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The Effectiveness of Several Bioactivators in Influencing Compost Quality

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ABSTRAK

Penggunaan pupuk anorganik secara berlebihan dalam jangka panjang telah berkontribusi terhadap penurunan kualitas tanah di Indonesia. Oleh karena itu, penggunaan pupuk organik, seperti kompos, menjadi salah satu alternatif yang lebih berkelanjutan untuk meningkatkan kesuburan dan kesehatan tanah. Penelitian ini bertujuan untuk mengevaluasi pengaruh berbagai bioaktivator terhadap kualitas kompos serta kesesuaiannya dengan Peraturan Menteri Pertanian Republik Indonesia Nomor 7763/2024. Penelitian ini menggunakan metode eksperimental dengan Rancangan Acak Lengkap (RAL) yang terdiri dari satu faktor, yaitu jenis bioaktivator (kontrol, konsorsium jamur, eco-enzyme, biofilm biofertilizer, dan EM4), dengan lima ulangan. Data dianalisis secara statistik menggunakan ANOVA, dilanjutkan dengan uji DMRT. Hasil penelitian menunjukkan bahwa jenis bioaktivator secara signifikan memengaruhi kualitas kompos. Kompos yang diberi perlakuan biofilm biofertilizer menghasilkan kompos dengan kualitas tertinggi karena meningkatkan kandungan karbon organik (10.45%), nitrogen total (1.36%), fosfor total (1.31%), dan rasio C/N (7.68), serta menghasilkan pH mendekati netral (7.96), sedangkan kompos tanpa bioaktivator (kontrol) menunjukkan kualitas terendah. Sebagian besar perlakuan memenuhi standar kualitas kompos sesuai Peraturan Kementerian Pertanian Republik Indonesia No. 7763/2024 untuk pH, rasio C/N, dan kandungan NPK (<2%); namun, tidak ada perlakuan yang memenuhi persyaratan minimum karbon organik (≥15%). Hal ini disebabkan oleh pemanenan kompos yang dilakukan 3 bulan setelah proses pengomposan. Semakin lama pengomposan, C-organik cenderung menurun karena aktivitas mikroorganisme menguraikan bahan organik dan mengoksidasi karbon menjadi CO_2. Penurunan biasanya lebih besar pada fase awal karena fraksi organik yang mudah terdekomposisi masih banyak, sedangkan pada fase pematangan laju penurunannya melambat karena bahan yang tersisa lebih stabil dan resisten terhadap dekomposisi. Secara keseluruhan, biofilm biofertilizer dan konsorsium jamur merupakan bioaktivator yang paling efektif karena menghasilkan kompos dengan kualitas terbaik dan paling mendekati standar mutu yang telah ditetapkan.

Keywords: bioactivator, biofilm, eco enzyme, fungal consortium, organic fertilizer

ABSTRACT

Excessive long-term use of inorganic fertilizers has contributed to the decline in soil quality in Indonesia. Therefore, the use of organic fertilizers, such as compost, is considered a more sustainable alternative to improve soil fertility and health. This study aimed to evaluate the effects of various bioactivators on compost quality and its compliance with the Regulation of the Minister of Agriculture of the Republic of Indonesia No. 7763/2024. The study employed an experimental method using a Completely Randomized Design (CRD) with one factor, namely bioactivator type (control, fungal consortium, eco-enzyme, biofilm biofertilizer, and EM4), with five replicates. The data were statistically analyzed using analysis of variance (ANOVA), followed by Duncan's Multiple Range Test (DMRT). The results showed that the type of bioactivator significantly affected compost quality. Compost treated with biofilm biofertilizer exhibited the highest quality, with organic carbon content of 10.45%, total nitrogen of 1.36%, total phosphorus of 1.31%, and a C/N ratio of 7.68, while maintaining a near-neutral pH of 7.96. In contrast, the compost without a bioactivator (control) exhibited the lowest quality. Most treatments met the compost quality standards stipulated in the Regulation of the Minister of Agriculture of the Republic of Indonesia No. 7763/2024 for pH, C/N ratio, and NPK content (<2%); however, none met the minimum organic carbon requirement (≥15%). This was attributed to the compost being harvested three months after the composting process. As composting progresses, organic carbon tends to decrease because microorganisms decompose organic matter and oxidize carbon into CO_2. The decrease is generally greater during the early stage of composting because readily decomposable organic fractions are still abundant, whereas during the maturation stage, the rate of carbon loss slows as the remaining organic matter becomes more stable and resistant to decomposition. Overall, biofilm, biofertilizer, and the fungal consortium were the most effective bioactivators, as they produced compost with the highest quality and the closest compliance with the established quality standards.

Keywords: bioactivator, biofilm, eco enzyme, fungal consortium, organic fertilizer

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1. INTRODUCTION

Rapid population growth has placed increasing pressure on the environment, as evidenced by the rising volume of organic waste generated by households, the agricultural sector, and the food industry (Sudamarji et al., 2025). In addition, efforts to increase agricultural productivity to meet food demand often lead farmers to rely on inorganic fertilizers, as they yield faster results than organic fertilizers (Leonardo et al., 2024). Excessive application of inorganic fertilizers can damage soil structure, lower soil pH, cause nutrient imbalances, reduce organic matter (OM) content, and decrease microbial abundance.

Using organic waste as compost is one approach to mitigate its accumulation in landfills and reduce the use of inorganic fertilizers. Compost can be derived from many organic materials, including leaves, grasses, and straw (Hamzah et al., 2020). The composting process involves the decomposition of plant and animal remains with the assistance of microbes (Imas & Munir, 2017). Microorganisms play a key role as decomposers in composting, significantly affecting the compost's duration and quality. To accelerate compost maturation and enhance nutrient content, bioactivators containing specific microbes can be added.

Bioactivators are microbial isolates capable of decomposing various organic compounds, particularly cellulose and other components such as hemicellulose, lignin, proteins, and lipids, depending on their enzymatic capabilities. Their activities accelerate and enhance the composting process (Sutrisno et al., 2020). According to Lerner et al. (2021), the addition of bioactivators to the soil can improve soil physical conditions, enhance plant resistance to water stress, and increase plant tolerance to diseases, pests, and nematodes. The application of bioactivators in composting can accelerate the decomposition of organic materials, thereby improving process efficiency and compost quality (Ariny & Syadzadhiya, 2024). Bioactivators can be in the form of mixed cultures of various types that are ready-to-use and available on the market under various brands, as well as microorganisms that we can make ourselves, such as ecoenzymes, fungal consortia, and biofilm biofertilizers.

EM4 is a solution containing a mixed culture of microorganisms (*Lactobacillus, Actinomycetes, Streptomyces*, photosynthetic bacteria, and yeast) that accelerates the decomposition and fermentation of organic materials without causing harmful effects during the process (Suharwati & Fadolul, 2025). EM4 is already produced for commercial purposes.

Eco-enzymes are liquid fermentation products derived from the decomposition of organic waste, such as fruit and vegetable residues, in the presence of sugar and water. During fermentation, microorganisms metabolize organic substrates and produce various bioactive compounds, including organic acids, enzymes, and other metabolites, which contribute to the functional properties of the resulting solution (Hemalatha et al., 2020). The resulting eco-enzyme is generally dark brown and has a strong, fresh, and acidic odor. Unlike compost, which produces a predominantly solid organic amendment, eco-enzyme production uses water as the fermentation medium, allowing microbial activity and the accumulation of soluble metabolites in the final liquid product.

