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Effect of Papaya and Shrimp Waste Bioactivators on Household Organis Waste Composting

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ABSTRACT: This study aims to evaluate the effect of papaya bioactivator (Carica papaya) and shrimp waste bioactivator on the composting process of household organic waste, as well as changes in the levels of carbon (C), nitrogen (N), phosphorus (P), potassium (K), and the C/N ratio. The study was conducted on a laboratory scale with three treatments: R1 (papaya bioactivator), R2 (shrimp waste bioactivator), and R3 (without bioactivator). The parameters observed included pH, temperature, humidity, and color on a daily basis, as well as changes in C, N, C/N ratio, P, and K levels at the beginning and end of the composting process. The results showed that the C/N ratio decreased in all treatments, while the levels of N, P, and K increased. The shrimp waste bioactivator (R2) produced the fastest composting process in 12 days and yielded the best compost quality, with the lowest C/N ratio and the highest increases in N, P, and K levels. Conversely, the treatment without bioactivator showed a slower process, with a final C/N ratio of 33.54, indicating that the compost was not yet mature. Shrimp waste bioactivators have the potential to improve the quality and efficiency of the composting process.

KEYWORDS: Papaya bioactivator; shrimp waste; composting; C/N ratio; macronutrient content

1. Introduction

The amount of waste generated continued to rise in tandem with population growth. Nationally, 50.79% of waste originated from the household sector. This household waste consisted primarily of organic waste in the form of food scraps (55.48%) and inorganic waste in the form of plastic (22.01%) [1]. Household organic waste was generally composed of easily decomposable materials, such as vegetable scraps, fruit waste, and fish waste. Fruit waste included papaya, whereas fish waste included, for example, shrimp waste. Most household organic waste was not optimally utilized as compost and instead ended up in landfills, raising concerns about water, soil, and air pollution, unpleasant odors, and increased greenhouse gas emissions [2]. Therefore, effective waste management was necessary to prevent environmental pollution.

Composting was a technique for processing organic waste into a stable product with economic value through the action of microorganisms. Compost contained organic matter together with high concentrations of macro- and micronutrients [3]. Compost served as an organic fertilizer that could be used as an alternative to chemical fertilizers, thereby improving soil fertility, enhancing water retention, and supplying essential mineral nutrients required for plant growth [4]. Natural composting generally required a long processing time and did not always produce high-quality compost [5], making the process less efficient [6]. To overcome these limitations, bioactivators were needed as additives to accelerate decomposition and improve compost quality. Bioactivators were liquid formulations containing microorganisms that facilitated the breakdown of organic matter [7]. Many people used the commercial bioactivator Effective Microorganisms-4 (EM4) to accelerate the composting process. However, bioactivators could also be produced from various organic materials that served as potential growth media for microorganisms, including vegetable and fruit waste, golden apple snails, and fish waste [4, 8].

Fruit waste included papaya. Several previous studies investigated the use of papaya fruit as a bioactivator because it contained *Pseudomonas*, *Bacillus*, and *Aspergillus niger*, which functioned as phosphorus-solubilizing microorganisms and contributed to carbon and nitrogen cycling in organic matter [9, 10]. Previous studies reported that compost prepared with papaya-based bioactivators contained higher levels of nitrogen (N), phosphorus (P), and potassium (K) than compost prepared with bioactivators derived from local microorganisms, such as those obtained from tomatoes and rice [11].

Shrimp waste, consisting of heads, shells, tails, and legs, accounted for 35–50% of the total shrimp weight. If not properly managed, shrimp waste produced unpleasant odors that caused environmental pollution and adversely affected environmental health [12]. Although numerous studies had investigated fruit-based bioactivators, the use of shrimp waste as a bioactivator for organic waste composting had rarely been explored. Shrimp waste had primarily been used for the production of organic liquid fertilizer or as a source of chitin, whereas its effectiveness in accelerating the composting process had not been widely investigated. Shrimp shell waste contained protein (20–40%), chitin (15–20%), and calcium carbonate (20–40%) [13]. Therefore, shrimp waste had the potential to serve as an energy source while supporting the growth of decomposing microorganisms during composting [14].

Shrimp waste contained various nutrients that could serve as a suitable growth medium for microorganisms. These nutrients made shrimp waste a promising bioactivator for accelerating the composting process and improving compost quality. Likewise, papaya waste was rich in natural enzymes and beneficial microorganisms that supported the decomposition of organic matter. The utilization of shrimp and papaya waste as bioactivators not only improved the composting process but also reduced the amount of organic waste disposed of in the environment by converting it into valuable compost that enhanced soil fertility [15, 16]. Therefore, this study aimed to evaluate the effects of different bioactivators, specifically those derived from papaya and shrimp waste, on the composting process and the quality of the compost produced. The findings were expected to provide an alternative approach to sustainable organic waste management by promoting circular economy principles and encouraging greater community participation in environmentally responsible waste utilization.

2. Materials and Methods

This study aimed to accelerate the composting process and improve the quality of compost produced from household organic waste by incorporating bioactivators derived from papaya fruit waste and shrimp waste. The research was conducted on a laboratory scale using three treatment groups: papaya bioactivator, shrimp waste bioactivator, and a control without bioactivator. These treatments were evaluated to determine their effects on composting efficiency and the quality of the resulting compost. The study consisted of three main stages: preparation of the bioactivators, composting with the addition of the bioactivators, and evaluation of composting performance and compost quality. The experimental work was carried out at the Waste Management Laboratory of PGRI Adi Buana University, Surabaya Indonesia, while compost quality analyses were performed at the Environmental Engineering Laboratory of the Sepuluh Nopember Institute of Technology (ITS), Surabaya, Indonesia.

2.1. Material and Tools.

The materials used in this study included household organic waste, papaya fruit, shrimp waste, palm sugar, rice washing water, mature compost, and chemicals required for laboratory analyses. The equipment consisted of plastic tubs, plastic bottles, spatulas, measuring cups, analytical balances, knives, sieves, choppers, thermometers, pH meters, digital hygrometers, and laboratory instruments for compost quality analysis.

