

# Circular Bioeconomy Solutions: Transforming Mushroom Waste into High-Quality Fertilizer with Seashell Additives

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**Abstract.** This study aims to develop an innovative composting method that transforms mushroom cultivation waste into high-quality organic fertilizer, promoting sustainable agriculture and supporting circular economy principles. Over a 50-day period, the decomposition process was closely monitored, with a focus on pH, temperature, and microorganism activity, including the presence of *Escherichia coli* and *Coliform* bacteria. A key innovation in this study was the addition of seashell powder in the MR3 treatment, which aimed to improve decomposition efficiency and stabilize the compost's pH. Decomposition significantly accelerated after day 14, reaching its peak between days 22 and 23 with temperatures exceeding 50°C. This process resulted in a compost weight reduction of 1 to 1.5 kg. All trials yielded high-quality organic fertilizers, with an organic matter content exceeding 20%, thereby meeting national standards for organic fertilizers. This research suggests a practical approach to managing mushroom waste, potentially contributing to sustainable agricultural practices and circular economy applications. The incorporation of seashell powder appeared to enhance decomposition efficiency and stabilize pH levels, thereby improving the functional properties of the compost. However, additional large-scale studies are required to validate these findings. The economic potential of the project has also been estimated, demonstrating that the payback potential makes it a worthwhile investment.

**Keywords:** Composting, mushroom waste, circular economy, pH stabilization, shell powder, organic fertilizers, sustainable agriculture.

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## 1. Introduction

Currently, in Vietnam as well as worldwide, organic waste management is shifting towards various methods such as landfilling, incineration, or recycling. Among these, composting, also known as organic fertilization, is seen as the optimal approach [1]. Composting not only facilitates the reuse of organic waste that would otherwise be discarded into the environment, but also enriches the soil and plants with nutrients. Importantly, it can also generate economic benefits [2]. Organic composting is an aerobic method involving the breakdown of organic matter, ultimately producing organic fertilizer, carbon dioxide, water, and heat. This process not only helps in recycling organic waste but also enhances soil health by adding essential nutrients and improving soil structure. The conventional composting process can be divided into four key microbiological phases based on temperature: mesophilic, thermophilic, cooling, and maturation [3]. Throughout these stages, the microbial community undergoes significant changes, leading to the final product of organic fertilizer. Each phase plays a crucial role in transforming the organic materials, ensuring the efficient decomposition and stabilization of the compost [4].

Mushrooms are a nutritious food, widely consumed and favored in Vietnam. Mushroom cultivation serves as a significant industry meeting the daily consumption needs of the Vietnamese people. Corresponding to the large volume of mushrooms produced, the volume of post-harvest waste is considerable [5]. In India, it is estimated that mushroom cultivation facilities generate approximately 130,000 metric tons of mushroom cultivation waste annually. This substantial amount of waste underscores the need for effective waste management strategies [6]. Therefore, the critical issue at hand is the management of this post-harvest waste. Mushrooms can be grown with diverse substrates such as straw, sawdust, corn cobs, and cotton waste. These materials share the common property of being rich in cellulose, readily available, and reasonably priced. Consequently, to save time, after a harvest, workers often bypass waste management, choosing to either discard the waste directly and replace the mushroom substrate for the next cycle or use it as a planting medium without processing or treatment. This can potentially cause human disease, environmental pollution, aesthetic degradation, and is a waste of resources. Mushroom cultivation waste, high in minerals, phosphates, and porosity, can effectively regulate soil conditions and stimulate seed germination. Mushroom substrate is a material where the mycelium can grow and form. The substrate provides the mushrooms with nutrients, moisture, and energy necessary for growth and fruiting. A good substrate has a dense composition of fibrous, woody materials like lignin, cellulose, and hemicellulose. These post-harvest substrates still contain many unused nutrients beneficial for plants. Thus, directly discarding them constitutes a waste of natural nutrients [7].

Compost production research encompasses a variety of materials, but studies on post-harvest mushroom waste are notably limited. Recent study illustrates that the changing C:N ratio and blend composition (animal manure) significantly impact the composting process [8]. A literature review also reveals the feasibility of reusing Spent Mushroom Substrate (SMS) with coir as a component of casing material for mushroom cultivation. Some study have used SMS of three types of oyster mushrooms as fertilizer for Spinach (*Spinacea oleracea*). Recent study has utilized it as an alternative to peat moss substrate for the production of Kale in Malaysia. SMS was repurposed for the cultivation of oyster (*Pleurotus ostreatus*) and white button (*Pleurotus florida*) mushrooms. Furthermore, SMS has been employed by *Lycopersicon esculentum* for tomato cultivation [9]. Overall, recent studies aim at exploiting post-harvest mushroom waste for agricultural purposes. From this basis, an experimental compost production model is established to support crop growth in agriculture from mushroom cultivation waste. This experimental produces an organic

substrate to leverage and manage the waste generated from mushroom cultivation. It may not only enhance the mushroom production economy but also reduce or limit the amount of chemical fertilizer currently used in agriculture. Utilizing compost from this process improves soil environment, creates moisture, and mitigates pest and disease issues, steering towards products that offer ecological value [10]. However, deeper research into the composting process to produce higher-quality post-treatment products for agricultural application is still limited.

