisture content treatments exhibited an initial increase followed by a decrease. These results indicate that MMM maintains a considerably high moisture content in the composting materials. Furthermore, the 63% moisture content treatment demonstrated greater stability in both fresh weight and air-dried moisture content throughout the entire composting process.

Enzyme activity

Cellulase activity

Overall, in Experiment I, both MMM and WCM resulted in an increase in cellulase activity during the early stages of composting. However, MMM showed significantly higher cellulase activity and a greater rate of increase (Figure 6). In Experiment II, all three moisture content treatments exhibited an increasing trend in cellulase activity. Notably, the 63% and 68% moisture content treatments reached their highest cellulase activity levels on day 30 of composting, measuring 26.34 U/g and 32.54 U/g, respectively. These results suggest that during the early stages of composting, MMM promotes higher cellulase activity compared to WCM. This indicates that MMM is more effective in breaking down complex substances like cellulose in the organic fertilizer.

Protease activity

In Experiment I, protease activity in the organic fertilizer treated with MMM exhibited an initial increase followed by a decrease as composting progressed. In contrast, WCM showed a continuous increase in protease activity (Figure 7). In Experiment II, the 63% moisture content treatment showed the highest protease activity during the middle stage of composting, reaching a peak of 20.34 U/g. However, in the later stages of composting, the 73% moisture content treatment exhibited the highest protease activity, measuring 30.24 U/g. The overall trend suggests that protease plays a continuous role in decomposition throughout the composting process.

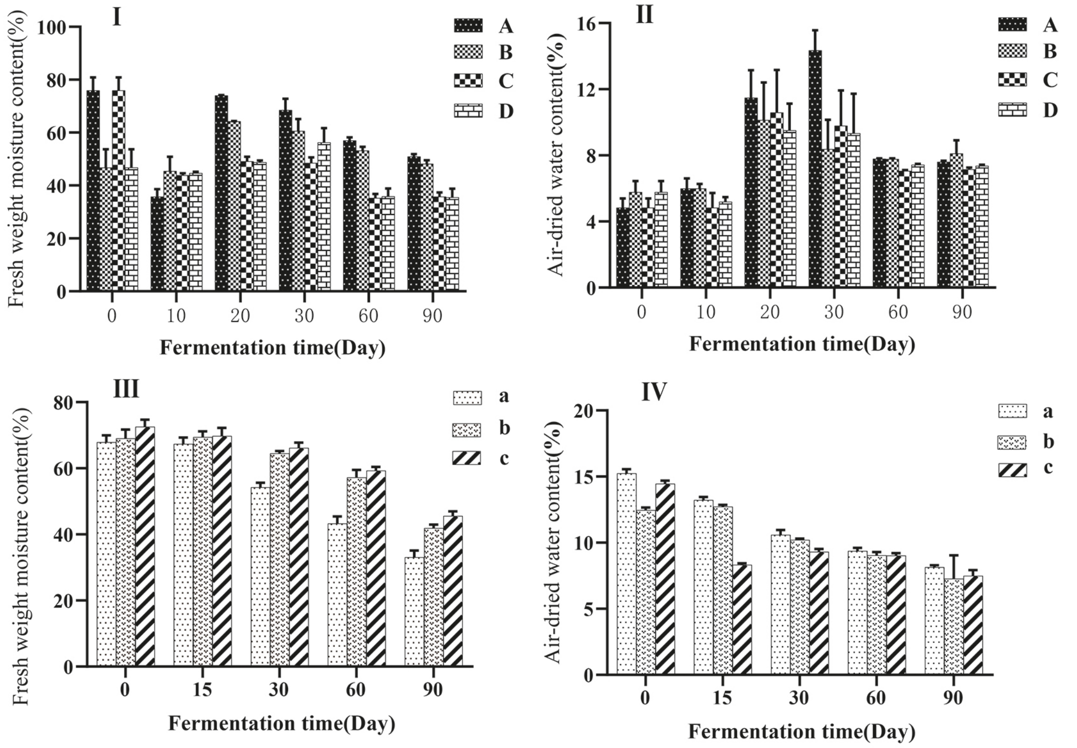

Figure 5. Moisture changes; I – the influence of different ingredients and fermentation methods on the fresh weight moisture content in organic fertilizer; II – the influence of different ingredients and fermentation methods on the air-dried moisture content in organic fertilizer; III – the influence of different moisture content treatments on the fresh weight moisture content in organic fertilizer; IV – the influence of different moisture content treatments on the air-dried moisture content in organic fertilizer; A – molecular membrane distiller's grains; b – molecular membrane fungal residue; C – strip pile distiller's grains; d – strip pile fungal residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