2.2 Methods

2.2.1. Production of Bioactivator.

Two types of bioactivators were prepared in this study. The papaya bioactivator was produced by mixing 200 g of mashed papaya, 200 g of palm sugar, and 1000 mL of rice washing water. The mixture was stirred until homogeneous, transferred into a sealed bottle, and stored in a shaded area away from direct sunlight for seven days. The shrimp waste bioactivator was prepared by mixing 200 g of mashed shrimp waste, 200 g of palm sugar, and 1000 mL of rice washing water. The mixture was processed and stored under the same conditions as the papaya bioactivator.

2.2.2. Composting Using Bioactivators.

Composting was carried out using three plastic reactors, each measuring 35 cm × 25 cm × 11 cm. Reactor R1 received the papaya bioactivator, reactor R2 received the shrimp waste bioactivator, and reactor R3 served as the control without bioactivator. The concentrated bioactivator was applied at a dosage of 1 mL kg^{-1} of organic waste. Before application, it was diluted with distilled water at a ratio of 1:5 (v/v), resulting in 6 mL of diluted bioactivator. Reactors R1 and R2 each contained 1 kg of shredded organic waste and 1 kg of mature compost, followed by the addition of 6 mL of the diluted bioactivator. Reactor R3 contained the same amounts of shredded organic waste (1 kg) and mature compost (1 kg) but received no bioactivator. All reactors were maintained in a shaded room protected from direct sunlight throughout the composting period.

2.2.3. Measurement of pH, Temperature, Humidity, and Color Observation.

The pH, temperature, and moisture content of the compost, together with visual observations of compost color, were measured daily throughout the 14-day composting period. For pH determination, 5 g of compost sample was weighed into a 50 mL beaker, mixed with 12.5 mL of distilled water, and stirred for 30 minutes before measurement with a calibrated pH meter. Compost temperature was measured using a thermometer, while moisture content was determined using a digital hygrometer by inserting the probe into the center of the compost mass. Compost color was assessed through direct visual observation. The collected data were used to monitor the progression of organic matter decomposition during the composting process.

2.2.4. Compost Quality Analysis.

Compost quality analyses were conducted at the beginning and the end of the composting experiment. Samples were randomly collected from each reactor, placed in labeled plastic bags, and analyzed at the Environmental Engineering Laboratory of the Sepuluh Nopember Institute of Technology (ITS), Surabaya, Indonesia. Total carbon (C) and total nitrogen (N) were analyzed using the ASTM D5373-2002 method. Total phosphorus (P) was determined according to the SNI 02-3776-2005 method, while potassium (K) content was measured using Inductively Coupled Plasma (ICP) analysis. The quality of the compost produced was evaluated against the Indonesian National Standard for compost fertilizer (SNI 19-7030-2004) [17]. The experimental data were analyzed descriptively using univariate analysis to compare the decomposition rate, changes in pH, temperature, moisture content, compost color, C, N, P, and K contents, as well as the C/N ratio among the three treatment reactors throughout the composting process.

3. Results and Discussion

3.1. Measurment of pH, Temperature, Humadity, and Color Observation.

3.1.1. pH Changes During the Composting Process.

pH played an important role in the composting process because it influenced the activity of microorganisms responsible for decomposing organic matter. pH was measured daily throughout the experiment. Changes in pH values across the three reactors during the composting process are presented in Figure 1. On day 0, the pH values of all three reactors were relatively neutral, averaging approximately 7.2. From day 1 to day 2, the pH decreased markedly to around 6.6. This decline was attributed to the activity of microorganisms degrading readily biodegradable organic matter, which produced organic acids [7, 18]. Reactors supplemented with bioactivators (R1 and R2) exhibited a more rapid decrease in pH than the control reactor (R3), suggesting that the bioactivators accelerated the initial decomposition process. During the intermediate phase (days 3–7), the pH remained relatively stable, ranging from 6.6 to 6.8. This stability occurred because the organic acids initially produced began to be utilized by microorganisms, particularly cellulose- and protein-degrading bacteria. The reactor treated with the shrimp waste bioactivator (R2) maintained a more stable pH than the papaya bioactivator reactor (R1), which showed slight fluctuations. The greater pH stability observed in R2 was likely due to the protein, mineral, and buffering components present in shrimp waste, which helped neutralize the organic acids generated during the early stage of fermentation [4]. In contrast, the papaya bioactivator contained papain, a proteolytic enzyme that actively degraded proteins and promoted the temporary formation of organic acids, making the pH more susceptible to fluctuation [11].

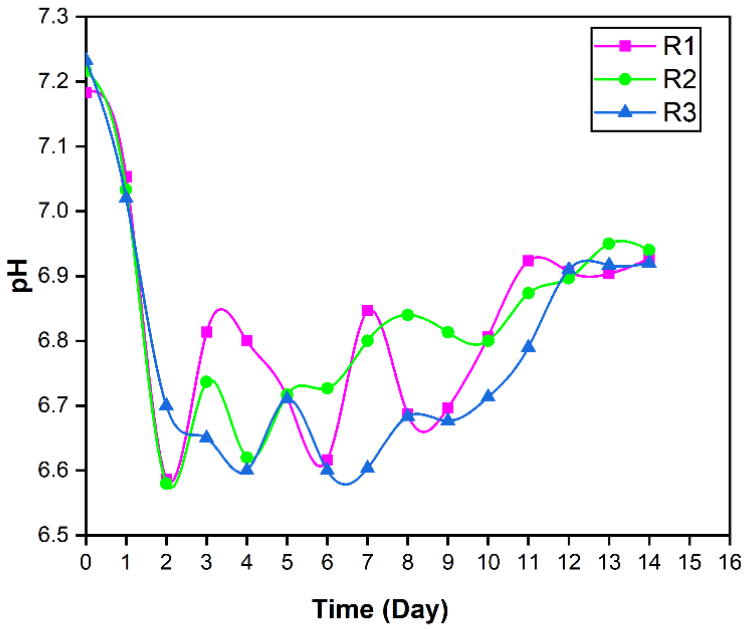

Figure 1. pH Changes During Composting.