In theory, a drop in pH can occur during the initial stages of composting. This is due to the commencement of organic matter decomposition, during which the microbes involved produce organic acids such as acetic and propionic acids. These acids have the ability to lower the pH of the compost mixture [2]. To adjust the pH value for composting, lime (Calcium Oxide) is commonly used to bring the pH to an optimal range, usually between 5.5 and 8.5. This can improve the environmental conditions for decomposing microorganisms, accelerate decomposition and composting [11]. An ideal pH environment will stimulate the growth of beneficial microorganisms, contributing to organic degradation and the production of nutrient-rich compost. Furthermore, the current trend is to co-treat wastes as a sustainable solution. The use of crushed seashell powder as a replacement for lime powder in composting is a valuable solution. Seashells contain a large amount of calcium carbonate and other minerals, providing essential nutrients for the composting process [12]. In addition, seashell powder is a recycled source from natural resources, whereas lime powder is often produced from mineral mining processes. Using seashell powder helps reduce environmental impact and sustainably utilize natural resources [13]. With the presence of seashell powder in the blend, calcium carbonate in seashells can help maintain or increase the alkalinity of the compost mixture [14]. This can enable the initial decomposition process to occur well without a significant decrease in pH. The increase in alkalinity can stabilize the pH environment, which is beneficial for the decomposing microbes to continue their activities.

Therefore, the study aims to innovate composting methods by combining various agricultural wastes, including seashells and spent mushroom substrates, to produce high-quality compost. By integrating these materials, the study seeks to enhance the decomposition process and stabilize pH levels, thereby producing an effective organic fertilizer. The innovative aspect of this research lies in the use of seashell powder as a pH stabilizer and nutrient source, which has not been extensively studied in previous composting research. Through rigorous experimental trials, the study evaluates the decomposition capacity and the production of natural organic fertilizer based on different blend materials while maintaining a consistent C/N ratio. The findings will provide valuable scientific data for farmers and environmental managers, supporting policy planning and proposing sustainable waste management solutions. The study's outcomes are expected to contribute significantly to sustainable agriculture and the circular economy by reducing agricultural waste, enhancing soil quality, and decreasing reliance on chemical fertilizers, thereby offering both environmental and economic benefits.

## **2. Materials and Methods**

### **2.1. Research Materials**

The spent mushroom substrate, derived from harvested oyster mushroom spawns, was sourced from a mushroom production facility located at Cau Xe market in Hung Thuan commune, Trang Bang town, Tay Ninh, Vietnam. Coir and kale seeds were obtained from

local agricultural supply stores (Thu Duc District, Ho Chi Minh City). Seashell powder was collected and ground in To Hien Thanh, neighborhood 3, Duc Thang ward, Phan Thiet city, Binh Thuan, Vietnam. The nutrient composition of these blended materials is detailed in Table 1.

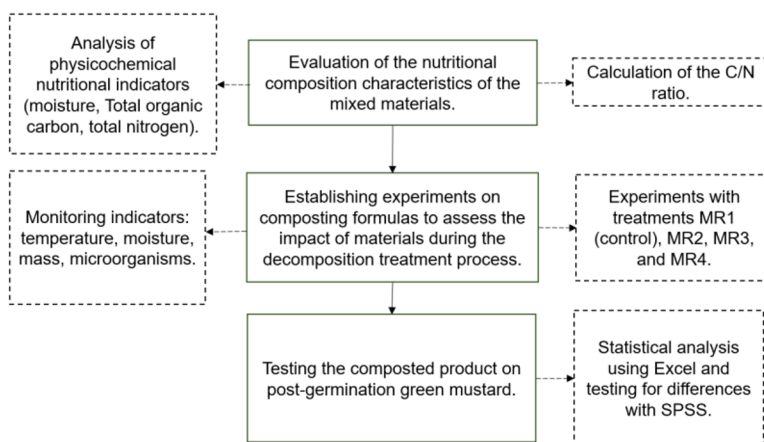
**Table 1.** The basic nutritional composition of the materials

Materials	Humidity (%)	Total Organic Carbon (TOC) (%)	Total Nitrogen (TN) (%)	CaCO <sub>3</sub> (%)
Waste residue after mushroom cultivation	51.8	50.5	1.13	
Coir	70	48.9	0.23	
Shell powder	0.23	0.26	0.23	35.4

The fungal product, Trichoderma, containing Trichoderma spp. at 10<sup>8</sup> CFU/g and Bacillus subtilis at 10<sup>8</sup> CFU/g, was acquired from Dien Trang company. The microbial assessment environment included various chemicals from Himedia brand, such as Nutrient Agar, Hichrome Chromogenic Coliform Agar (CCA), and Carboxymethyl Cellulose (CMC) substrate. CCA is used to test levels of *E. coli* and *Coliform*, while CMC and Nutrient Agar are used to assess cellulose-decomposing microorganisms

## 2.2. Experimental Procedure and Evaluation Process

First, the nutritional composition of the mixed materials is evaluated by analyzing the spent oyster mushroom substrate, coir, and seashell powder to determine their suitability for composting (Figure 1). Next, composting formulas are established to assess the impact of these materials during the decomposition process, monitoring key indicators such as temperature, moisture, mass, and microbial activity. Physicochemical indicators such as moisture content, total organic carbon, and total nitrogen are analyzed to evaluate the quality and nutritional value of the compost.