Eco-enzyme can function as a bioactivator because its microbial population and bioactive compounds can support the decomposition of organic matter. Microorganisms present in the fermented product contribute directly to the breakdown of organic substrates, while extracellular enzymes produced during fermentation can facilitate the hydrolysis of complex organic compounds into simpler molecules that are more readily utilized by microorganisms. In addition, organic acids and other bioactive metabolites may modify the decomposition environment and support microbial activity. Therefore, the bioactivator function of eco-enzyme is associated not only with its nature as an organic solution but also with the combined effects of microorganisms, enzymes, organic acids, and other metabolites generated during the fermentation process (Dewi et al., 2022).

The innovation in the organic fertilizer industry continues to improve year over year. One of the innovations is the use of biofilm biofertilizer as a decomposer. The impact of biofilm biofertilizer on sustainable agriculture is very significant. According to Ghiasian (2020), Biofilm-based biofertilizers are composed of beneficial microorganisms capable of forming biofilms, with exopolysaccharides (EPS) serving as key components of the extracellular matrix. The formation of this biofilm matrix enhances microbial colonization, persistence, and interaction with plants and soil, thereby providing potential benefits for plant growth, soil health, and environmental sustainability. Biofilm-based biofertilizers may offer advantages over conventional bioactivators because microorganisms immobilized in the EPS matrix are better protected from environmental fluctuations and may exhibit greater persistence and engage in more microbial interactions during composting. The novelty of this study lies in the direct comparison of four bioactivators, fungal consortium, eco-enzyme, EM4, and biofilm biofertilizer, under identical composting conditions, an approach that remains limited in previous studies.

Another bioactivator is a fungal consortium obtained from the western slopes of Mount Lawu, an area known for its ecosystem heterogeneity and diverse land uses, ranging from natural forests to intensive agriculture. According to Solihin (2017), these differences in land use can lead to variations in microbial populations within a given area.

This study used a biofilm biofertilizer and fungal consortia developed from microbial isolates identified in previous studies on the western slopes of Mount

Lawu (Rosariastuti et al., 2023; Rosariastuti et al., 2024). which included two fungal species, namely *Purpureocillium lilacinum* and *Aspergillus ibericus*, as components of the fungal consortium. Meanwhile, the biofilm biofertilizer contains four bacterial isolates (*Paraburkholderia terrae, Paraburkholderia caribensis, Betaproteobacteria bacterium*, and one nitrogen-fixing bacterium) and five fungal isolates (*Talaromyces purpureogenus, Aspergillus aculeatus, Aspergillus ibericus, Penicillium* sp., and *Aspergillus* sp.). Several previous studies have compared the effects of different bioactivators on compost quality (Wikurendra et al., 2022; Sutrisno et al., 2020; Walpajri et al., 2023). As done by Philipus et al. (2021) by comparing the effectiveness of EM4 with banana peel MOL in composting leaf waste. This study compares four (4) bioactivators, namely EM4, Eco Enzym, Biofilm Biofertilizer, and fungal Consortium in decomposing plant litter. Thus, this research is expected to provide information on the most effective bioactivators for composting, thereby offering farmers an alternative to reduce reliance on inorganic fertilizers and support sustainable agricultural systems.

2. METHODOLOGY

The study employed a completely randomized design (CRD) with a single treatment factor. The treatment factors were the types of bioactivators: B0 (without inoculum), B1 (Fungal consortium), B2 (Eco-enzyme), B3 (Biofilm biofertilizer), and B4 (EM4). The treatments were replicated five (5) times, resulting in 25 experimental units.

2.1. Location and Time of Study

The study was conducted at the Soil House, Faculty of Agriculture, Universitas Sebelas Maret. The preparation of the biostarter and compost analysis was carried out at the UNS Soil Science Laboratory (Soil Chemistry-Fertility Laboratory and the Soil Biology-Biotechnology Laboratory).

2.2. Tools

The tools used in the research include micropipettes, chips, vortex, autoclave, inoculating needles, test tubes, volumetric flasks, and Bunsen burners (for biofilm and fungal consortium production); drums and filter cloths (for eco-enzymes); laboratory equipment such as pH meters, Kjeldahl tubes, distillation flasks, UV-Vis spectrophotometers, and SSA.

2.3. Materials

The materials used in the research include molasses and organic waste from the UNS campus (compost production); Effective Microorganisms 4/EM4; waste from dragon fruit, pineapple, guava, and oranges, brown-sugar, and non-chlorinated water (eco-enzyme production); isolates from the western slope of Mount Lawu from previous research, including isolates of *Purpureocillium lilacinum* and *Aspergillus ibericus* (fungal consortium), fungal isolates of *Paraburkholderia terrae, Paraburkholderia caribensis, Betaproteobacteria bacterium,* and one N-fixing bacterium, and bacterial isolates of *Talaromyces purpureogenus, Aspergillus aculeatus, Aspergillus ibericus, Penicillium* sp., and *Aspergillus* sp. (biofilm-biofertilizer) (Rosariastuti et al., 2024; Rosariastuti et al., 2023).

2.4. Research Procedures

2.4.1. Preparation of the Bioactivator

The preparation of the bioactivator involves activating EM4, producing eco-enzymes, and cultivating biofertilizer biofilms and fungal consortia in liquid media. EM4 activation was performed by mixing 30 mL of EM4 and molasses (1:1) into a container of non-chlorinated water (1 L). The solution was then incubated on a shaker for 5 days with a 2-hour daily shaking interval.

In this study, a fruit-based eco-enzyme solution was used. Dragon fruit, pineapple, guava, and oranges that were still fit for consumption, along with their peels, were cut into 3 parts (300 g); 1 part (100 g) of brown sugar was thinly sliced; all these ingredients were then mixed in a container containing chlorine-free water 1 L (10 parts). The container was then tightly closed and stored in a cool, dark place. During the first month, regular stirring is performed for 10–15 minutes per day to reduce the gas content that forms. There is no stirring during the second and third months. The eco-enzyme is ready for harvest after 3 months of fermentation. Harvesting is done by filtering to separate the filtrate from the residue. The bioactivator used in this study is the filtrate from this eco-enzyme.

The fungal and bacterial isolates identified in previous studies were revived on slant media containing appropriate selective agents. Each pure bacterial isolate was individually cultured in 50 mL of nutrient broth (NB), while each pure fungal isolate was individually cultured in 50 mL of potato dextrose broth (PDB). The bacterial and fungal cultures were incubated separately on a shaker at 90 rpm for 3 days. After 3 days, the bacterial and fungal cultures were combined to obtain a mixed inoculum. The mixed inoculum was subsequently incubated on a shaker at 90 rpm for 7–24 days until biofilm formation was observed, with a target inoculum density of 10^{10} cells/mL. All fungal isolates produced spores under the culture conditions used in this study. After incubation and shaking, the fungal suspension was used directly for spore counting without filtration or surfactant addition. The suspension was appropriately diluted when necessary, and spore density was determined using a hemocytometer by counting the spores in the designated counting squares under a microscope. The spore concentration was then calculated based on the number of spores counted and the corresponding dilution factor, following the method described by Rosariastuti et al. (2023). (Rosariastuti et al., 2023).