During the final phase (days 8–14), the pH gradually increased and returned to near-neutral conditions (6.9–7.1). This increase was associated with the mineralization of complex organic compounds and the formation of ammonia during protein degradation. By the end of the composting period, the pH values of all three reactors had become relatively similar, indicating that the compost had reached a mature stage characterized by stable pH conditions. These findings were consistent with previous studies, which reported that compost pH typically decreased during the initial stage because of the accumulation of organic acids and then increased as mineralization progressed, proteins decomposed, and ammonia was released [7, 19]. Previous studies also demonstrated that bioactivators accelerated the production of organic acids during the early stage of composting [7], thereby enhancing microbial activity and accelerating the decomposition process [20]. Overall, the results indicated that the application of bioactivators influenced pH dynamics primarily during the initial stage of composting, whereas all treatments reached similar pH stability during the compost maturation stage.

3.1.2. Temperature Changes During the Composting Process.

Temperature changes during the composting process served as an important indicator of microbial activity during the degradation of organic matter. Compost temperature was measured daily throughout the experiment. Figure 2 shows that all reactors followed a similar pattern of temperature change. During the initial phase (day 2), the temperature increased from approximately 30°C to 40–43°C. This increase indicated the mesophilic phase, which was characterized by rapid microbial growth and heat generation resulting from the degradation of readily biodegradable organic compounds, such as sugars and amino acids. This process released energy in the form of heat, carbon dioxide (CO_2), and water vapor [21]. The reactors treated with papaya and shrimp waste bioactivators recorded higher temperatures than the control reactor without bioactivator. This finding suggested that the bioactivators enhanced microbial activity because they contained mesophilic microorganisms, including *Escherichia*, *Micrococcus*, and *Lactobacillus*, which were capable of degrading organic waste [7]. Consequently, the addition of bioactivators accelerated the decomposition process, as reflected by the more rapid rise in temperature compared with the control treatment.

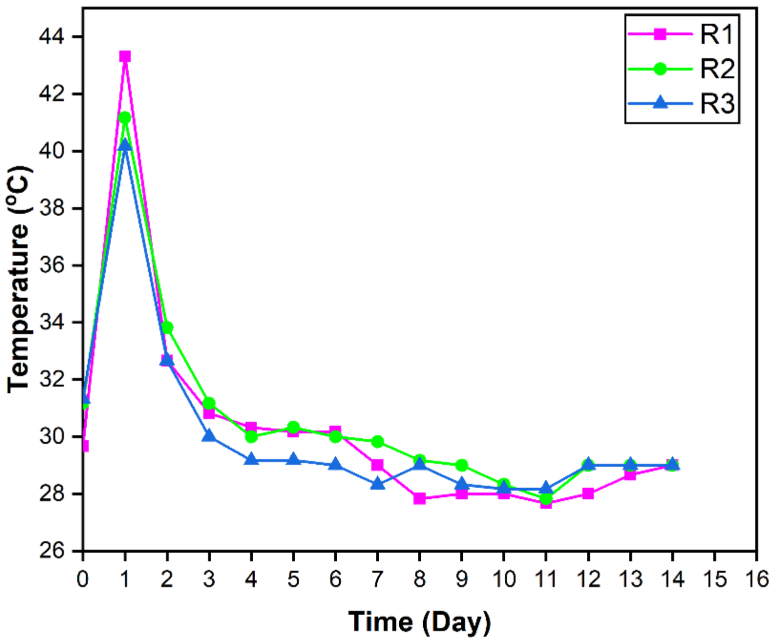

Figure 2. Temperature Changes During the Composting.

From days 4 to 11, the temperature gradually declined to approximately 28°C. On day 12, it increased slightly to 29°C and remained stable until day 14. By the end of the composting period, the temperature in all reactors stabilized at approximately 29°C, meeting the compost maturity requirement specified in the SNI 19-7030-2004 standard [17]. The decline in temperature indicated that the compost had entered the cooling and maturation phase. During this stage, microbial activity decreased because the supply of readily degradable organic matter became limited, indicating that the compost had reached maturity [7, 18]. The reduction in temperature also suggested that a substantial proportion of the organic carbon had been consumed by microorganisms during the decomposition process.

Despite these changes, the maximum composting temperature did not reach the thermophilic range (45–70°C) and remained within the mesophilic phase. This outcome was likely caused by the relatively small quantity of composting material, which limited heat accumulation within the compost mass and prevented the temperature from reaching thermophilic conditions. These findings were consistent with previous studies, which reported that bioactivators accelerated the increase in compost temperature and improved the stability of the composting process. Because bioactivators contained microorganisms capable of decomposing organic matter [7], they enhanced the degradation process, resulting in a more rapid increase in temperature than that observed in composting systems without bioactivators [22].

3.1.3. Moisture Changes During the Composting Process.

Moisture content played a crucial role in the composting process by maintaining microbial activity and facilitating nutrient transport within the compost matrix. Compost moisture content was measured daily throughout the experiment. Figure 3 shows the changes in moisture content observed in the three reactors. In all reactors (R1, R2, and R3), the moisture content increased from approximately 50% on day 1 to 70–75% by day 3. This increase was attributed to the intensive activity of microorganisms during the initial stage of composting, during which the decomposition of organic matter generated water as a metabolic byproduct [23].

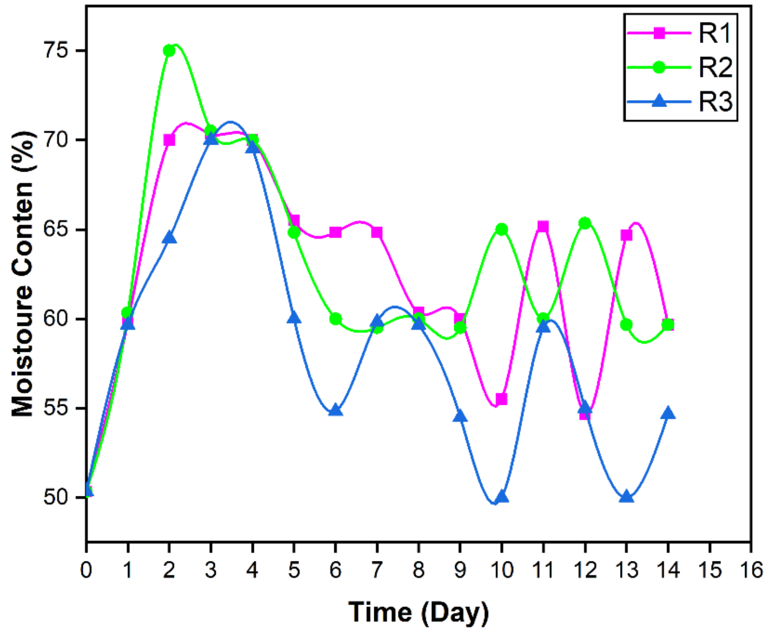

Figure 3. Moisture Changes During Composting.