**Fig. 1.** The process flow diagram for conducting evaluation experiments

The carbon-to-nitrogen (C/N) ratio is calculated to ensure an optimal balance for microbial activity during composting. This process requires continuous monitoring of temperature, moisture, mass, and microbial activity. Subsequently, experiments are conducted with different formulas, including a control group (MR1) and various mixtures (MR2, MR3, and MR4), to compare the effectiveness of the formulas. After composting, the product is tested on post-germination green mustard plants. Parameters such as germination rate, plant height, root length, and leaf count are measured to assess the impact of the compost on plant growth. Finally, the data collected are statistically analyzed using Excel and SPSS to determine significant differences between the experimental formulas and validate the results.

### 2.3. Experimental method for reuse of substrate bags after growing Grey Oyster mushroom as fertilizer for green mustard.

#### 2.3.1. Method to evaluate of different mixed composting materials impact on the decomposition process.

Table 1 shows that the initial composition of the material indicates that the moisture and organic content of the spent mushroom substrate are quite high. This makes it suitable as the primary material for composting to produce compost. Coir, with its high moisture content, is used as an additional material to retain moisture and enhance nutrients. Seashell powder, with a high calcium content, is added to the composting process to raise the pH, creating an optimal environment for decomposing microbes. From there, this study calculated the blending of materials and balanced the C/N ratio at around 30 [15]. The results of balancing the weight of the materials are described in Table 2.

**Table 2.** Balance the volume and composition of the composting materials.

Treatments	MR1	MR2	MR3	MR4
Waste residue after mushroom cultivation (kg)	13	13	10.5	10
Coir (kg)	-	-	-	2
Shell powder (kg)	-	-	2.5	-
Additional NPK fertilizer (kg)	-	-	0.7	0.7
Additional <i>Trichoderma</i> (kg)	-	0.013	-	-
Total weight (kg)	13	13.013	13.7	12.7
C/N	29.9	30.0	30.0	30.1

The balancing of the C and N ratios is calculated based on (1) material weight; (2) total carbon content of raw materials; (3) total nitrogen content of raw materials; and (4)

sample moisture content [16]. The experiments were conducted with blended materials and evaluated decomposition processes in styrofoam boxes. Each box weighs about 0.5 kg and has a capacity of 20 kg. Each experiment will be mixed evenly and given appropriate moisture content around 45 - 55% [17]. They are then put into the boxes and the box lid is tightly closed. After 3 days, they are stirred once and water is added to maintain the initial moisture level.

Throughout the composting process, the following parameters are used to evaluate decomposition: (1) Temperature (°C) is recorded daily at 10 AM using a digital sensor placed in the middle of the composting feedstock. (2) pH is measured every 3 days over a total of 50 days in a solution of organic substrate and distilled water (ratio 1:5). (3) Moisture is assessed using a moisture balance, with samples taken regularly. (4) Microbial content, including total aerobic microbes, cellulose-decomposing microbes, and *E. coli* - *Coliform* bacteria, is tested three times during the composting process (initial, middle, and final stages) [18].

### ***2.3.2. Method to quality assessment of green mustard crop following early stage compost application.***

After evaluating the final compost product, we assessed its effectiveness on the germination and early growth of green mustard plants. The experiment was conducted using plastic seedling trays filled solely with the compost from the MR1, MR2, MR3, and MR4 treatments, without any added soil. The compost was placed in seedling holes on each tray, with one seed per hole, and each treatment was repeated with 30 cells. All treatments were kept under the same light, temperature, and irrigation conditions to ensure consistency and reliability in the results

To evaluate the effectiveness of the compost treatments, several criteria were considered. Firstly, the germination rate was measured [19], indicating the percentage of seeds that successfully germinated. This provided an initial assessment of how well each compost treatment supported seed germination. Secondly, the height of each plant was measured by placing a centimeter ruler at the seedling base and straightening the stem to the tip. This measurement helped determine the growth rate and overall health of the plants under different compost treatments.

Additionally, the root length of each plant was measured after harvest. This was done by placing a ruler from the base of the root and straightening it to the root tip. Measuring root length provided insights into the root development and nutrient uptake capabilities of the plants. Finally, the number of leaves was counted by recording the leaves and leaf branches on each plant for each treatment after harvest. The number of leaves is a crucial indicator of plant vitality and photosynthetic capacity [20].

### ***2.3.3. Method of sample analysis and data statistics.***

The nutritional evaluation criteria were analyzed by methods based on standard methods, including moisture dried at 70°C (TCVN 9297:2012) [21], organic matter content (TCVN 9294:2012) [22], total nitrogen content (TCVN 10682:2015)[23], and total phosphorus content (TCVN 8563:2010)[24]. The sample's moisture was checked with the Ohaus Drying Scale Model MB25, and pH was assessed using the HANNA HI9811-51 pH measuring device.

The study data were collected and entered using Excel 2019. They were then processed for statistical evaluation and difference assessment using Minitab 21.3 software, employing ANOVA with a 95% confidence level.

#### **2.4. Experimental method for reuse of substrate bags after growing Grey Oyster mushroom as fertilizer for green mustard.**

This study investigates the germination potential of green mustard (*Brassica juncea*) seeds cultivated on a substrate composed of a blend of mushroom compost and clean soil. The control group, used for comparison, consists of clean soil mixed with the commercial fertilizer Con co SS - Born AT 02.

Initially, the seeds undergo a pre-sowing treatment where they are soaked in warm water at 40-50°C for 8 hours. The physical properties of the mushroom compost substrate, once combined with clean soil, are treated similarly to the control group using Con co SS - Born AT 02 fertilizer. In a 50-cell seedling tray, the first 5 rows are filled with soil mixed with Con co SS - Born AT 02, while the subsequent 5 rows are filled with soil mixed with mushroom compost post-cultivation. The experimental setup is alternated and replicated across five seedling trays (50 cells per tray).