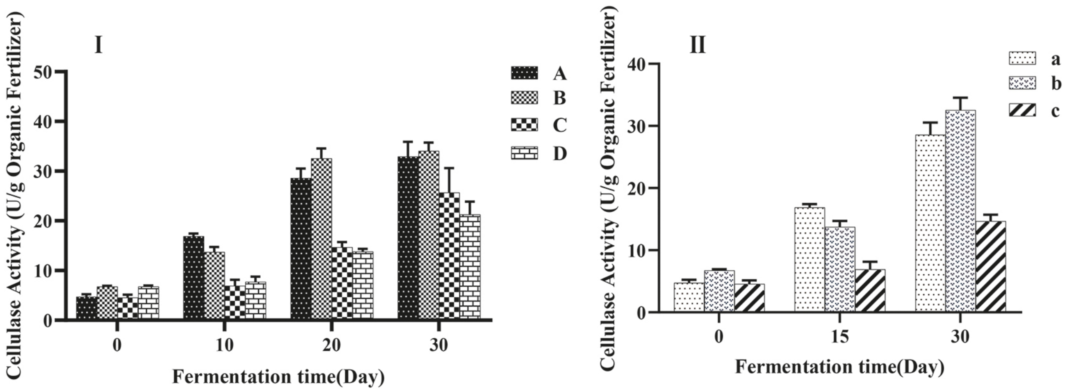

Figure 6. Cellulase activity; I – the influence of different ingredients and fermentation methods on the cellulase activity in organic fertilizer; II – the influence of different moisture content treatments on the cellulase activity in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

Total nitrogen content

Overall, in Experiment I, the highest total nitrogen content was observed in the mushroom residue-based organic fertilizer treated with MMM on day 60, reaching 3.24 g/100 g (DW). Conversely, the lowest total nitrogen content (1.94 g/100 g (DW)) was observed in the distillery waste-based organic fertilizer treated with WCM on day 60 (Figure 8). In Experiment II,

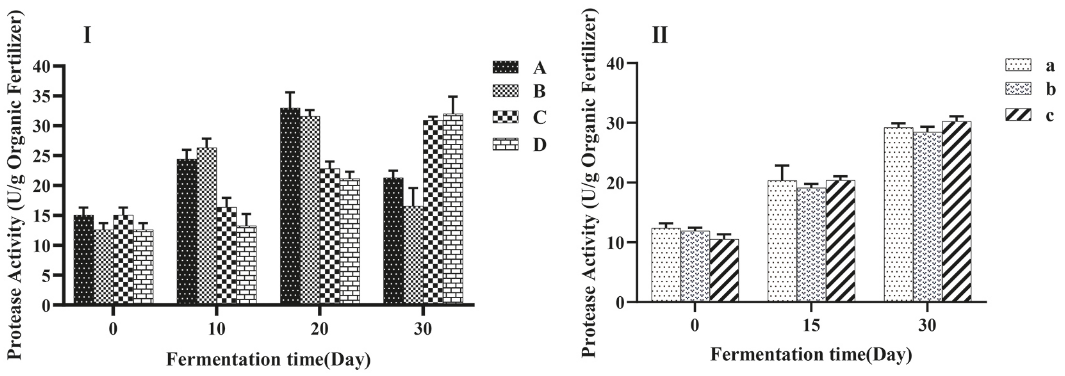

Figure 7. Protease activity; I – the influence of different ingredients and fermentation methods on the protease activity in organic fertilizer; II – the influence of different moisture content treatments on the protease activity in organic fertilizer; A – molecular membrane distiller's dregs; b – molecular membrane mycelial residue; c – strip pile distiller's dregs; d – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