The fungal consortium consists of two fungal isolates from the study by Rosariastuti et al. (2024), namely *Purpureocillium lilacinum* and *Aspergillus ibericus*. These two isolates were cultured in 50 mL of liquid PDB medium and incubated on a shaker at 90 rpm for 3 days. After 3 days, 1 mL of the liquid inoculum was transferred with a micropipette into fresh PDB (100 mL) and the mixed inoculum was subsequently incubated on a shaker at 90 rpm for 7–14 days until the target microbial density of 10^{10} propagules/mL was achieved. The microbial density was determined using a hemocytometer. For bacterial isolates, density was expressed as cells/mL, whereas for filamentous fungal isolates, density was expressed as spores (conidia)/mL.

2.4.2. Composting

The compost used in this study was made from organic waste collected on the UNS campus, specifically plant debris. The waste was ground in a grinder to accelerate the composting process by reducing particle size. A 5-kg portion of the waste was then weighed and placed in a bucket with 12 holes drilled in the bottom. The waste was sprayed with water until the desired moisture level was reached, after which it was homogenized by turning it over. The homogenized waste was mixed with 100 mL of a 1% bioactivator solution (10 mL bioactivator + 1 L non-chlorinated water), 30 mL of molasses, and inorganic fertilizers were added as supplemental sources of N, P, and K to support microbial growth and activity during the composting process and to maintain an appropriate nutrient balance in the composting substrate, with an N:P ratio of 3:2:1. For every 5 kg of compost material, 12 g of urea (N), 8 g of SP-36 (P), and 4 g of KCl (K) were added. The compost material was then homogenized, and the bucket was tightly closed (incubated) for 3 months. During the incubation, the material was turned, and the temperature was measured every 2 days.

2.4.3. Harvesting

Harvesting was carried out after the composting process had been completed for 3 months. The mature compost was then re-chopped to make it finer, placed in plastic bags, and labeled. It was then subjected to chemical analysis.

Chemical analysis was conducted to determine the quality of the compost produced from the study. The analysis includes pH, total N (Kjeldahl method), total P-K (100 mg/L HCl extraction method), and organic C (Walkey and Black method) (Indonesian Agency for Agricultural Research and Development, 2023).

2.5. Data Analysis

The observational data were statistically analyzed using ANOVA. When a significant effect between treatments was detected, the analysis was followed by Duncan's Multiple Range Test (DMRT).

3. RESULT AND DISCUSSION

3.1. pH

Analysis of variance (ANOVA) showed that the type of bioactivator had a highly significant effect on compost pH ($p<0.01$). The highest pH value was observed in the control treatment (8.33), which was not significantly different from the EM4 treatment (8.20), but was significantly lower than the fungal consortium (8.01), biofilm biofertilizer (7.96), and eco-enzyme (7.92).

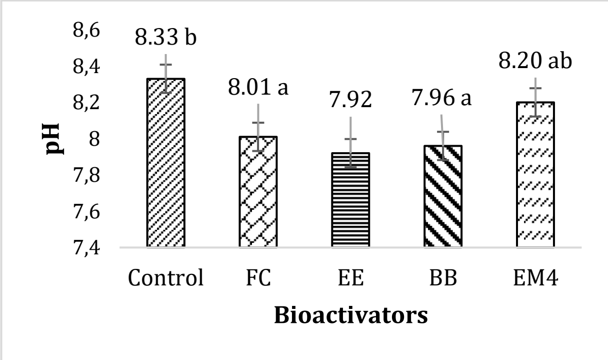

Figure 1. pH Value of Compost in Each Bioactivator Treatment. FC (Fungal consortium), EE (Eco-enzyme), BB (Biofilm biofertilizer). Values are Presented as Mean ± SD of Five Replicates (n = 5). Different lowercase Letters Indicate Significant Differences among Treatments According to DMRT at $p < 0.05$.

The addition of a bioactivator lowered the pH of the compost to near-neutral levels, from 7.43–8.46 to 7.18–7.39 (Susilowati et al., 2020). The decrease in pH in compost with bioactivators compared to the control is attributed to increased microbial diversity and activity, which lead to more intensive decomposition and the production of more organic acids (Agustin et al., 2025). Compost treated with the eco-enzyme bioactivator had the lowest pH (7.92) because ecoenzymes are derived from fermentation, which produces various important organic acids, making the compost acidic. During this process, carbohydrates are converted into organic acids, and volatile acids, derived from the organic material, dissolve due to bacterial activity (Fadlilla et al., 2023). Adding the acidic ecoenzyme bioactivator to the compost lowers its pH.

The measurement of compost pH (Figure 1) showed a range of 7.92–8.33, with variations among bioactivators; all were in the neutral to alkaline category. These results were consistent with the study by Yusi et al. (2025), which reported that the addition of bioactivators could significantly alter compost pH, although it remained within a neutral range around pH 7. The pH range obtained (6–8) indicates that the compost has reached maturity, making it suitable for application on acidic soils, as commonly found in several regions of Indonesia (Rosita et al., 2024). This occurs because, during the maturation phase, organic matter decomposes more steadily, the production of organic acids decreases, and the microbial community shifts to break down complex compounds such as cellulose and lignin. This decomposition process produces ammonia and other basic compounds that increase pH (Saypariya et al., 2024).

3.2. Organic C

C-organic is one of the main parameters for assessing the quality of compost and mineral soil, as it serves as an energy source for microorganisms and contributes to soil structure formation and enhanced soil fertility (Fitriah & Sitti, 2025).

Analysis of variance (ANOVA) indicates that differences in bioactivator types have a significant effect on the organic-C of compost ($p<0.05$). Although the final C/N ratio indicated that the compost had reached a relatively mature and stable condition, the organic-C content remained relatively low (4.43–10.45%) and did not meet the minimum quality standard of ≥15%. The low organic-C content may be attributed to substantial carbon loss during composting through microbial decomposition and mineralization of organic compounds, with part of the carbon released as CO_2. Thus, a low C/N ratio does not necessarily indicate a high organic-C content because the C/N ratio represents the relative proportion of carbon to nitrogen rather than the absolute amount of carbon retained in the compost. The relatively low organic-C content may reduce the compost's capacity to contribute to soil organic matter accumulation, aggregate formation, water-holding capacity, cation exchange capacity, and the provision of carbon substrates for soil microorganisms. Therefore, although the compost may have reached maturity based on its C/N ratio, its low organic-C content should be considered when evaluating its overall quality and potential agronomic performance. The results of the DMRT analysis of bioactivators on compost organic C were presented in Figure 2.