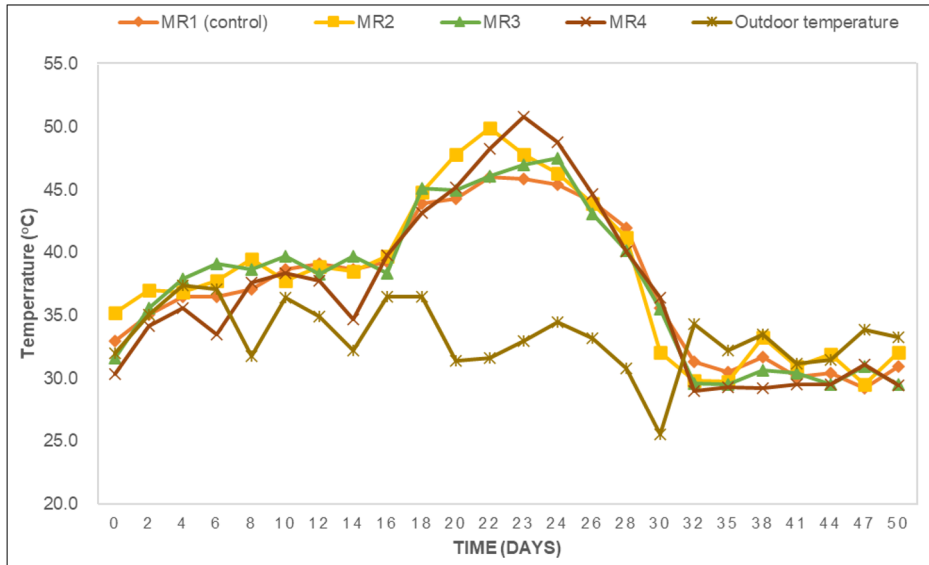
Each cell is sown with one seed, and after 7 days, the following parameters are recorded: (1) germination rate and (2) seedling height. Data collected is then entered and analyzed statistically using Excel 2021, with differences evaluated using SPSS 20 software.

### **3. RESULTS**

#### **3.1. Decomposition process of co-mixing treatments.**

##### *3.1.1. Evaluation of temperature during decomposition.*

Figure 2 illustrates the temperature fluctuations during the initial stage, which range from 31.2°C to 35°C. Although these fluctuations are not very pronounced, this stage, known as the hydrolysis fermentation process, involves the metabolic activity of various heterogeneous microbial groups. These microbes gradually increase the temperature as they utilize organic nitrogen and carbon. The decomposition of soluble compounds, such as sugars, produces organic acids, creating a fermenting environment.



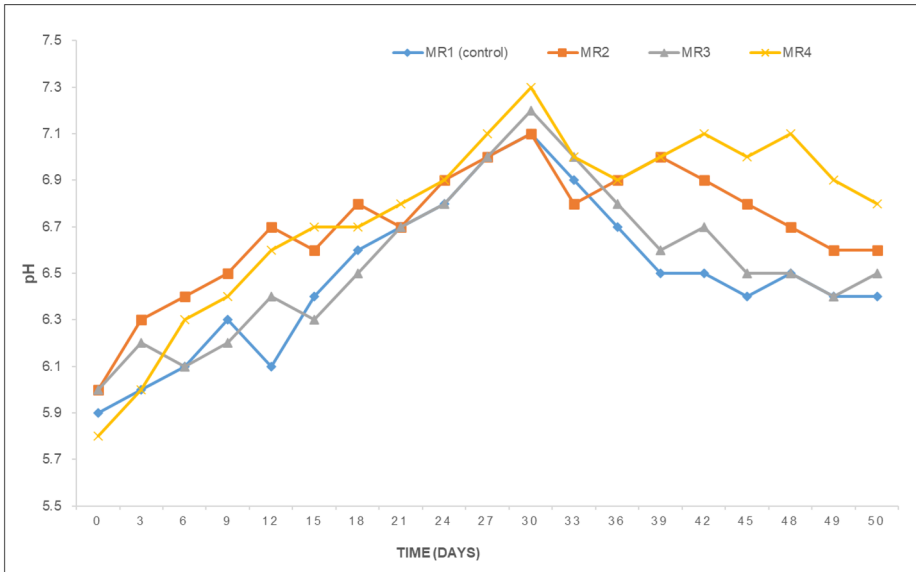
**Fig. 2.** Temperature of the treatments compared to the outdoor background temperature.

In the middle stage, around days 18 to 28, temperatures range from 45°C to 50.8°C, with the highest being in MR4. During this phase, compost piles maintain a high temperature to facilitate decomposition and destroy harmful bacteria, including fungi, *E. coli*, Coliforms, worms, and other pathogens. The temperature begins to cool around day 32, stabilizing at approximately 30°C. The changes in temperature during this middle stage of decomposition are due to the breakdown of substrates, which causes a rapid rise in temperature.

After the decomposition process, the temperature gradually decreases and stabilizes between 28.2°C and 31°C. The fluffiness and humidity of the compost pile, which also rely on temperature, are crucial for determining the quality of the final compost product. The results indicate that, across all four treatments, the composting temperatures ranged from 28°C to 51°C. Sustained high temperatures of about 45°C or higher are necessary to kill worm eggs and pathogens in the compost pile. The maturity of the compost pile is also assessed based on temperature parameters, which help determine the quality of the post-compost organic substrate.