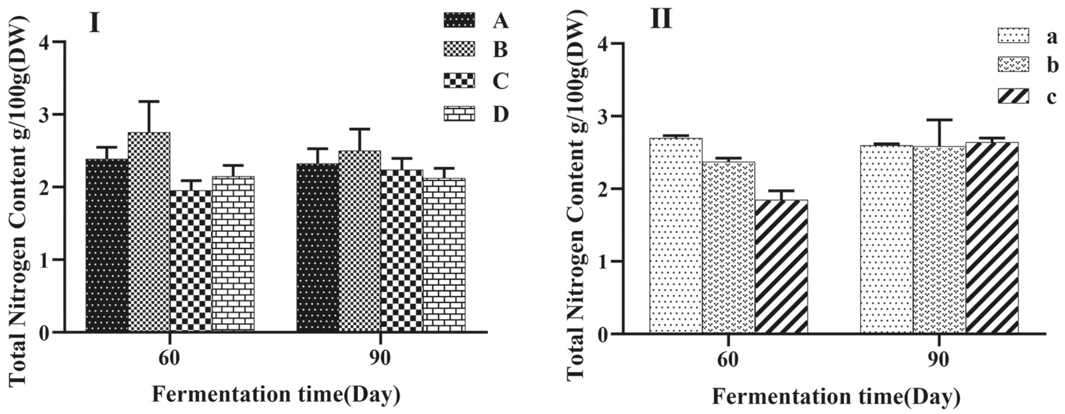

Figure 8. Total nitrogen content; I – the influence of different ingredients and fermentation methods on the total nitrogen content in organic fertilizer; II – the influence of different moisture content treatments on the total nitrogen content in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

the total nitrogen content in the finished organic fertilizer with a 73% moisture content exhibited an increasing trend, reaching its maximum value (2.64 g/100 g (DW)) on day 90. This value was comparable to the total nitrogen content of the 63% moisture content treatment (2.59 g/100 g (DW)). In conclusion, MMM resulted in slightly higher total nitrogen content in the finished organic fertilizer compared to WCM. Moreover, the 63% moisture content treatment reached its peak total nitrogen content by day 60.

P_2O_5 content

The P_2O_5 content in the finished organic fertilizer remained relatively stable (Figure 9). On day 90 of composting, the mushroom residue-based organic fertilizer treated with MMM exhibited the highest P_2O_5 content (3.00 g/100 g (DW)), while the same material treated with WCM showed the lowest content (2.40 g/100 g (DW)). Similarly, in Experiment II, the 63% moisture content treatment demonstrated favorable results by day 60, essentially reaching the composting effectiveness observed in the other two higher moisture content treatments after 90 days. Overall, while the differences in P_2O_5 content among the finished organic fertilizers were not statistically significant, the highest content was observed in the mushroom residue-based fertilizer treated with MMM. However, the 63% moisture content treatment for the same material exhibited promising results within just 60 days of composting.

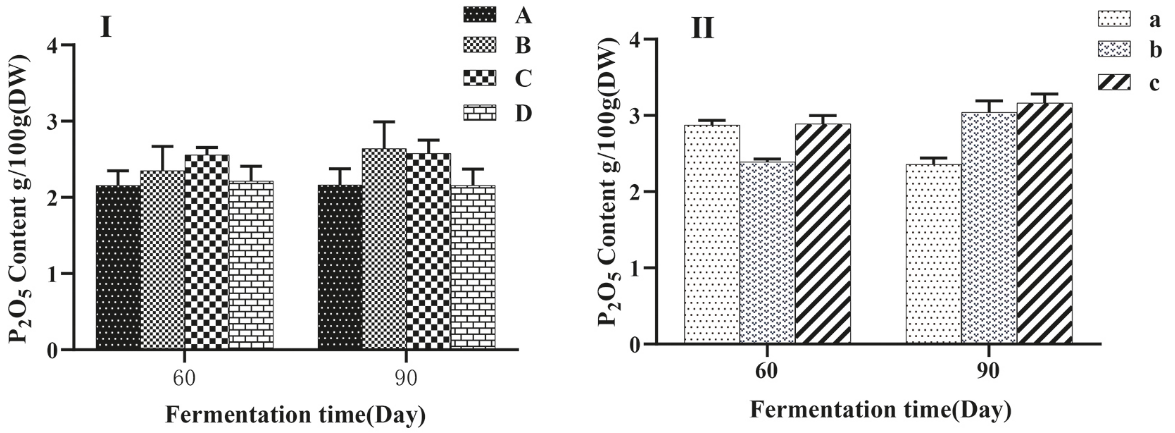

Figure 9. Phosphorus pentoxide (P_2O_5) content; I – the influence of different ingredients and fermentation methods on the p_2o_5 content in organic fertilizer; II – the influence of different moisture content treatments on the p_2o_5 content in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