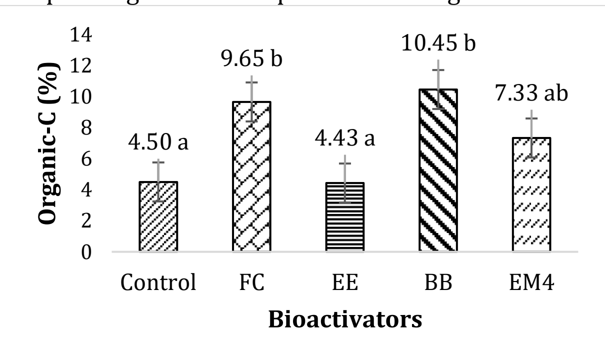

Figure 2. Organic Carbon (OC) Content of Compost in Each Bioactivator Treatment. FC (Fungal consortium), EE (Eco-enzyme), BB (Biofilm biofertilizer). Values are Presented as Mean ± SD of Five Replicates (n = 5). Different Lowercase Letters Indicate Significant Differences among Treatments According to DMRT at $p < 0.05$.

Figure 2 showed that the ecoenzyme treatment resulted in the lowest organic carbon content (4.43%), although this was not statistically different from the control (4.5%) or EM4 (7.33%). The lower organic carbon content in the ecoenzyme treatment compared to other bioactivators is likely due to a different mechanism of action. This is consistent with findings by Cahyani et al. (2023), who confirmed that bioactivators influence the biochemical conditions of compost, mainly through microbial decomposition of organic matter (Saidi et al., 2023). The increase in organic carbon content in the bioactivator treatment is likely due to decomposer microbial populations that accelerate the breakdown of organic matter. In addition to speeding up decomposition, these microbes produce more stable humic compounds, leading to a significant increase in the compost's organic carbon content (Wikurendra et al., 2022).

Microbial-based bioactivators can break down complex organic compounds into simpler, more stable forms, thereby keeping carbon bound within the compost (Sokra & Srun, 2026). Conversely, ecoenzymes rich with lipase, protease, and amylase enzymes accelerate the degradation of organic matter into unstable compounds and CO_2 gas. This process releases most of the organic carbon into the atmosphere (Narang et al., 2024), resulting in a lower final organic carbon content in the compost than in treatments with microbial bioactivators.

The results of this study indicate that microbial-based bioactivators, particularly biofilm-biofertilizer and fungal consortia, can increase the organic carbon content of compost to a greater extent than eco-enzymes. The highest organic carbon content was observed in the biofilm-biofertilizer treatment, although it did not differ statistically from the fungal consortium or EM4 treatments. These findings confirm that biofilm-biofertilizer has an advantage in increasing compost's organic carbon content. This advantage stems from the synergistic combination of fungi and bacteria, resulting in a more optimal decomposition process compared to fungal consortia containing only fungi or EM4 containing only bacteria. The role of fungi is crucial because they produce lignocellulolytic enzymes that degrade lignin and cellulose complex compounds that are difficult for bacteria to break down (Suryadi et al., 2022).

3.3. Total N

ANOVA showed that the type of bioactivator significantly affected the total N in the compost ($p < 0.05$). The total-N content of the compost ranged from 0.58% to 1.36%. The lowest value was obtained in the control (0.32%), followed by ecoenzyme (0.58%), EM4 (0.95%), fungal consortium (1.32%), and the highest was biofilm biofertilizer (1.36%) (Figure 3). These data confirm that the use of bioactivators can increase the total-N content in compost. This increase occurs because bioactivators stimulate the decomposition and mineralization rates of nitrogen by microorganisms, thereby increasing the concentration of inorganic nitrogen (NH_4^+ and NO_3^-) in line with the total N content (Walpajri et al., 2023). Additionally, biodegradation dissolves minerals in organic material, thereby increasing nutrient availability. The addition of microorganisms actively promotes the release of nitrogen compounds, thereby further increasing the compost's macronutrient content (Panisson et al., 2021).

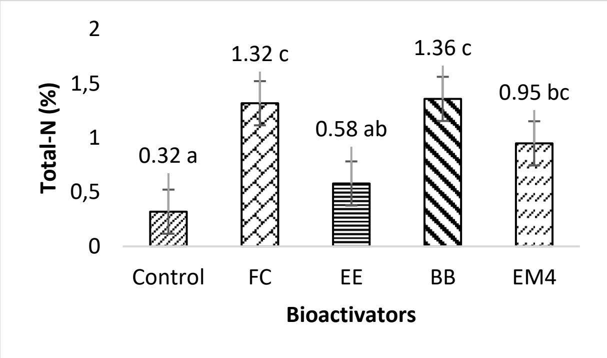

Figure 3. Total-N Content of Compost in Each Bioactivator Treatment. FC (Fungal consortium), EE (Eco-enzyme), BB (Biofilm biofertilizer). Values are Presented as Mean ± SD of Five Replicates (n = 5). Different Lowercase Letters Indicate Significant Differences among Treatments According to DMRT at p < 0.05.

Figure 3 showed that treatment with biofilm biofertilizer resulted in the highest total N content (1.36%), which was not significantly different from that of the fungal consortium (1.32%). This confirms the effectiveness of multi-species microbial biofilm biofertilizer. The biofilm composition, consisting of *Paraburkholderia* sp., *Betaproteobacteria, Aspergillus, Talaromyces*, and *Penicillium*, enables synergistic metabolic interactions that enhance nitrogen fixation, phosphate solubilization, and organic matter decomposition. Research by Yang et al. (2024) showed that the addition of *Penicillium oxalicum* accelerates the decomposition of organic matter through enzymatic activity, thereby releasing nitrogen more quickly and making it available in the compost. Asghar et al. (2023) reported that the combination of the AS2022 fungal strain (*Aspergillus* sp.) with cow manure compost increases nitrogen availability and extracellular enzyme activity compared to single-component compost. *Aspergillus* sp. is known to contribute to the degradation of organic matter, nutrient mineralization in the rhizosphere, and the solubilization of P and Fe, thereby making fungal inoculation with compost an environmentally friendly approach (Mahmood et al., 2023).

3.4. C/N Ratio

The C/N ratio is a key indicator of compost maturity and stability. A ratio that is too high indicates that the organic material still contains relatively high amounts of carbon that have not been sufficiently decomposed, while limited nitrogen availability may restrict microbial activity and slow decomposition. Conversely, an excessively low C/N ratio may indicate substantial carbon loss and/or nitrogen accumulation or retention during decomposition, which can reduce compost quality. According to the Indonesian Compost Quality Standard (SNI 19-7030-2004), a C/N ratio of 10–20 is considered an acceptable range for mature compost. Therefore, compost with a final C/N ratio within this range can be considered sufficiently mature and relatively stable for soil application. In this study, the C/N ratio after three months of composting was evaluated against this range to assess the maturity of the resulting compost (Zhan et al., 2021).

ANOVA results showed that the type of bioactivator significantly affects the C/N ratio of compost ($p<0.05$), confirming differences in the mechanisms by which each bioactivator regulates the carbon-nitrogen balance during decomposition. The mean C/N values of the resulting compost ranged from 7.31 to 14.06. The results of the DMRT for bioactivators on compost C/N were presented in Figure 4.