### 3.1.2. Evaluation of pH during decomposition.

pH is a critical factor affecting the functionality of microorganisms, so maintaining optimal pH during the composting process is essential for effectiveness and applicability. According to recent studies, a pH range of 5.5 to 8.5 is optimal for microorganisms during composting. A higher or lower pH can slow down and inhibit microbial activity [25]. During the initial phase, organic acids released by bacteria and fungi reduce the pH, signaling a healthy composting process, as long as the pH stays above 4.5. By the end of composting, a pH lower than 7 may indicate incomplete decomposition or anaerobic conditions due to insufficient oxygen.



**Fig. 3.** The pH of the treatments in the composting process.

Throughout the composting process, Figure 3 shows that the pH values in all treatments ranged from 5.8 to 7.5, varying with the composting stage. pH values significantly increased in the mid-stage (days 20 to 30), peaking on day 28. The highest recorded pH values for each treatment were as follows: MR1 (7.1), MR2 (7.5), MR3 (7.2), and MR4 (7.5). This increase is attributed to the decomposition of soluble compounds like sugars, which produce organic acids and create a fermenting environment known as the hydrolysis fermentation process.

After the fermentation stage, the pH values in all treatments gradually decreased from day 37 and remained lower until the end of composting: MR1 (6.4-6.5), MR2 (6.8-7.1), MR3 (6.4-6.5), and MR4 (6.8-7.1). Therefore, the pH of all treatments stayed within the optimal range of 5.8-7.5 throughout the composting process. The final pH values of the organic fertilizers met the standard 10TCN 526:2002 for organic microbial fertilizers derived from household waste, indicating effective microbial decomposition. Optimal decomposition occurs within a pH range of 6.0-8.0, as shown by the gradual increase in pH, reflecting the successful breakdown of organic substances by microorganisms and fungi.

### 3.1.3. Evaluation of weigh during decomposition.

Determining the volume shrinkage of the compost pile is relatively complex because this parameter depends on the moisture content of the compost pile as well as the composition of the input materials used in various composting models. The volume shrinkage trends of the four organic fertilizer treatments are monitored every three days, as depicted in Figure 4.

Figure 4 illustrates the weight shrinkage of the treatments over the composting period. After 50 days of composting, the model with the highest volume shrinkage is MR4, at 13%. Treatment MR2 shows a 12% reduction, followed by treatment MR3 at 9%. The treatment with the least volume shrinkage is MR1, at 5%. This indicates that, due to the lack of suitable mixing materials in MR1, the decomposition of organic substances occurred more slowly, resulting in less volume shrinkage compared to the other models.

Overall, the results show a steady decrease in weight, which is maintained consistently throughout the composting process. This indicates that beneficial microorganisms have successfully decomposed complex organic substances into simpler forms. Consequently, the quality of the post-compost product is improved, feeling fluffier and lighter than before.



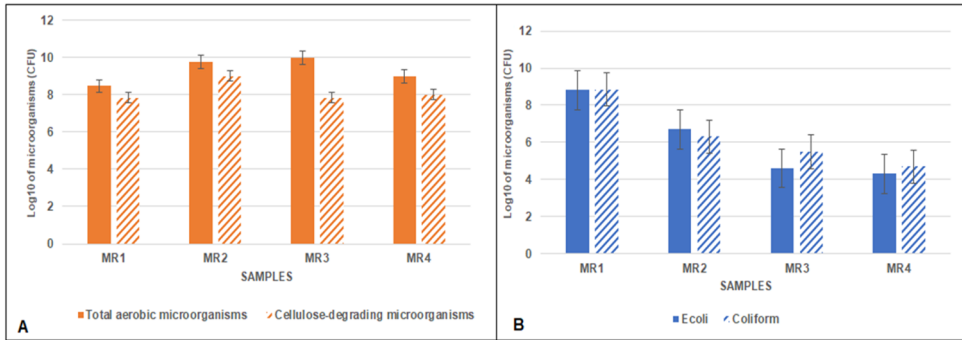
**Fig. 4.** Change in weight of treatments over time of composting.

### 3.2. Evaluation of the product after the decomposition process.

Beneficial microorganisms examined during the compost pile formation include total aerobic microorganisms and cellulose-degrading microorganisms. In which, total aerobic microorganisms are one of the main agents in decomposing complex organic substances into simpler organic ones, participating in stages throughout the decomposition process. Cellulose-degrading microorganisms are among the beneficial microorganisms in decomposing complex organic substances such as lignin into organic acids, converting organic matter into nutrients after decomposition.

Materials are crushed to a moderate size to create ventilation, appropriate moisture, and adequate oxygen supply every three days. The temperature is at a thermotolerant and thermophilic level, so the beneficial microorganisms grow and develop. Figure 5A shows that total aerobic microorganisms and cellulose-degrading microorganisms of the product after composting both meet QCVN 01-189:2019/BNNPTNT in the category of organic microbial fertilizers with a condition of beneficial microbial density greater than  $10^6$ . Beneficial microorganisms that support compost decomposition include bacteria, actinomycetes, and fungi. This development rate is appropriate for the decomposition process. If these microorganisms grow excessively, it will still affect the quality of the compost pile, cause odors, and affect human and animal health as they can cause dangerous diseases [26]. Figure 5B shows the evaluation of the *E. coli* and Coliform content in the product after compost decomposition. These bacteria are potential pathogens that often proliferate during the decomposition of organic matter. However, they are usually eliminated during the high heat stage when the temperature in the compost piles rises to  $48^{\circ}\text{C}$  for a sufficient duration [27]. The results indicate that the *E. coli* and Coliform content in most samples is below the permissible level of  $10^3$ , according to Vietnamese standards QCVN 01 - 189:2019/BNNPTNT. However, MR1 still has levels up to  $10^4$ , nearly meeting the standard. This discrepancy can be attributed to the independent

decomposition process in MR1, which does not include supplementary substrates or decomposition-supporting microorganisms, resulting in insufficient temperatures to eliminate all pathogenic microorganisms.