K_2O content

In Experiment I, the K_2O content in the finished organic fertilizer remained relatively stable across different composting treatments (Figure 10). The highest K_2O content was observed in the mushroom residue-based organic fertilizer treated with MMM. In Experiment II, the 63% moisture content treatment yielded the highest K_2O content (2.26 g/100 g (DW)) among all tested samples on day 60 of composting. After 90 days, the K_2O content in the finished organic fertilizers remained relatively stable across different treatments. Similar to the findings for P_2O_5, the differences in K_2O content in the finished organic fertilizers were not statistically significant. However, the highest K_2O content was consistently observed in the mushroom residue-based fertilizer treated with MMM. Furthermore, the 63% moisture content treatment demonstrated superior results within just 60 days of composting, surpassing the effectiveness observed in the higher moisture content treatments even after 90 days.

Viable microbial count

Overall, the viable bacterial count exhibited an increasing trend throughout the composting

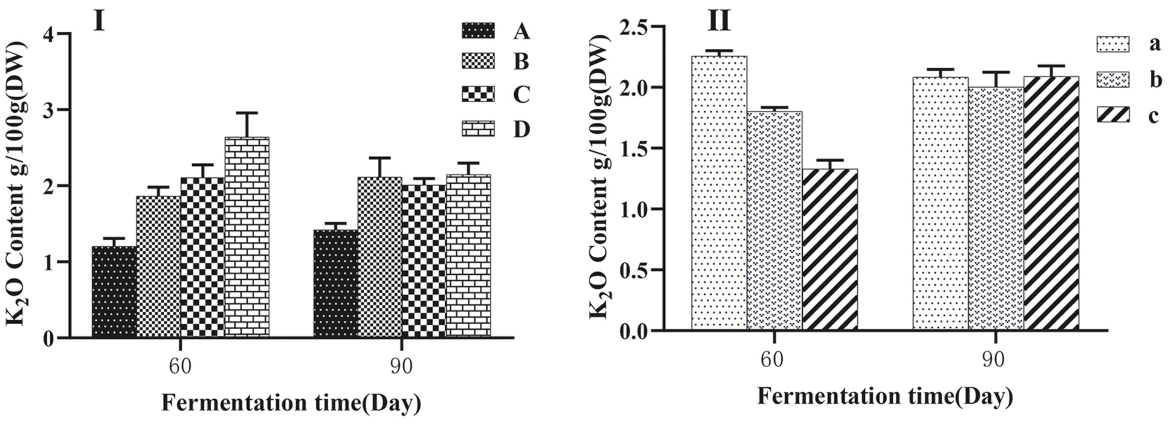

Figure 10. Potassium oxide (K2O) content; I – the influence of different ingredients and fermentation methods on the k2o content in organic fertilizer; II – the influence of different moisture content treatments on the k2o content in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