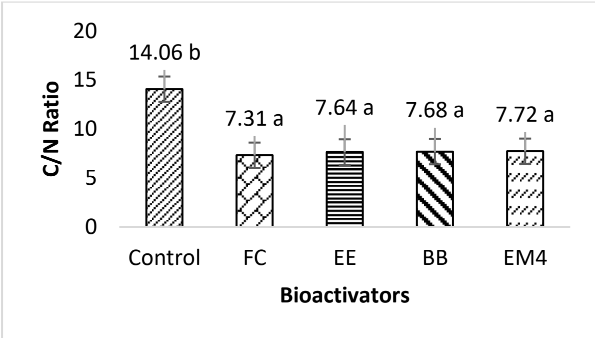

Figure 4. C/N Ratio of Compost in Each Bioactivator Treatment. FC (Fungal consortium), EE (Eco-enzyme), BB (Biofilm biofertilizer). Values are Presented as Mean ± SD of Five Replicates (n = 5). Different Lowercase Letters Indicate Significant Differences among Treatments According to DMRT at p < 0.05.

Based on Figure 4, the fungal consortium produced the lowest C/N ratio (7.31), which was not significantly different from that of the eco-enzyme (7.64), EM4 (7.72), or biofilm (7.68). Conversely, the highest value was obtained in the control (14.06).

The control compost has a higher C/N ratio due to low microorganism activity, primarily because of limited microbial respiration (Aslanzadeh et al., 2019). The addition of bioactivators was shown to reduce the C/N ratio by stimulating microbial activity during the decomposition of organic matter. A low C/N ratio shows that the organic matter has nearly completely decomposed. This decrease in the ratio is primarily influenced by a reduction in organic carbon content, while nitrogen remains relatively constant or increases, resulting in a lower C/N ratio by the end of the composting process (Sukmawati et al., 2023). Throughout the process, microorganisms act as the primary agents that break down organic matter, using carbon as an energy source.

The effectiveness of EM4 and ecoenzymes in reducing the C/N ratio is related to the activity of enzymes produced by microorganisms, such as lignin peroxidase, polyphenol oxidase, and manganese peroxidase, which directly accelerate the decomposition of lignocellulose and organic carbon (Yang et al., 2021). Carbon is utilized by microorganisms as an energy source, leading to a significant decrease in its content, while nitrogen levels increase relatively due to microbial activity that produces ammonia and other nitrogen compounds (Panataria et al., 2022). Thus, the higher the enzyme activity, the more efficient the decomposition process and the lower the compost's C/N ratio. This indicates that the use of fermentation-based bioactivators, such as EM4 and eco-enzymes, is effective at accelerating nutrient availability to plants.

3.5. Total P

ANOVA showed that the type of bioactivator significantly affected the compost's total phosphorus content ($p < 0.05$). The total-P content of the compost ranged from 0.59% to 1.34%. The results of the DMRT analysis of the bioactivator effect on the total-P content of the compost were presented in Figure 5.

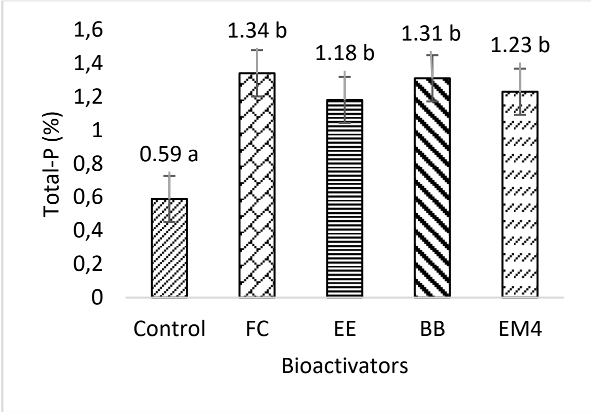

Figure 5. Total-P Values of Compost in Each Bioactivator Treatment. FC (Fungal consortium), EE (Eco-enzyme), BB (Biofilm biofertilizer). Values are Presented as Mean ± SD of Five Replicates (n = 5). Different Lowercase Letters Indicate Significant Differences among Treatments According to DMRT at $p < 0.05$.

Based on Figure 5, the lowest value was observed in the control (0.59%), which differed significantly from the bioactivator treatments. However, no significant differences were observed among the bioactivator treatments, with the highest total N content observed in the fungal consortium treatment (1.34%), followed by biofertilizer biofilm (1.31%), EM4 (1.23%), and eco-enzyme (1.18%). The relatively low macronutrient content suggests the compost may have limited potential to serve as a major source of NPK for plants. Instead, its agronomic value may be more strongly associated with its role as a soil amendment that adds organic matter and improves soil physical, chemical, and biological properties. Therefore, the application of this compost may be more appropriate as a complementary input rather than a sole substitute for inorganic fertilizers, particularly for crops with high nutrient requirements. Combining compost with appropriate mineral fertilization may provide both soil-conditioning benefits and sufficient nutrient availability to support plant growth. These values were influenced not only by the phosphorus content of the source material but also by the type of bioactivator used (Ardiyansyah et al., 2023).

The increase in total P under bioactivator treatment is associated with the activity of phosphate-solubilizing microbes, which dissolve insoluble phosphate compounds through various mechanisms. The relatively lower nutrient content observed in this study compared with that reported by Li et al. (2025) may be attributed to differences in raw material composition, bioactivator characteristics, and composting conditions. Li et al. (2025) specifically used phosphate-solubilizing bacterial bioactivators, which can enhance nutrient transformation and availability, particularly by solubilizing poorly available phosphorus. In contrast, the bioactivators used in the present study had distinct microbial compositions and functional characteristics, which may have led to different nutrient transformation patterns. In addition, differences in the initial C/N ratio, nutrient content of the raw materials, moisture content, aeration, pH, temperature, composting duration, and microbial population can influence the retention and transformation of N, P, and K during composting. Nitrogen may also be lost through ammonia volatilization and denitrification, while phosphorus and potassium concentrations are strongly influenced by the initial nutrient composition and the degree of organic matter decomposition. Therefore, differences in nutrient content between studies should be interpreted in the context of both the bioactivator characteristics and the composting substrate and process conditions.

The relatively low NPK content observed in this study also indicates that the application of bioactivator alone may not be sufficient to substantially increase the nutrient concentration of the final compost when the initial nutrient content of the substrate is limited. Future studies could improve compost quality by optimizing the initial C/N ratio and nutrient balance, selecting microbial consortia with complementary functions such as nitrogen fixation, phosphate solubilization, and potassium mobilization, and optimizing moisture, aeration, pH, and composting duration. The use of nutrient-rich co-substrates or appropriate nutrient supplementation may also increase the final product's NPK content. In addition, monitoring nutrient dynamics throughout the composting process would help identify the stages at which nutrient losses occur and allow process conditions to be adjusted accordingly. These approaches may improve both nutrient retention and the agronomic value of the resulting compost. These findings confirm the role of microbes in accelerating OM decomposition while increasing nutrient availability. Microbes in fungal consortia and biofertilizer-biofilms are known to produce organic acids such as citric, oxalic, and malic acids, which function to dissolve phosphate bound to Fe and Al complexes. This mechanism increases the availability of phosphorus in compost, making it more readily absorbed by plants (Macias-Benitez et al., 2020).

The fungal consortium and biofilm-biofertilizer were known to contain *Aspergillus* sp., which plays a key role in dissolving phosphorus, thereby increasing the compost's total P content. The mechanisms by which *Aspergillus* sp. increases phosphorus availability include the production of low-molecular-weight organic acids, the binding of metal ions, the release of complex compounds (such as protons, siderophores, CO_2, exopolysaccharides, and hydroxyl), secretion of extracellular enzymes for phosphorus mineralization, and release of phosphorus during substrate degradation (Nayak et al., 2020).