After reaching its peak, the moisture content gradually declined to approximately 50–60% between days 6 and 14. This reduction was caused by water evaporation resulting from the elevated temperatures during the early composting stage, together with the progressive consumption of moisture as the decomposition process continued [24]. At the end of the composting period, the moisture content of the compost ranged from 55% to 60%. Consequently, the compost did not meet the moisture requirement specified in the SNI 19-7030-2004 standard, which established a maximum moisture content of 50% [17]. The relatively high moisture content was likely due to the composition of the household organic waste, which contained large proportions of water-rich materials, such as vegetables, fruit waste, and food scraps. As a result, the moisture generated and retained within the compost could not evaporate completely during the 14-day composting period [24]. Overall, the addition of bioactivators contributed to maintaining moisture stability throughout the composting process by enhancing the activity of decomposing microorganisms. These findings were consistent with those of previous studies, which reported that bioactivators accelerated the decomposition process by stimulating microbial metabolism, thereby influencing both temperature and moisture dynamics during composting [25].

3.1.4. Color Changes During the Composting Process.

Color change served as one of the visual indicators for assessing compost maturity. Based on daily observations of the three reactors (R1, R2, and R3), the compost underwent a gradual color transition from green at the beginning of the process to black by the end of the composting period (Table 1). Among the three treatments, reactor R2, which received the shrimp waste bioactivator, reached a black color most rapidly, on day 12. This color change indicated that the organic material had decomposed extensively and had begun to reach a stable, mature state. The faster darkening observed in R2 was likely associated with the high protein, chitin, and readily degradable organic compound contents of the shrimp waste bioactivator, which stimulated microbial activity and accelerated humus formation [5]. In addition, the green pigments present in the organic waste were degraded more rapidly into dark brown and black compounds, making the color change more apparent than in the other treatments [26]. In contrast, reactor R3 (control) remained brownish-black on day 14, indicating that the organic matter had only partially stabilized and that humus formation was still progressing. Based on the color criterion specified in the SNI 19-7030-2004 standard [17], the compost in reactor R2 reached maturity on day 12, whereas reactor R1 reached maturity on day 13. By comparison, the compost in reactor R3 had not yet reached full maturity by day 14. These findings were consistent with previous studies, which reported that mature, high-quality compost was characterized by a black color [24].

Tabel 1. Color Changes During Composting.

Day	Colour		
	R1	**R2**	**R3**
0	Green	Green	Green
1	Green	Green	Green
2	Yellowish green	Yellowish green	Yellowish green
3	Yellowish green	Yellowish green	Yellowish green
4	Brownish yellow	Brownish yellow	Yellowish green
5	Brownish yellow	Brownish yellow	Brownish yellow
6	Brownish yellow	Dark brown	Brownish yellow
7	Dark brown	Dark brown	Dark brown
8	Dark brown	Dark brown	Dark brown
9	Dark brown	Dark brown	Dark brown
10	Dark brown	Dark brown	Dark brown
11	Dark brown	Dark brown	Dark brown
12	Dark brown	Black	Dark brown
13	Black	Black	Dark brown
14	Black	Black	Blackish brown

3.2. Compost Quality Analysis.

3.2.1. Impact of Bioactivators on Organic Carbon Content.

The effect of bioactivator application on the organic carbon (C) content of the compost is presented in Figure 4. Three treatment reactors were evaluated: reactor R1 (papaya waste bioactivator), reactor R2 (shrimp waste bioactivator), and reactor R3 (control without bioactivator). Organic C content was analyzed at the beginning and the end of the composting process. The results showed that the organic C content changed differently among the treatments. At the beginning of the experiment, the organic C content was 31.02% in R1, 24.02% in R2, and 34.80% in R3. At the end of the composting process, the organic C content was 24.74% in R1, 28.48% in R2, and 27.57% in R3 (Figure 4a). Based on the changes in organic C content (Figure 4b), reactors R1 and R3 exhibited similar reductions in organic C during composting. Reactor R1 showed a 20.70% decrease, from 31.02% to 24.74%, while reactor R3 recorded a 20.80% decrease, from 34.80% to 27.57%. In contrast, reactor R2 showed an 18.60% increase in organic C content, from 24.02% to 28.48%. The reduction in organic C was attributed to its utilization by microorganisms as an energy source for growth and metabolism, during which carbon was released as carbon dioxide (CO_2). Therefore, the decline in organic C content indicated that carbon mineralization had occurred during the decomposition of organic matter [24].

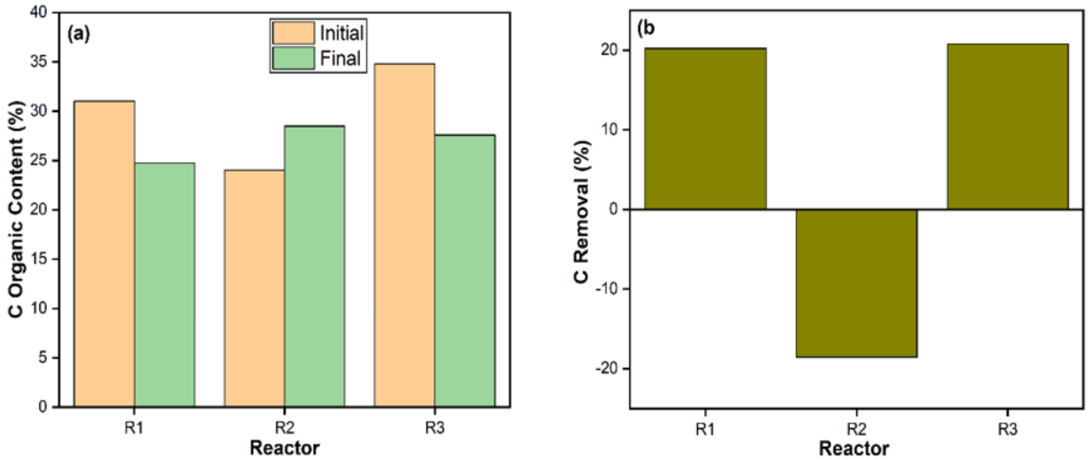

Figure 4. Effect of Bioactivator Addition on C Organic Content: (a) C Organic Content (%), and (b) C Organic Removal (%).