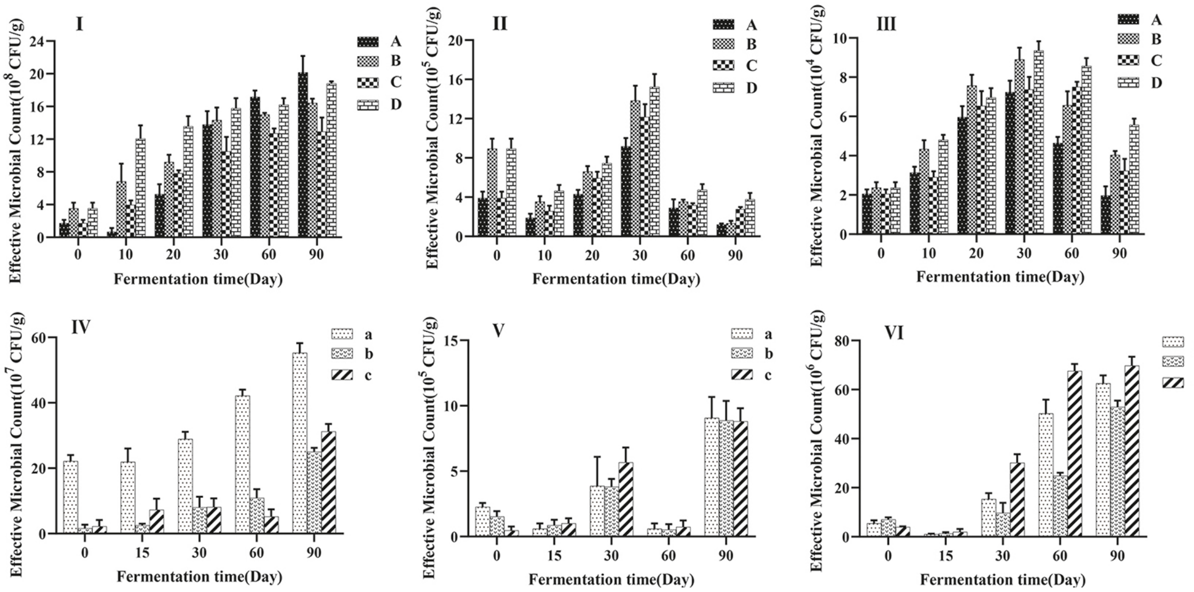

Figure 11. Effective live bacterial count; I – the change in effective live bacterial count in organic fertilizer due to different ingredients and fermentation methods; II – the change in effective live fungal count in organic fertilizer due to different ingredients and fermentation methods; III – the change in effective live actinomycete count in organic fertilizer due to different ingredients and fermentation methods; IV – the change in effective live bacterial count in organic fertilizer due to different moisture content treatments; V – the change in effective live fungal count in organic fertilizer due to different moisture content treatments; VI – the change in effective live actinomycete count in organic fertilizer due to different moisture content treatments; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

process, while the viable fungal and actinomycetes counts showed an initial increase followed by a decline (Figure 11). On day 90, the highest viable bacterial count (1.90×10^9 CFU/g organic fertilizer) was observed in the distillery waste-based organic fertilizer treated with MMM. In contrast, the highest viable fungal and actinomycetes counts were observed on day 30 in the mushroom residue-based organic fertilizer treated with WCM, reaching 1.65×10^6 CFU/g and 9.65×10^4 CFU/g, respectively. The 63% moisture content treatment yielded the highest total viable counts for both bacteria (5.52×10^8 CFU/g) and fungi (9.06×10^5 CFU/g). Interestingly, the 73% moisture content treatment showed the highest viable actinomycetes count (6.97×10^7 CFU/g). Consistent with Experiment I, the distillery waste-based organic fertilizer treated with MMM exhibited the highest viable bacterial count.

pH value

In Experiment I, the finished organic fertilizer treated with MMM exhibited a pH value below 7, indicating slight acidity. In contrast, the windrow composting method resulted in a pH value above 7, suggesting slight alkalinity (Figure 12). In Experiment II, the pH values of the finished organic fertilizers remained relatively stable across different composting treatments after both 60 and 90 days of composting (Figure 12). All three moisture content treatments yielded a pH value above 7, indicating slight alkalinity. The slightly acidic nature of the organic fertilizer produced through MMM suggests its potential benefit in ameliorating acidic soil conditions in tobacco fields, potentially contributing to increased farmer income.

Temperature

In Experiment I, WCM initially exhibited a rapid increase in temperature. However, this was followed by a significant decline in subsequent stages. In contrast, MMM maintained a relatively high composting temperature throughout the process (Figure 13). In Experiment II, the higher moisture content treatments (68% and 73%) showed a gradual increase in temperature with time, which eventually stabilized. In the later stages of composting, all three moisture content treatments reached similar temperatures. Notably, during the molecular membrane composting phase and the