The fungal consortium was known to contain *Purpureocillium lilacinum*, while the biofertilizer-biofilm consists of *Talaromyces* sp. and *Penicillium* sp. These three fungal species belong to the group of cellulolytic fungi, which have been shown to increase the total-P content in compost. Fikrinda et al. (2022) reported that *Talaromyces* sp., *Penicillium* sp., and *Purpureocillium* sp., as phosphate-solubilizing microbes, can increase phosphorus content by 84.81%, 81.54%, and 86.51%, respectively. This increase occurs through two main mechanisms: the synthesis of phosphatase and phytase enzymes, which facilitate the mineralization of organic phosphate, and the release of organic acids (oxalate, citrate, acetate, succinate, and lactate) during decomposition, which effectively solubilize bound phosphate. Conversely, the low phosphorus content in the eco-enzyme and control treatments indicates that, without phosphate-solubilizing microbes, the release of phosphorus from organic matter occurs more slowly and less efficiently. Eco-enzyme is an organic fertilizer produced through microbial fermentation and rich in organic acids, making it beneficial for soil improvement, root protection, and plant growth (Novianto, 2022). However, the eco-enzyme did not specifically contain phosphate-solubilizing microbes such as *Bacillus* sp. or *Pseudomonas* sp., which are commonly found in biofertilizer consortia; thus, its effectiveness in increasing total-P content was lower than that of phosphate-solubilizing microbe-based bioactivators.

3.6. Total K

Analysis of variance results showed that the type of bioactivator had a significant effect on the total-K content of the compost ($p < 0.05$). The total-K content in the compost produced in this study ranged from 0.15% to 0.42%. The results of the DMRT analysis of the effect of bioactivators on the total-K content of compost were presented in Figure 6.

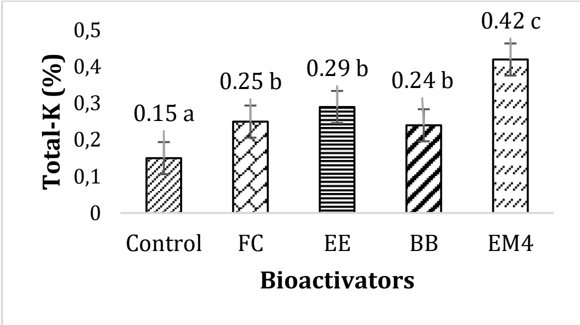

Figure 6. Total-K Values of Compost in Each Bioactivator Treatment. FC (Fungal consortium), EE (Eco-enzyme), BB (Biofilm biofertilizer). Values are Presented as Mean ± SD of Five Replicates (n = 5). Different Lowercase Letters Indicate Significant Differences among Treatments According to DMRT at $p < 0.05$.

Figure 6 showed that the control treatment had the lowest total-K content, at 0.15%, which was significantly lower than all treatments with bioactivators. Conversely, the EM4 treatment had the highest total-K content, at 0.42%, which was significantly higher than that of the other treatments. The biofilm-biofertilizer treatment (0.24%), fungal consortium (0.25%), and eco-enzym (0.29%) showed relatively similar total-K content and were not significantly different.

The increase in potassium content in the EM4 treatment is associated with the activity of fermentative microbes. The EM4 solution is a mixed culture consisting of various selected fermentation microorganisms, including photosynthetic bacteria, lactic acid bacteria, yeast, *Streptomyces* sp., and *Actinomycetes* sp. These microbes effectively decompose organic matter and add nutrients (Kurniawan et al., 2024). Fermentative microorganisms can also produce mineral-dissolving enzymes and organic compounds, such as organic acids and secondary metabolites, that accelerate the decomposition of organic matter and the release of K^+ ions (Widyabudiningsih et al., 2025). Meanwhile, eco-enzymes derived from fruit waste fermentation also contribute to potassium solubilization, although their effectiveness is lower than that of EM4 because they lack the complex community of fermentative microbes found in EM4.

The increase in potassium content in the biofilm-biofertilizer and fungal consortium treatments is associated with the microbial activity contained within them, namely *Talaromyces* sp., *Penicillium* sp., and *Aspergillus* sp. Several fungal strains, particularly *Aspergillus* and *Penicillium*, produce organic acids that promote the release of K^+ ions by dissolving and decomposing insoluble organic substrates, thereby significantly contributing to the potassium cycle (Youssef et al., 2023). The study by Yu et al. (2021) reported that *Aspergillus* and *Penicillium* dominate the fungal community during composting, accounting for about 40% and playing important roles in compost maturation. *Aspergillus* degrades lignin, producing harmful xenobiotic compounds (PAHs), whereas *Penicillium* breaks them down, resulting in more mature, healthier compost. Although microbial consortia have the potential to mobilize nutrients, their effectiveness for potassium is not as strong as for phosphorus, because the release of K from organic matter requires more specific enzymatic activity and environmental conditions. The differences in potassium content among treatments emphasize that the type of bioactivator significantly determines the effectiveness of potassium release in compost. The EM4 treatment proved to be the most effective in increasing potassium availability, while the biofilm-biofertilizer, although it did not produce the highest total-K content, still demonstrated the effectiveness of specific microbes in aiding nutrient solubilization.

3.7. Compliance with Ministerial Regulation No. 7763/2024

The results of the compost observations were compared with Ministerial Regulation No. 7763/2024 to assess whether the quality of the produced compost meets the established standards. The comparison of compost nutrient levels with the Ministerial Regulation No. 7763/2024 standard is presented in Table 1.

As shown in Table 1, the organic-C content in all treatments during composting did not meet the quality standards set by the Ministry of Agriculture. The Ministry of Agriculture's quality standard for organic-C in organic fertilizer is a minimum of 15%. This is due to the composting process taking place over 3 months and to the low C/N ratio of the compost materials used. This is consistent with the findings of Oviedo-Ocaña et al. (2017), which indicate that compost materials derived from green waste (leaves, twigs, and grass clippings) have a low C/N ratio and moisture content, leading to rapid carbon depletion during the composting process. As a result, the organic-C content is low and less than ideal when used as a sole composting material (Oviedo-Ocaña et al., 2017). Compost from leaves and twigs has relatively low levels of nitrogen, phosphorus, potassium, calcium, and magnesium, which are not immediately available to plants; however, over time, these nutrients are gradually released when applied in large quantities (Hashim et al., 2022).