Among the treatments, reactor R1 demonstrated greater effectiveness in reducing organic C content than reactor R2. Papaya contained carbon (C) and nitrogen (N), which served as nutrient and energy sources for microorganisms involved in the composting process [27]. In addition, papain, a proteolytic enzyme naturally presents in papaya, facilitated the degradation of complex organic compounds, thereby accelerating decomposition and promoting compost stabilization [28]. The reduction in organic C observed in reactor R3 (control) was likely caused by the activity of indigenous microorganisms naturally present in the organic waste.

In contrast, reactor R2 showed an increase in organic C content. This increase was likely associated with the addition of carbon-rich compounds from the shrimp waste bioactivator. Shrimp waste contained approximately 25–40% protein, 45–50% calcium carbonate, 15–20% chitin, and smaller amounts of lipids and other organic compounds [29]. Chitin and proteins possessed complex carbon structures that were more resistant to microbial degradation over a short composting period. Consequently, the accumulation of these compounds could increase the organic C content during the early and intermediate stages of composting [30]. These findings suggested that the shrimp waste bioactivator had not yet been as effective in accelerating carbon mineralization as the papaya bioactivator, although it contributed to increasing the total organic fraction of the compost mixture.

Overall, the organic C results indicated that reactors R1 and R3 had likely reached the stabilization stage of composting, whereas reactor R2 remained in an earlier stage of decomposition because a substantial proportion of its complex carbon compounds had not yet decomposed. In general, the findings demonstrated that the papaya bioactivator was more effective than the shrimp waste bioactivator in accelerating the decomposition of organic matter. By the end of the composting process, the organic C contents of R1 (24.74%), R2 (28.48%), and R3 (27.57%) all complied with the SNI 19-7030-2004 standard, which specifies an acceptable organic C content of 9.8–32% for mature compost [17].

3.2.2. Impact of Bioactivators on Nitrogen Content.

Nitrogen (N) served as an essential nutrient for microorganisms because it was required for cell growth and biomass formation [11]. Low nitrogen content in composting materials resulted in a slower composting process because microbial growth and metabolic activity were limited [24]. Based on the observations, the nitrogen content increased in all reactors, both with and without bioactivators, as shown in Figure 5. The initial N content was 0.99% in reactor R1, 0.61% in reactor R2, and 0.64% in reactor R3. By the end of the composting process, the N content had increased to 1.23% in R1, 1.59% in R2, and 0.82% in R3 (Figure 5a). Among the treatments, reactor R2 recorded the greatest increase in nitrogen content, reaching 160.60% (Figure 5b).

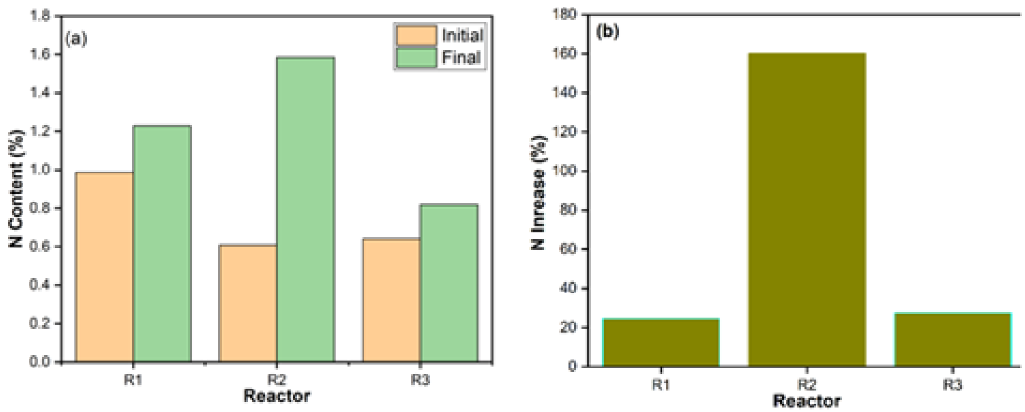

Figure 5. Effect of Bioactivator Addition on N Content: (a) N Content (%), and (b) N Removal (%).

The changes in nitrogen content during composting reflected microbial activity and the rate of organic matter mineralization. The increase in nitrogen was attributed to ammonification, during which proteins and amino acids were converted into ammonia or ammonium ions (NH_4^+) by microorganisms. These compounds were subsequently oxidized to nitrate through the nitrification process [31]. Reactor R1, which received the papaya bioactivator, showed a 24.24% increase in nitrogen content, from 0.99% to 1.23%. This increase suggested that the papaya bioactivator enhanced the activity of decomposing microorganisms through the action of papain, a proteolytic enzyme that facilitated protein degradation [32]. As a result, papain accelerated the ammonification and nitrification processes, leading to higher concentrations of mineral nitrogen (NH_4^+ and NO_3^-) during composting. These findings were consistent with previous studies, which reported that compost produced with papaya bioactivators contained higher nitrogen levels [11].

Reactor R2, treated with the shrimp waste bioactivator, showed the greatest increase in nitrogen content, rising by 160.60% from 0.61% to 1.59%. Shrimp waste contained high concentrations of organic nitrogen, primarily in the form of proteins and chitin, which served as important nitrogen sources for microorganisms [11]. The high protein content enhanced nitrogen availability during composting and supported the growth of proteolytic and ammonifying microorganisms. Consequently, the decomposition of these protein-rich materials resulted in a substantial increase in the total nitrogen content of the final compost [33]. The control reactor (R3), which received no bioactivator, showed a 28.13% increase in nitrogen content, from 0.64% to 0.82%. Although nitrogen content increased, the final value remained considerably lower than those observed in reactors R1 and R2. This finding indicated that decomposition occurred naturally through the activity of indigenous microorganisms but proceeded at a lower rate and with reduced efficiency. The relatively low nitrogen availability limited microbial activity, resulting in a smaller increase in nitrogen accumulation within the compost [24]. The highest final nitrogen content was recorded in reactor R2, indicating that the shrimp waste bioactivator was more effective in enhancing nitrogen availability and promoting compost maturation than the papaya bioactivator or the control treatment. By the end of the composting process, the nitrogen content in all reactors met the mature compost requirement specified in the SNI 19-7030-2004 standard, which requires a minimum nitrogen content of 0.40% [17].