**Fig. 5.** Microorganisms in the post-compost treatment samples

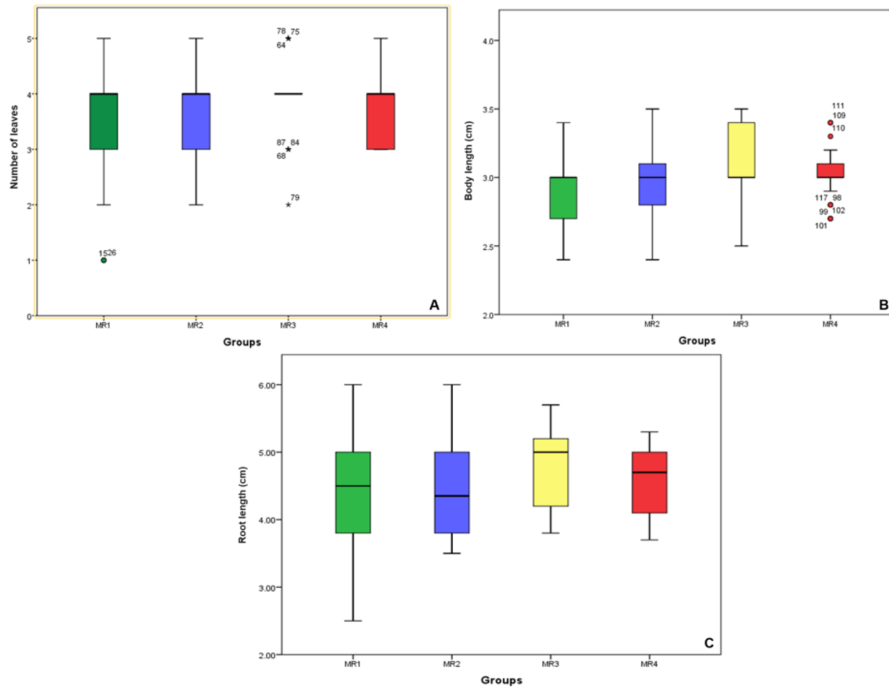
The treatments are evaluated for the quality of the product after composting, the results are shown in Table 3. The results show that all products after composting meet the standard for organic fertilizer compared to Vietnamese standard QCVN 01-189:2019/BNNPTNT. Treatment MR4 has an organic content of 50.7%, the highest compared to the other treatments. The moisture content of the treatments after decomposition is also at an appropriate level of 20-30%, this moisture level is suitable for storage for agricultural applications. Nutrient indicators such as nitrogen and phosphorus are basically approximate to the minimum content of Vietnamese standards, but not too much to provide necessary nutrients for plants [28].

**Table 3.** Quality and nutritional parameters of the product after composting.

Treatments	Humidity (%)	TOC (%)	Total Nitrogen (%)	Total phosphorus (%)
MR1 (control)	27.2	22.2	0.71	0.16
MR2	25.0	49.1	1.55	0.23
MR3	21.0	30.9	1.0	1.00
MR4	25.7	50.7	1.34	0.31

### 3.3. Testing of post-compost products on green mustard at the early stages of germination

The compost products were used as the primary substrate for seed germination, achieving a 100% germination rate across all treatments, with 30 seeds per treatment. After 14 days, the early-stage growth metrics of green mustard, including leaf count, stem length, and root length, were evaluated and are depicted in Figures 6.



**Fig. 6.** (A) Number of leaves, (B) Stem length, and (C) Root length of green mustard grown on different treatments, comparing various substrates with MR1 as the control group.

Figure 6A illustrates that the leaf counts across treatments were similar, averaging four leaves per plant. Among the treatments, MR1 (control) had the lowest leaf count, while MR3 had the highest. MR4 exhibited the smallest range of fluctuation, with leaf counts between 3 and 5 leaves. Statistical analysis indicated that 75% of the total leaves across treatments ranged from 2 to 4 leaves. These results suggest that plants fertilized with the organic substrate from treatment MR4 demonstrated the best growth in terms of leaf production.

Figure 6B shows that all treatments resulted in greater stem lengths compared to MR1, with MR3 showing a statistically significant difference. MR3 exhibited the most green mustard plants with the highest stem length, with 100% of the plants measuring 3 cm or more. This indicates that plants fertilized with the organic substrate from treatment MR3 achieved the greatest stem growth.

Finally, Figure 6C highlights the variations in root length among the treatments. MR1 showed the greatest fluctuation in root length, ranging from 2.5 cm to 6 cm, with only 25% of the plants having roots longer than 4.3 cm. MR2 achieved the highest root length, with 75% of the plants having roots longer than 4.3 cm. MR3 also had a high root length with minimal fluctuation, ranging from 3.7 cm to 5.7 cm, with about 75% of the plants having roots between 4.7 cm and 5 cm. This suggests that the organic substrate from treatment MR3 best supports root growth.