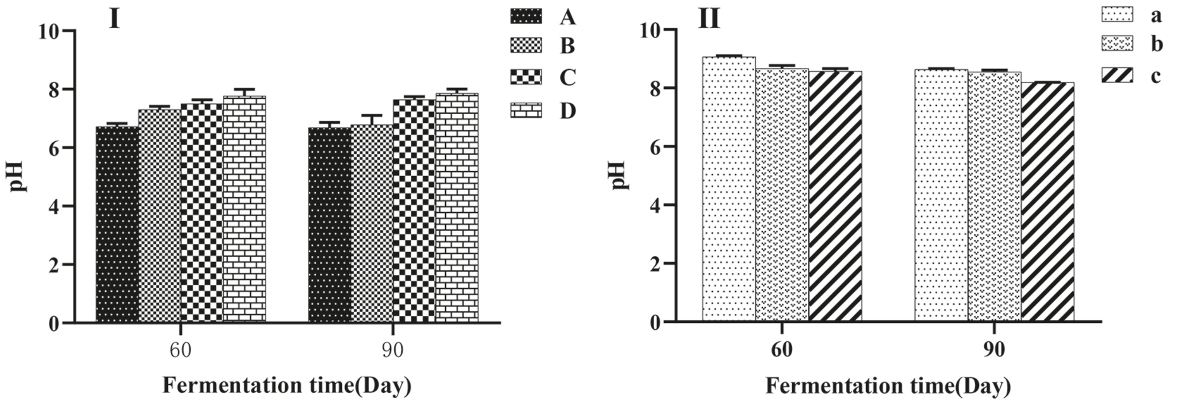

Figure 12. pH value; I – the influence of different ingredients and fermentation methods on the ph of organic fertilizer; II – the influence of different moisture content treatments on the ph of organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

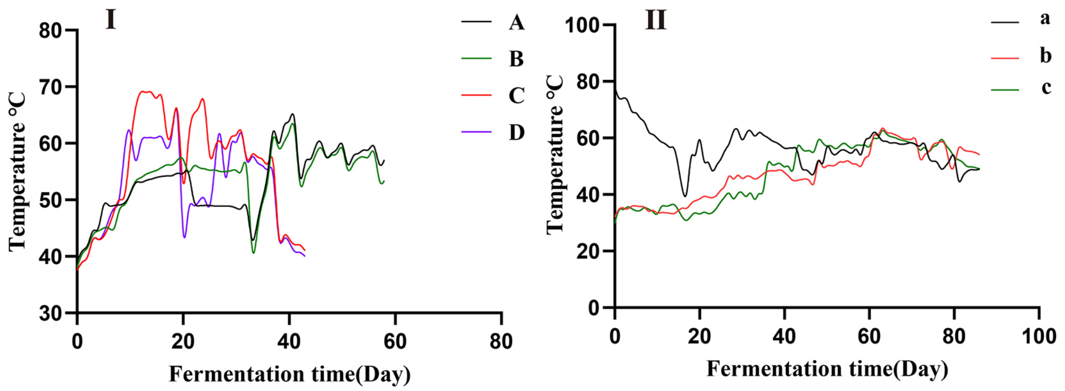

Figure 13. Continuous temperature change curve; I – the influence of different ingredients and fermentation methods on temperature changes; II – the influence of different moisture content treatments on temperature changes in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

early maturation stage, the 63% moisture content treatment exhibited significantly higher temperatures compared to the other two treatments. This suggests that this moisture content is optimal for molecular membrane composting, while higher moisture contents may hinder the aeration process and subsequent maturation rate.

Changes in *E. coli* and ascaris egg count

E. coli count

On day 90, the distillery waste-based organic fertilizer treated with MMM exhibited the lowest *E. coli* count, measuring 0.5×10^4 CFU/g. Similarly, the 63% moisture content treatment showed the lowest *E. coli* count among all treatments. Notably, the 63% moisture content samples collected after both 60 and 90 days of composting exhibited significantly lower harmful microbial counts compared to the higher moisture content treatments (Figure 14). These results suggest that the 63% moisture content treatment with MMM achieves a comparable reduction in *E. coli* count within 60 days compared to 90 days of composting.

Ascaris egg count

The organic fertilizer treated with MMM showed a low Ascaris egg count, ranging from 7 to 12 eggs per 100 g. The lowest count (11 to 12 eggs per 100 g) was observed in the 63% moisture content treatment (Figure 15). Similar to the findings for *E. coli*, the 63% moisture content treatment with the rapid composting method achieved a comparable reduction in Ascaris egg