The final C/N ratios (7.31–14.06) for all treatments met the quality standards outlined in Ministry of Agriculture Regulation No. 7763 of 2024. This is because the compost sources used had a low C/N ratio, so they did not require a lengthy process to reduce them further. Leaves have the lowest C/N ratio due to their high nitrogen content for photosynthesis and metabolism, whereas stems have a high carbon content (lignin, cellulose) and very low nitrogen (Zhang et al., 2019). Organic materials with a C/N ratio that is near or equal to the soil's C/N ratio can be directly utilized by plants. In principle, the purpose of composting is to reduce the C/N ratio of organic materials to a level consistent with the soil's C/N ratio (<20) (Sukmawati et al., 2023). When the C/N ratio is too high, indicating an excess of carbon, the decomposition process is incomplete and requires further microbial activity to break down the composted organic material. Conversely, if the C/N ratio is too low, it can lead to ammonia volatilization, which removes nutrients from the compost (Nurhayati and Munawar, 2024). The C/N ratio decreased substantially from 14.06 in the initial composting material to 7.31–7.72 after three months of composting. Although a low C/N ratio can indicate advanced stabilization of organic matter, final values below 10 should be interpreted alongside the organic-C content and other compost quality parameters. In the present study, the low final C/N ratio was accompanied by relatively low organic-C contents (4.43–10.45%), suggesting that the decrease in the C/N ratio was likely associated with substantial carbon mineralization during composting. Microbial decomposition converts organic carbon into CO_2, resulting in carbon loss from the composting system and consequently reducing the C/N ratio. Therefore, the low C/N ratio in this study should not be interpreted solely as evidence of superior compost maturity but also as an indication that considerable carbon was lost during the composting process. This finding emphasizes the importance of evaluating the C/N ratio together with absolute organic-C content when assessing compost maturity and quality.

The relatively low organic-C content and low final C/N ratio may limit the resulting compost's ability to serve as a substantial source of organic matter and carbon for soil microorganisms. In addition, the relatively low NPK content indicates that the compost may provide limited nutrients as a sole fertilizer and may be more suitable as a soil amendment or complementary nutrient source. Therefore, optimization of the composting process is required to improve the overall quality of the final product. Process optimization could include adjusting the initial C/N ratio to ensure sufficient carbon and nitrogen for microbial decomposition, improving the composition of carbon-rich feedstocks, and controlling moisture, aeration, pH, temperature, and turning frequency to promote efficient decomposition while minimizing excessive losses of carbon and nitrogen. The use of nutrient-rich organic materials or appropriately selected microbial consortia with complementary functions, such as nitrogen fixation, phosphate solubilization, and potassium mobilization, may also improve nutrient retention and NPK content.

Table 1. Comparison of Compost Nutrient Elements with the Ministry of Agriculture Regulation No. 7763/2024

Parameters	Average Analysis Results	Average Analysis Results	Average Analysis Results	Average Analysis Results	Average Analysis Results	Ministry of Agriculture Standard No. 7763/2024
	Control	FC	EC	EM4	BB	Ministry of Agriculture Standard No. 7763/2024
pH	8.33	8.01	7.92	8.20	7.96	4-9
Organic-C (%)	4.50	9.65	4.43	7.33	10.45	>15%
C/N ratio	14.06	7.31	7.64	7.72	7.68	<25
Total-N (%)	0.32	1.32	0.58	0.95	1.36	>2%
Total-P (%)	0.59	1.34	1.18	1.23	1.31	>2%
Total-K (%)	0.15	0.25	0.29	0.42	0.24	>2%

Note: FC (fungal consortium), EC (eco-enzyme), BB (Biofilm-biofertilizer)

Future studies should monitor changes in organic C, total N, available or total P, K, and the C/N ratio at different stages of composting, rather than measuring these parameters only at the beginning and end of the process. A carbon and nitrogen mass balance would also be valuable for quantifying actual C and N losses and determining whether the low final C/N ratio is primarily due to carbon mineralization, nitrogen retention, or both. Optimization experiments using different initial C/N ratios, carbon-rich co-substrates, microbial consortia, and composting conditions could further identify the most effective strategy for producing compost with an appropriate C/N ratio, higher organic-C content, and improved NPK concentration.

The NPK content of compost with the addition of bioactivators, namely fungal consortium (2.91%), ecoenzyme (2.05%), EM4 (2.6%), and biofilm biofertilizer (2.91%) met the quality standards set by the Ministry of Agriculture for 2024, which stipulate a minimum NPK content of 2% in compost, whereas the control compost did not meet the minimum NPK content threshold. Therefore, the use of more efficient methods and bioactivators is an important step toward improving compost quality. According to Rosariastuti et al. (2025), Biofilm Biofertilizer (BFBF) is a consortium of bacteria and fungi that forms a biofilm to protect roots from pathogens, support the growth of soil microbes, and decompose organic matter, thereby enhancing nutrient availability for plants. Compost quality standards. Among several treatments, the use of fungal consortia and biofilm-biofertilizer as bioactivators is highly recommended because they can accelerate decomposition while enriching nutrient content, thereby improving both the quality and quantity of compost.

4. CONCLUSION

Biofilm-biofertilizer produced the best overall compost quality because it increased organic-C content by up to 10.45%, total-N by 1.36%, and total P by 1.31%, and generated a C/N ratio of 7.68. Meanwhile, the treatment without a bioactivator results in the lowest compost quality. Most treatments met the compost quality standards of the Indonesian Minister of Agriculture Regulation No. 7763/2024 for pH, C/N ratio, and NPK content (>2%); however, they did not meet the minimum requirement for organic-C content (≥15%). This was due to the compost being harvested after 3 months of the composting process. Of the several bioactivators tested, the treatment with biofilm-biofertilizer and fungal consortium was the closest to the SNI Ministry of Agriculture Regulation No. 7763/2024; it can be considered the most promising bioactivator in producing high-quality compost under the conditions of this study.

REFERENCES

Agustin, D.R., Suprapti, E., & Wiyono. 2025. The influence of types of bacteria and types of compost materials on composting results. Journal of Rural and Urban Community Studies,3(1), 11–20. https://doi.org/10.36728/jrucs.v3i1.4667

Ardiyansyah, W., Aryanti, E., & Rahmadhani, E. 2023. Kualitas Kimia kompos bahan asal serasah daun dan serbuk gergaji. InPROSIDING Seminar Nasional Ketahanan Pangan (Vol. 1, No. 1, pp. 183-192).

Ariny, M., & Nisa, S.Q.Z. 2024. Tinjauan terhadap parameter dan kualitas kompos organik perusahaan galangan kapal dengan penggunaan aktivator PROMI dan Ecoenzymes. Botani: Publikasi Ilmu Tanaman Dan Agribisnis,1(2), 15-27.

Asghar, W., Asghar, N., Iftikhar, F., Mahmood, A., Latif, A., Nawab, J., Imran, M., Khan, M., Arsalan, M., Ehsan, M., Ullah, R., & Bilal, M. 2023. Response of wheat (*Triticum aestivum* L.) to combined application of organic compost along with plant growth-promoting *Aspergillus* fungi. Journal of Applied Research in Plant Sciences,4(02), 545–552. https://doi.org/10.38211/joarps.2023.04.02.186

Aslanzadeh, S., Kho, K., & Sitepu, I. 2020. An evaluation of the effect of takakura and effective microorganisms (em) as bio-activators on the final compost quality. IOP Conference Series: Materials Science and Engineering,742(1), 012017. https://doi.org/10.1088/1757-899X/742/1/012017

Cahyani, V. R., Rahayu, R., Lakshitarsari, K. P., Megow, R. A. Z. W., & Azzahra, N. Y. 2023. Composting of rice straw–based materials using aerobic bioactivator isolated from rice straw, mahogany bark, and cassava peels. Caraka Tani: Journal of Sustainable Agriculture,39(1), 48. https://doi.org/10.20961/carakatani.v39i1.74297