Overall, the combined results indicate that the MR3 treatment, which includes a blend of post-mushroom cultivation waste and seashell powder, most effectively supports the development of green mustard plants.

### 3.4. Analysis of economic efficiency of investment for mushroom growers

Through the experiment applying organic fertilizer made from spent mushroom substrate (SMS) after rice straw mushroom cultivation to green mustard greens, the MR3 treatment proved to be more effective than the other three treatments. The research results indicated that with a ratio of 10.5 kg of spent mushroom substrate to 2.5 kg of oyster shell powder (MR3), the highest quality organic fertilizer was produced among the four models.

In practice, one crop cycle of rice straw mushrooms lasts between 25 and 30 days, resulting in 500 kg to 1 ton of spent substrate. Therefore, if the method of reusing spent mushroom substrate as in the MR3 treatment is applied, the estimated cost of production would be calculated as shown in Table 4.

**Table 4.** Compost production costs with raw material components and initial investment.

Raw materials	Unit	Quantity	Unit price (VND)	Total amount (VND)
Additional NPK fertilizer	Kg	6	40,000	240,000
Seashell powder	Kg	240	3,000	720,000
Packaging	Packet	2.000	500	1.000.000
Labor	People	3	3,000,000	9,000,000
Tarps	Scroll	10 scroll /6 months	1,200,000/scroll	2,000,000/month
Equipment depreciation	-	-	2,916,000	2,916,000
Electricity	Kw/hour	500	1,555	777,500
Water	m <sup>3</sup>	20	14,740	294,400
Material transportation costs	Trip	1	500,000	500,000
Other costs	-	-	2,000,000	2,000,000
Total input costs	-	-	-	25,808,000
Production cost/product	kg	1	25,808	25,808

With a production cost of 25,808 VND per kilogram, the proposed selling price is 40,000 VND/kg. Compared to commercial organic fertilizers on the market, the production cost of this organic substrate is relatively high. For instance, Sông Gianh HC-15 bio-organic fertilizer is sold at 4,500 VND/kg, and Đặng Gia Trang organic vermicompost is priced at 11,000 VND/kg. However, if a steady and abundant supply of spent mushroom substrate can be secured, the production cost could be significantly reduced. The market

price of fertilizers is influenced by several factors, such as raw materials, machine maintenance, labor, and transportation costs, making such comparisons potentially unfair in terms of price. Nonetheless, producing organic substrates from spent mushroom substrate and other materials not only generates valuable compost for agricultural use but also helps reduce the amount of agricultural waste and post-agricultural or industrial by-products that are directly disposed of into the environment, thereby reducing environmental pollution.

**Table 5.** Cost planning based on production volume scenarios

Product volume (tons)	Production cost – labor (VND/month)	Number of workers	Workers cost (VND/month)	Total cost of raw materials and production (VND/month)	Cost per unit of product (VND/kg)	Revenue (VND/month)
1	16,808,000	3	9,000,000	25,808,000	25,808	40,000,000
3	50,424,000	3	9,000,000	59,424,000	19,808	120,000,000
5	84,040,000	5	15,000,000	99,040,000	19,808	200,000,000
7	117,656,000	5	15,000,000	132,656,000	18,950	280,000,000
10	168,080,000	5	15,000,000	183,080,000	18,308	400,000,000
20	336,160,000	8	24,000,000	360,160,000	18,008	800,000,000

**Table 6.** Estimate project payback period with production volume scenarios.

Product volume (tons)	Volume Selling expenses (20% of revenue value)	Profit before tax (VND/month)	Profit after tax (VND/month)	Payback period (Month)
1	8,000,000	6,192,000	4,953,600	100.93
3	24,000,000	36,576,000	29,260,800	17.09
5	40,000,000	60,960,000	48,768,000	10.25
7	56,000,000	91,344,000	73,075,200	6.84
10	80,000,000	136,920,000	109,536,000	4.56
20	160,000,000	279,840,000	223,872,000	2.23

Due to the small-scale nature of the experiment, material and transportation costs were relatively high, leading to an increase in production costs per product. However, producing organic substrates from spent mushroom substrate (SMS) and other materials not only yields compost products with economic value but also contributes to reducing the volume of SMS and other organic waste that would otherwise be directly discarded into the environment, thereby mitigating environmental pollution.

Tables 5 and 6 present the estimated costs and market revenue projections in Vietnam. From this, it is evident that the payback period for the project is approximately 10 months. For agricultural investment projects, a payback period of less than one year (12 months) is considered optimal, making the investment plan for this project highly viable.

## 4. Discussion

Temperature is a crucial indicator in assessing the effectiveness of the composting process. Higher temperatures correlate with better-quality organic fertilizer and a higher success rate in destroying pathogens harmful to plants and humans. During decomposition, microorganisms must operate at full capacity to convert organic compounds into nutrients, generating heat as a byproduct. The composting process of organic substrates progresses through four stages: warm, very hot, gradually cooling, and stable. Different types of bacteria are active at each stage, with thermophobic bacteria operating at the beginning and end of composting and thermophilic bacteria taking over during the middle stage when the compost pile temperature peaks. In this study, temperature, pH, and humidity parameters were recorded daily at 10 o'clock.