3.2.3. Impact of Bioactivators on C/N Ratio.

The carbon-to-nitrogen (C/N) ratio served as an important indicator of compost maturity because it reflected the balance between carbon, which functioned as an energy source for microorganisms [24], and nitrogen, which was required for microbial protein synthesis and growth during the composting process [11]. As shown in Figure 6a, the initial C/N ratios were 31.44 for reactor R1, 39.43 for reactor R2, and 54.29 for reactor R3. At the end of the composting period, the C/N ratios decreased to 20.13, 17.97, and 33.72 for reactors R1, R2, and R3, respectively. Overall, the C/N ratio decreased by 35.96% in R1, 54.42% in R2, and 37.89% in R3 (Figure 6b). The substantial reduction in the C/N ratio across all treatments indicated that the decomposition of organic matter progressed actively throughout the composting process. Organic carbon decreased because it was utilized by microorganisms as an energy source, resulting in carbon loss through microbial respiration and the release of carbon dioxide (CO_2). In contrast, nitrogen content increased because of the ammonification of organic matter, during which organic nitrogen compounds were converted into ammonium and subsequently transformed into other available nitrogen forms [31].

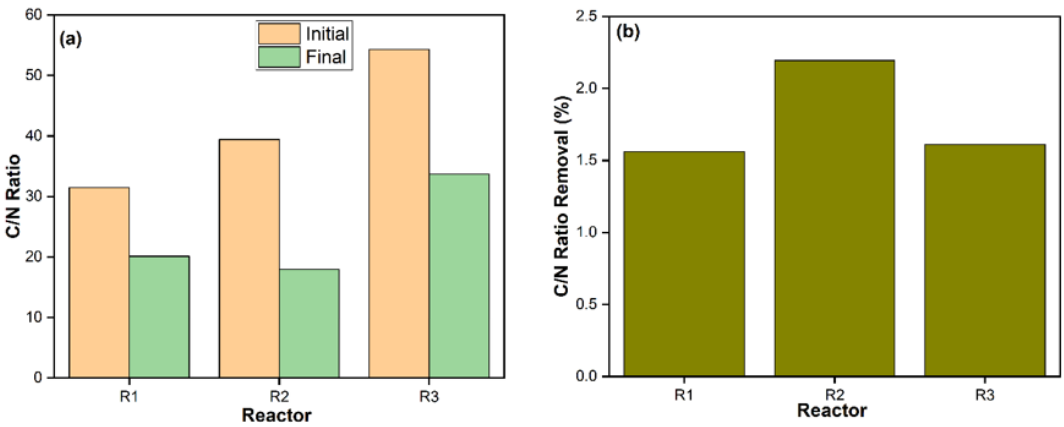

Figure 6. Effect of Bioactivator Addition on the C/N Ratio. (a) C/N Ratio, (b) C/N Ratio Removal (%).

In reactor R1, which received the papaya waste bioactivator, the C/N ratio decreased by 35.97%, from 31.44 to 20.13. The addition of the papaya bioactivator enhanced microbial decomposition through the action of papain, a proteolytic enzyme that facilitated the degradation of complex organic compounds, thereby accelerating compost stabilization. Reactor R2, treated with the shrimp waste bioactivator, showed the greatest reduction in the C/N ratio, decreasing by 54.42% from 39.43 to 17.97. This pronounced decrease was attributed to the high nitrogen content of shrimp waste, which originated primarily from proteins and chitin [13]. The greater availability of nitrogen improved the initially high C/N ratio and stimulated the activity of decomposing microorganisms. In addition, the shrimp waste bioactivator increased the total nitrogen content of the compost mixture, resulting in a more rapid decline in the C/N ratio than those observed in reactors R1 and R3. Shrimp waste also contained proteolytic enzymes and indigenous microorganisms, including *Bacillus* spp., that were capable of efficiently hydrolyzing complex organic compounds. Previous studies reported that shrimp waste served as an effective substrate for protease production by microorganisms such as *Bacillus subtilis*, *Bacillus licheniformis*, and *Pseudomonas aeruginosa* [34].

In the control reactor (R3), the C/N ratio decreased by 37.89%, from 54.29 to 33.72. Although this reduction indicated that decomposition occurred through the activity of indigenous microorganisms, the process proceeded more slowly than in the reactors supplemented with bioactivators. The relatively high final C/N ratio of 33.72 suggested that compost maturation had not yet been completed and that additional composting time was required for further decomposition of the organic matter. According to the SNI 19-7030-2004 standard, mature compost should have a C/N ratio between 10 and 20 [17]. Based on this criterion, the compost produced in reactor R2 reached the maturity standard with a C/N ratio of 17.97, while reactor R1, with a C/N ratio of 20.13, was very close to the upper limit of the standard. In contrast, reactor R3, with a C/N ratio of 33.72, had not yet reached compost maturity, indicating that the composting process needed to continue.

3.2.4. Impact of Bioactivators on Phosporus Content.

Phosphorus (P) served as an essential macronutrient that played an important role in the formation of energy-carrying compounds, such as adenosine triphosphate (ATP), nucleic acids, and plant root development [24]. Analysis of the initial phosphorus content of the composting materials showed that reactors R1 and R2 each contained 3.66% P, whereas reactor R3 contained 3.22%. At the end of the composting process, the phosphorus content increased to 4.50% in reactor R1, 5.09% in reactor R2, and 3.83% in reactor R3 (Figure 7a). These values represented increases of 22.97%, 39.07%, and 18.75% for reactors R1, R2, and R3, respectively (Figure 7b). During composting, phosphorus content generally increased because of the decomposition of organic matter and the mineralization of complex phosphorus compounds. The increase in phosphorus was also associated with the death and decomposition of microorganisms during compost maturation, which released phosphorus previously incorporated into microbial biomass back into the compost [21]. These findings were consistent with previous studies, which reported that phosphorus content increased progressively throughout the composting process [21, 24].