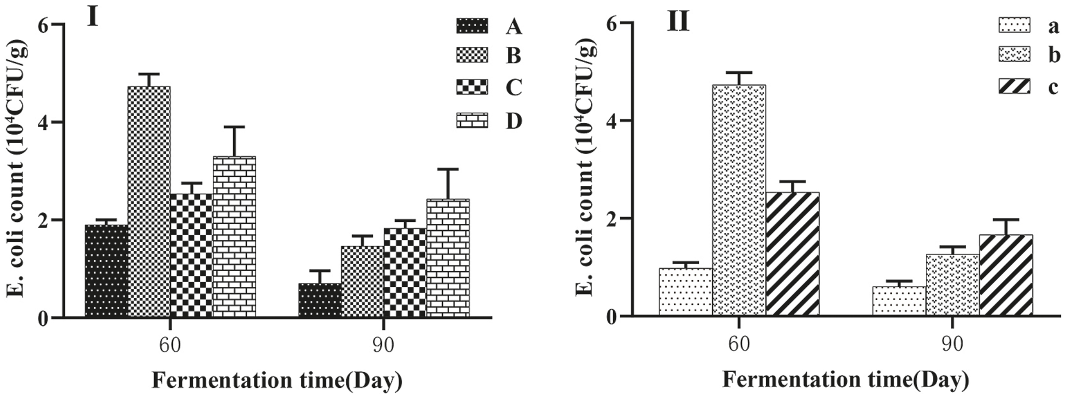

Figure 14. *E. coli* count; I – the influence of different ingredients and fermentation methods on the *e. coli* count in organic fertilizer; II – the influence of different moisture content treatments on the *e. coli* count in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

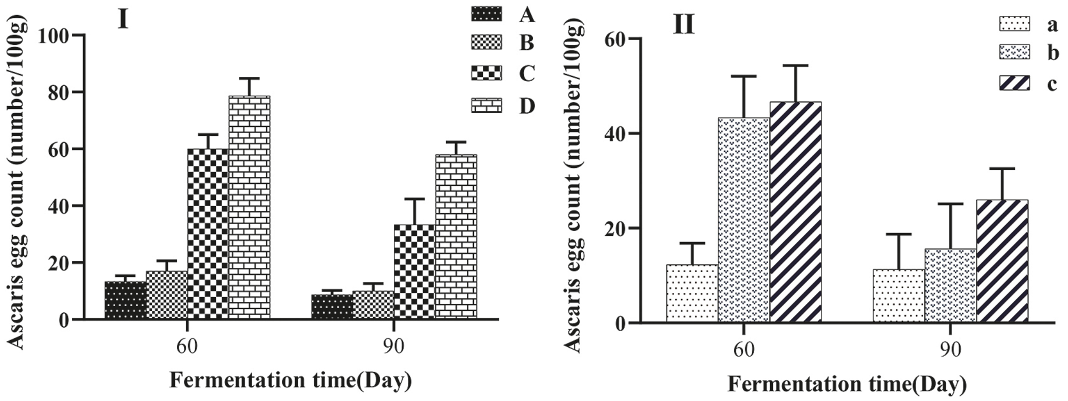

Figure 15. Ascaris egg count; I – the influence of different ingredients and fermentation methods on the ascaris egg count in organic fertilizer; II – the influence of different moisture content treatments on the ascaris egg count in organic fertilizer; A – molecular membrane distiller's grains; B – molecular membrane mycelial residue; C – strip pile distiller's grains; D – strip pile mycelial residue; a – moisture content 63%; b – moisture content 68%; c – moisture content 73%

count within 60 days compared to 90 days of composting. No significant differences were observed between the two time points.

DISCUSSION

With technological advancements and economic development, environmental concerns are becoming increasingly prominent. While the extensive use of chemical fertilizers has boosted crop yields, it has also led to environmental problems such as soil acidification and compaction [32]. Organic fertilizers, on the other hand, not only reduce the dependence on chemical fertilizers and pesticides but also contribute to the remediation of contaminated soils [33]. Furthermore, organic fertilizers utilize waste materials like animal manure, agricultural residues, industrial byproducts, and municipal waste, promoting sustainable resource utilization, turning waste into valuable resources, and mitigating the adverse environmental impacts of waste accumulation [34, 35]. Applying organic fertilizers to tobacco fields enhances soil health, improves tobacco quality, and ultimately increases farmer income [36–38]. Incorporating beneficial microorganisms into organic fertilizers can also help overcome continuous cropping obstacles, providing a solid foundation for consecutive tobacco cultivation on the same land and reducing land rental costs [39]. However, conventional composting methods often require more than three months to produce effective organic fertilizers, significantly impacting production efficiency and operational costs for specialized tobacco organic fertilizer manufacturers.