The initial hypothesis of this study was that integrating seashell powder into the composting process of post-harvest mushroom cultivation waste would enhance the efficiency of decomposition and result in high-quality organic fertilizer. This hypothesis was based on the idea that seashell powder, rich in calcium carbonate, could stabilize the pH of the compost [29], thus creating an optimal environment for microbial activity and improving the overall quality of the compost.

The study's findings confirmed the hypothesis, demonstrating that the addition of seashell powder significantly improved the decomposition process and the quality of the resulting compost. The decomposition process accelerated notably after day 14, reaching its peak between days 22 and 23, with temperatures exceeding 50°C. This rapid decomposition led to a compost weight reduction of 1-1.5 kg. All treatments produced high-quality organic fertilizers with an organic matter content exceeding 20%, meeting national standards for organic fertilizers. Notably, the MR3 treatment, which included seashell powder, exhibited enhanced decomposition efficiency and stabilized pH levels. This stabilization in pH and improvement in decomposition efficiency significantly enhanced the functional properties of the compost, making it a more effective organic fertilizer [30].

The enhanced decomposition efficiency observed in the MR3 treatment can be attributed to several factors. The pH levels in treatments MR2, MR3, and MR4 were higher compared to MR1 due to the presence of seashell powder in their composition. Seashell powder acts as a natural pH buffer, helping to neutralize acidity and maintain a more stable pH environment. The calcium carbonate in the seashells reacts with the acidic components produced during composting, thereby preventing the pH from dropping too low. This buffering effect ensures that the composting process remains within the optimal pH range for microbial activity, promoting efficient decomposition and producing high-quality compost. Primarily, the presence of calcium carbonate in the seashell powder played a crucial role in maintaining the pH within an optimal range for microbial activity [31]. Microbial activity is highly pH-sensitive, and most decomposing microorganisms,

including bacteria and fungi, thrive in a neutral to slightly alkaline environment [32]. The calcium carbonate in the seashell powder neutralized the organic acids produced during the initial stages of decomposition, thus preventing the pH from dropping to levels that could inhibit microbial processes [33].

Additionally, the seashell powder likely provided essential nutrients, such as calcium, which are vital for microbial metabolism and enzyme functions [34]. These nutrients acted as catalysts, accelerating the decomposition of organic matter [35]. The high temperatures observed during the peak decomposition phase were indicative of vigorous microbial activity, particularly by thermophilic bacteria [36]. These bacteria thrive at higher temperatures and are more efficient at breaking down complex organic compounds, such as lignin and cellulose, into simpler substances. The fine particulate nature of the seashell powder increased the surface area available for microbial colonization, further facilitating the efficient breakdown of organic material [37]. This combination of chemical and physical properties of the seashell powder significantly contributed to the overall effectiveness of the composting process in the MR3 treatment.

While the study demonstrated significant improvements in compost quality through the integration of seashell powder, it also faced limitations. One major limitation was the variability in the initial moisture content and organic composition of the mushroom waste, which could influence the consistency of the results. Furthermore, the study was conducted on a relatively small scale, and larger-scale trials would be necessary to confirm the findings and assess the practicality of this method for widespread application.

The results of this study have important implications for sustainable agriculture and waste management. By demonstrating an effective method for recycling mushroom cultivation waste into high-quality compost, the study provides a practical solution for reducing agricultural waste and promoting circular economy principles. This method not only enhances soil quality and plant growth but also reduces the reliance on chemical fertilizers, thereby contributing to environmental sustainability.

Compared to other studies in the literature, our results align with the findings [2, 7], who also reported improved compost quality through the addition of calcium-rich materials. Specifically, the use of seashell powder in our study was found to enhance the decomposition process and stabilize pH levels, similar to the results observed by recent studies [12, 38].

The composting method developed in this study can be applied in various agricultural settings, particularly in regions with significant mushroom cultivation [38]. Farmers can adopt this method to manage their agricultural waste more efficiently and produce high-quality organic fertilizers on-site. Additionally, the findings can inform policy planning and waste management strategies, promoting the use of sustainable practices in agriculture.

Future research should focus on scaling up the composting trials to assess the method's feasibility for large-scale applications. Studies should also explore the long-term effects of using the compost produced through this method on different crop types and soil conditions. Further investigation into the optimal ratios of seashell powder and other additives could enhance the composting process even more. Researchers are encouraged to explore other agricultural wastes that could be integrated into this composting method, expanding its applicability and benefits. By continuing to refine and optimize this composting process, we can make significant strides toward sustainable agricultural practices and effective waste management solutions.

## 5. Conclusion

During the recycling of mushroom cultivation waste, this research adopted an innovative approach by incorporating seashell powder as an additive. This method improved the quality of the final organic fertilizer and contributed to waste reduction, representing a significant advancement towards promoting a circular economy and sustainable agriculture. The key findings demonstrate that the MR3 treatment, which included seashell powder, was the most successful. This treatment showed superior decomposition efficiency and pH stabilization, resulting in high-quality compost with increased organic matter content. The seashell powder acted as a natural pH buffer, creating an optimal environment for microbial activity and enhancing the composting process.

For future research, it is recommended to further explore and optimize the composting process and evaluate the application of organic fertilizers produced from mushroom waste in various cropping conditions. This includes assessing the impact of the fertilizer on plant health, soil quality, and agricultural efficiency. This study emphasizes the potential of mushroom waste recycling to produce sustainable organic fertilizer and opens new avenues for research in waste management and sustainable agriculture, contributing to practical solutions for current environmental and agricultural challenges.

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