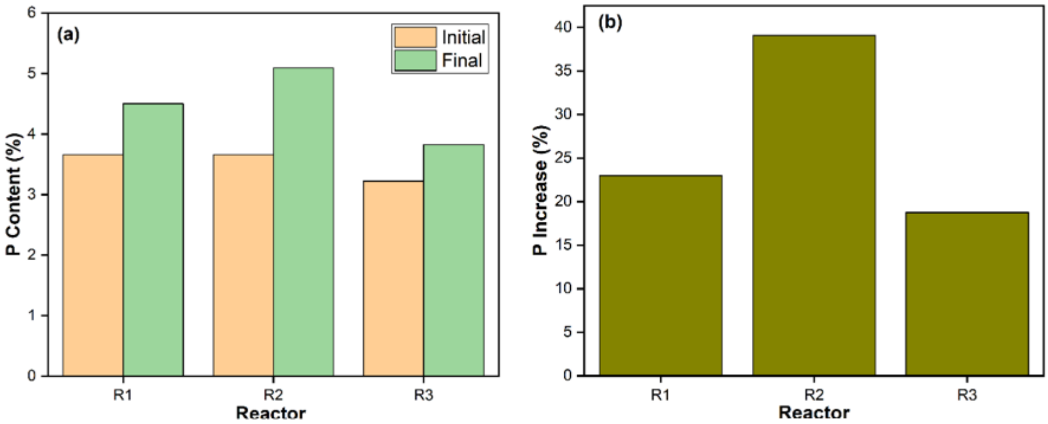

Figure 7. Effect of Bioactivator Addition on the P Content. (a) P Content, (b) P Content Increase (%).

Reactor R1, which received the papaya bioactivator, showed a 22.97% increase in phosphorus content, from 3.66% to 4.50%. Although papain, the principal proteolytic enzyme in papaya, enhanced the decomposition of organic matter, it did not directly contribute to phosphorus enrichment. The lower phosphorus content observed in R1 compared with R2 was likely due to the relatively low phosphorus content of papaya, which was reported to be approximately 0.02% [35].

Reactor R2, treated with the shrimp waste bioactivator, recorded the highest increase in phosphorus content, rising by 39.07% from 3.66% to 5.09%. This increase was attributed to the direct contribution of phosphorus from the shrimp waste bioactivator. Shrimp shells contained approximately 8–10% calcium phosphate ($Ca_3(PO_4)_2$) [36]. During composting, organic phosphorus compounds derived from shrimp waste underwent mineralization, releasing inorganic phosphorus into the compost. The relatively high phosphorus content in R2 may also have been associated with its higher nitrogen content, as previous studies suggested a positive relationship between nitrogen availability and phosphorus mineralization during composting [7].

In the control reactor (R3), phosphorus content increased by only 18.75%, from 3.22% to 3.83%. This finding indicated that phosphorus mineralization still occurred under natural composting conditions without the addition of bioactivators. The observed increase was likely caused by the concentration effect resulting from the reduction in organic matter mass during decomposition, whereby non-volatile phosphorus compounds became more concentrated in the remaining compost. However, without bioactivators, the mineralization process proceeded more slowly and depended primarily on the activity of indigenous microorganisms.

The increase in phosphorus content indicated an improvement in the agronomic quality of the compost. According to the SNI 19-7030-2004 standard, the recommended phosphorus content for mature compost ranges from 0.1% to 2.0% P_2O_5 [17]. The compost produced in this study contained phosphorus levels ranging from 3.83% to 5.09%, indicating a relatively high phosphorus content and suggesting strong potential as a macronutrient-rich organic fertilizer. Overall, the shrimp waste bioactivator (R2) produced compost with the highest phosphorus content and provided greater agronomic value than the papaya bioactivator (R1) and the control treatment (R3).

3.2.5. Impact of Bioactivators on Pottasium Content.

Potassium (K) served as an essential macronutrient that played important roles in enzyme activation, protein synthesis, and the regulation of plant osmotic balance. The results showed that potassium content increased in all three reactors during the composting process, as presented in Figure 8. The initial potassium content was 0.63% in reactor R1, 0.62% in reactor R2, and 0.48% in reactor R3. At the end of the composting period, the potassium content increased to 0.70% in reactor R1, 0.86% in reactor R2, and 0.67% in reactor R3 (Figure 8a). Overall, potassium content increased by 10.57% in R1, 38.71% in R2, and 41.26% in R3 (Figure 8b). The increase in potassium content during composting was attributed to the relatively non-volatile nature of potassium, which became more concentrated as easily degradable organic matter was decomposed. In addition, the mineralization of organic matter by microorganisms released potassium into forms that were more readily available within the compost [21]. As decomposition progressed and microbial activity increased, more potassium was liberated from the organic matrix, contributing to the observed increase in potassium content.

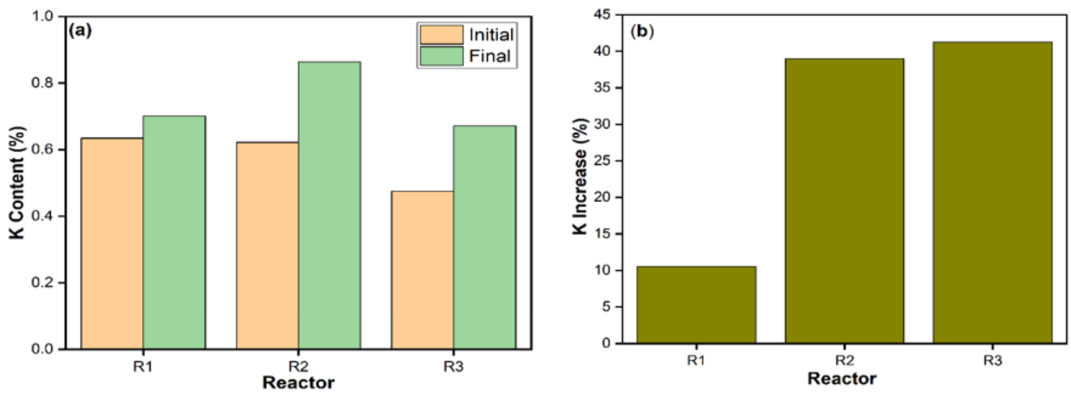

Figure 8. Effect of Bioactivator Addition on the K Content. (a) K Content, (b) K Content Increase (%).