The molecular membrane composting method, featuring bottom aeration and a molecular membrane cover to prevent the loss of ammonia nitrogen, nitrate nitrogen, and other volatile compounds [40, 41], can rapidly elevate the temperature of the composting materials when the material ratio is optimized. Both large-scale composting trials demonstrated that excessive moisture content hinders rapid temperature increases, thereby slowing down the composting process. Conversely, different material compositions, when subjected to the same composting process, resulted in relatively minor differences in the final product [42]. The total nitrogen content of the organic fertilizer produced using MMM was significantly higher than that of WCM, coupled with a lower C/N ratio, consistent with previous research [43, 44]. Further analysis of the impact of moisture content on composting, particularly on total nitrogen content and C/N ratio, revealed that lower moisture content substrates yielded the highest total nitrogen content. Notably, the C/N ratio at 60 days of composting was statistically similar to that at 90 days, with nearly identical total nitrogen content, indicating that this optimized technology achieves the effectiveness of 90 days of traditional composting within just 60 days.

Organic fertilizer produced from distillery waste and cow dung using MMM showed significantly lower P_2O_5 and K_2O contents compared to fertilizer produced from mushroom residue and cow dung [45]. This difference could be attributed to the high initial moisture content of the distillery waste, potentially leading to the loss of water-soluble nutrients during the composting process. In the second batch, adjusting the material ratio to 4:3:3 (cow dung: mushroom residue: distillery waste, dry weight basis) and maintaining a moisture content of 63% resulted in significantly higher K_2O content at 60 days compared to the higher moisture content treatments. This finding suggests that excessive moisture content can lead to the loss of water-soluble nutrients. As cow dung and distillery waste often have high moisture content, controlling the moisture content of the mixed materials below 63% is crucial for rapid composting.

Optimizing the molecular membrane composting technology with a subsequent maturation phase and adjusted parameters, particularly moisture content control, resulted in a germination index close to 90% for the organic fertilizer within 60 days. Additionally, the *E. coli* and Ascaris egg counts were comparable to those achieved after 90 days of composting. In contrast, the organic fertilizer with higher moisture content exhibited a germination index below 75% after 60 days, with *E. coli* and Ascaris egg counts several times higher than the optimized 63% moisture content treatment. These findings highlight that the molecular membrane composting method, when coupled with controlled moisture content, facilitates rapid temperature increases, effectively eliminating harmful organisms and minimizing the impact on seed germination[46].

The fulvic acid content continuously decreased with composting time, with no significant difference observed between 15 and 60 days of composting. However, the fulvic acid content at 90 days was only about half of that at 60 days, suggesting that excessively long composting periods may be detrimental to nutrient retention. Bacteria played a dominant role during the molecular membrane composting phase, while fungi and actinomycetes played a more significant role in the middle and later stages. Excessive moisture content was found to be unfavorable for microbial growth, particularly for bacteria. Analysis of cellulase and protease activity revealed that MMM significantly enhanced the activity of both enzymes compared to WCM[47]. Higher moisture content in the composting substrate significantly reduced the activity of both enzymes, especially cellulase, indicating that excessive moisture content hinders the production of cellulase by microorganisms, thereby affecting their ability to decompose complex substances like cellulose. These findings similar with previously reported results.

Compared to the traditional windrow composting method, incorporating the molecular membrane composting method in the early stages, followed by a maturation phase and optimization of parameters such as material composition and moisture content, can significantly reduce the composting time from over 90 days to just 60 days. This accelerated decomposition of organic matter significantly enhances the efficiency of the composting process, leading to increased levels of humic acid, N, P_2O_5, and K_2O in the finished product [48]. Moreover, the optimized rapid composting method minimizes nutrient losses, particularly of P_2O_5 and K_2O. By optimizing parameters, especially moisture content, MMM facilitates rapid temperature increases, effectively eliminating harmful organisms and ensuring the quality and safety of the finished organic fertilizer within a shorter timeframe. Importantly, harmful organism indicators, such as *E. coli* count, remained within safe limits. In conclusion, optimizing the organic fertilizer composting method and parameters can significantly shorten the composting cycle while ensuring product quality. This optimization enables organic fertilizer plants to increase their production capacity from four batches per year to six, reducing costs and making this technology highly suitable for wider adoption.

CONCLUSION

The optimal formula for rapid composting consists of cow dung, mushroom residue, and distillery waste at a dry weight ratio of 4:3:3, with a moisture content of ≤63%. Implementing the molecular membrane rapid composting method coupled with a subsequent maturation phase effectively reduces the traditional composting time from over 90 days to just 60 days, while ensuring the quality and safety of the finished organic fertilizer.

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