Among the treatments, reactor R1, which received the papaya bioactivator, showed the smallest increase in potassium content, rising by 10.57% from 0.63% to 0.70%. This relatively modest increase was likely because the primary function of the papaya bioactivator was to accelerate organic matter decomposition through the activity of the papain enzyme rather than to supply additional mineral nutrients. Furthermore, ripe papaya contained only approximately 0.24–0.275% potassium [37].

Reactor R2, treated with the shrimp waste bioactivator, showed a marked increase in potassium content, rising from 0.62% to 0.86% (Figure 8a). This increase was attributed to the mineral composition of shrimp waste, which contributed additional potassium to the compost. Shrimp shells contained approximately 0.74% potassium [36], a higher concentration than that found in papaya. Therefore, the shrimp waste bioactivator performed a dual function by accelerating the decomposition process while simultaneously supplying potassium to the compost mixture.

The control reactor (R3) recorded the highest percentage increase in potassium content, increasing by 41.26% from 0.48% to 0.67%. This substantial relative increase was primarily due to its lower initial potassium concentration rather than a greater absolute accumulation of potassium. Despite receiving no bioactivator, natural microbial decomposition still promoted the mineralization of organic matter, resulting in increased potassium availability.

By the end of the composting process, the potassium contents of reactors R1, R2, and R3 were 0.70%, 0.86%, and 0.67%, respectively. These values indicated that the compost produced had good potential as a source of potassium for plant growth. According to the SNI 19-7030-2004 standard, the recommended potassium content ranges from 0.2% to 2.0% K_2O [17]. The final potassium contents obtained in all treatments fell within this range, indicating that the compost produced met the standard and possessed good agronomic quality.

3.3. Effect of Bioactivators on Composting Performance and Compost Quality.

Based on the changes in compost color and the C/N ratio, the shrimp waste bioactivator (R2) produced mature compost within 12 days, as indicated by the change in color from green to black and a final C/N ratio of 17.97, which met the maturity criteria specified in SNI 19-7030-2004. After 14 days of composting, the treatments using papaya waste bioactivator (R1), shrimp waste bioactivator (R2), and the control without bioactivator (R3) produced compost of varying quality. Reactors R1 and R2 met the SNI requirements for pH, temperature, color, nitrogen content, C/N ratio, phosphorus, and potassium, indicating that the compost had reached an acceptable level of maturity and quality. However, the moisture contents of both reactors remained above the maximum value specified by the standard. In contrast, the control reactor (R3) did not meet the SNI criteria for compost color and C/N ratio, indicating that the compost had not yet reached full maturity and required a longer composting period. Among the three treatments, the shrimp waste bioactivator (R2) produced the highest-quality compost, with a pH of 6.94, a temperature of 29°C, a moisture content of 59.67%, a black color, a nitrogen content of 1.59%, a C/N ratio of 17.97, a phosphorus content of 5.09%, and a potassium content of 0.86% (Table 2). These results suggested that shrimp waste bioactivator could serve as an effective natural alternative for accelerating the decomposition of organic matter and improving compost quality.

Tabel 2. Compost Characteristics.

Reactor	pH	Temperature (ºC)	Moisture (%)	Colour	N (%)	C/N	P (%)	K (%)
R1	6.93	29.00	59.67	Black	1.23	20.13	4.50	0.70
R2	6.94	29.00	59.67	Black	1.59	17.97	5.09	0.86
R3	6.92	29.00	54.67	Blackish Brown	0.82	33.72	3.83	0.67

Overall, this study demonstrated that bioactivators derived from papaya and shrimp waste effectively accelerated the composting of household organic waste and improved the quality of the resulting compost. Among the treatments evaluated, the shrimp waste bioactivator showed the best performance by producing mature compost in a shorter time and yielding higher nitrogen, phosphorus, and potassium contents together with a lower C/N ratio than the other treatments. These findings indicated that the use of organic waste-derived bioactivators not only enhanced compost quality but also contributed to reducing the amount of organic waste disposed of in the environment, thereby lowering the risks of soil, water, and air pollution as well as greenhouse gas emissions associated with uncontrolled anaerobic decomposition. Consequently, composting technology based on locally available bioactivators represented an environmentally friendly and sustainable approach to organic waste management. By converting household organic waste and shrimp waste into value-added compost, this approach supported circular economy principles through waste minimization, efficient resource utilization, and the creation of economic value from organic residues.

4. Conclusions

The addition of bioactivators accelerated the composting process and improved the macronutrient content of the resulting compost. Among the treatments, the shrimp waste bioactivator (R2) showed the best performance, producing mature compost within 12 days. The compost contained the highest nitrogen, phosphorus, and potassium contents (1.59%, 5.09%, and 0.86%, respectively), had the lowest C/N ratio (17.97), and developed a black color, indicating a high degree of compost maturity. The papaya bioactivator (R1) also enhanced the decomposition process, producing compost with nitrogen, phosphorus, and potassium contents of 1.23%, 4.50%, and 0.70%, respectively, after 13 days. The compost had a C/N ratio of 20.13 and a black color, indicating that it had nearly reached the maturity criteria. In contrast, the control treatment without bioactivator (R3) showed the slowest decomposition process and produced compost with the lowest nitrogen, phosphorus, and potassium contents (0.82%, 3.83%, and 0.67%, respectively), a relatively high C/N ratio of 33.72, and a dark brown color, indicating that compost maturation had not yet been completed. Overall, the shrimp waste bioactivator proved to be the most effective treatment for accelerating composting and improving compost quality. Although the papaya bioactivator also enhanced the composting process, the shrimp waste bioactivator consistently produced superior compost characteristics. These findings demonstrated the potential of shrimp waste as a sustainable bioactivator derived from locally available organic resources. Its application could contribute to reducing household organic waste while promoting circular economy principles, supporting environmentally sustainable waste management, and creating value-added products for agricultural use.

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Author Contribution

Wilda Trisari: conceptualization, methodology, data collection, data analysis, writing, and funding. Indah Nurhayati: conceptualization, methodology, data analysis, writing, supervision, and funding. Sugito: methodology and supervision, writing and data analysis.

Conflict of Interest

The authors declare that there is no conflict of interest.

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