Fadlilla, T., Budiastuti, M. T., & Rosariastuti, M. R. 2023. Potential of fruit and vegetable waste as eco-enzyme fertilizer for plants. Jurnal Penelitian Pendidikan IPA,9(4), 2191–2200. https://doi.org/10.29303/jppipa.v9i4.3010

Fikrinda, F., Marlina, M., & Khalil, M. 2022. Cellulolytic fungi modify the nitrogen, phosphorus, and potassium contents of organic fertilizers. IOP Conference Series: Earth and Environmental Science,978(1), 012012. https://doi.org/10.1088/1755-1315/978/1/012012

Fitriah, F., & Saleha, S. 2025. Effect of Fermentation Duration on the Carbon-to-Nitrogen (C/N) Ratio of Liquid Organic Fertilizer Produced from Dami Jackfruit Waste Using Coconut Husk-Based Bioactivator. Cognitia: International Engineering Journal,1(1), 18–25. https://doi.org/10.63288/ciej.v1i1.3

Ghiasian, M. 2020. Microbial biofilms: Beneficial applications for sustainable agriculture. New and future developments in microbial biotechnology and bioengineering (pp. 145-155). Elsevier.

Hamzah, N., Farhana, H.N., Syahiza, Z.N., Kassim, J., Abdul, H.A., & Liza, R.N. 2020. Effect of organic matter on pathogen population during composting of municipal sludge. In IOP Conference Series: Earth and Environmental Science (Vol. 616, No. 1, p. 012055). IOP Publishing.

Hemalatha, M., & Visantini, P. 2020. Potential use of an eco-enzyme for the treatment of metal-based effluent. In IOP Conference Series: Materials Science and Engineering (Vol. 716, No. 1, p. 012016). IOP Publishing.

Indonesian Agency for Agricultural Research and Development. 2023. Chemical Analysis of Soil, Plants, Water, and Fertilizers. Dalam Petunjuk Teknis Edisi (3rd ed.). Kementerian Pertanian Republik Indonesia.

Kurniawan, L., Maryudi, M., & Astuti, E. 2024. Utilization of Tofu Liquid Waste as Liquid Organic Fertilizer Using the Fermentation Method with Activator Effective Microorganisms 4 (EM-4): A Review. Equilibrium Journal of Chemical Engineering,8(1), 100. https://doi.org/10.20961/equilibrium.v8i1.84056

Lerner, A. W., Guimarães, V. F., Brito, T. S., Röske, V. M., Cecatto Junior, R., Silva, A. S. L., & Weizenmann, J. C. 2021. Inoculation methods of *Azospirillum brasilense* associated to the application of soil bioactivator in the maize crop.

Leonardo, Y., Siga, W. D., Indah, K. K., & Daslan, M. 2024. Gagalnya Transisi Penggunaan Pupuk Organik Untuk Pertanian Di Dusun Cikubang, Desa Cintakarya, Kabupaten Pangandaran. Journal of Citizenship: Interdisciplinary Perspectives,1(1), 18-28.

Li, W., Yang, X., Bian, R., Ren, H., Zheng, M., Li, D., Liu, L., & Sun, Z. 2025. Improve Low-Ambient-Temperature Composting Process, Phosphorus Bioactivation, and Mature Compost Quality by Cold-adapted Phosphate-Solubilizing Bacteria. Waste and Biomass Valorization. https://doi.org/10.1007/s12649-025-03417-7

Macías-Benítez, S., García-Martínez, A. M., Caballero Jiménez, P., González, J. M., Tejada Moral, M., & Parrado Rubio, J. 2020. Rhizospheric Organic Acids as Biostimulants: Monitoring Feedbacks on Soil Microorganisms and Biochemical Properties. Frontiers in Plant Science,11, 633. https://doi.org/10.3389/fpls.2020.00633

Mahmood, A., Iguchi, R., & Kataoka, R. 2019. Multifunctional food waste fertilizer having the capability of Fusarium-growth inhibition and phosphate solubility: A new horizon of food waste recycle using microorganisms. Waste Management,94, 77–84. https://doi.org/10.1016/j.wasman.2019.05.046

Naeem, M., Iqbal, Z., Hussain, A., Jamil, M., Ahmad, H. T., Ismail, A. M., & Hadid, M. L. 2025. Conversion of organic waste into bio-activated zinc-enriched compost to improve the health of deficient soils and wheat yield. GLOBAL NEST JOURNAL, 27(7).

Narang, N., Hussain, A., & Madan, S. 2023. A comparative study on compost preparation using lab-prepared eco-enzyme and its effect on growth of plant species Phaseolus vulgaris. Environmental Science and Pollution Research,31(25), 36230–36240. https://doi.org/10.1007/s11356-023-27168-x

Nayak, S., Samanta, S., & Mukherjee, A. K. 2020.Bene cial Role of *Aspergillus* sp. In Agricultural Soil and Environment.

Novianto, N. 2022. Response of Liquid Organic Fertilizer Eco Enzyme (EE) on Growth and Production of Shallot (*Allium Ascalonicum* L). Jurnal Agronomi Tanaman Tropika (JUATIKA),4(1), 147–154. https://doi.org/10.36378/juatika.v4i1.1782

Panataria, L. R., Sianipar, E., Sembiring, H., Sitorus, E., Saragih, M., Simatupang, J., & Pakpahan, H. 2022. Study of Nutrient Content in Eco Enzymes From Various Types of Organic Materials. Journal of Agriculture,1(02), 90–95. https://doi.org/10.47709/joa.v1i02.1728

Panisson, R., Paiva Muscope, F., Müller, C., Treichel, H., & Korf, E. P. 2021. Increased quality of small-scale organic compost with the addition of efficient microorganisms. Revista Brasileira de Ciências Ambientais,56(3), 531–540. https://doi.org/10.5327/Z21769478949

Putri, M. S. A., Sulistiono, E., Prasidya, D. A., Ni'am, A. C., & Affandy, N. A. 2024. The EM4 Addition Affects Water Absorption Time and Compost Quality in Biopore Infiltration Hole. Jurnal Kesehatan Lingkungan: Jurnal Dan Aplikasi Teknik Kesehatan Lingkungan,21(1), 45–58. https://doi.org/10.31964/jkl.v21i1.715

Rosariastuti, R., Harir, A., Hartati, S., Irawan, E., & Nugraha, S. 2023. The effectiveness of biofertilizer biofilm formulation in promoting the growth of Pak choi (*Brassica rapa* L.) plant. E3S Web of Conferences, 467, 1–8. https://doi.org/10.1051/e3sconf/202346701027

Rosariastuti, R., Sutami, Nugraha, S., & Amanto, B. S. 2023. Bacterial diversity in the western slopes of Mount Lawu, Karanganyar, Indonesia. Biodiversitas, 24(4), 2125–2133. https://doi.org/10.13057/biodiv/d240423

Rosariastuti, R., Wulandari, N. M. P., Nugraha, S., Irawan, E., Maro'ah, S., & Sumani. 2024. Isolation and a Potential Test of Fungal Consortium as Biofertilizer from Mount Lawu, Indonesia. International Journal of Agriculture and Biology, 32(1), 35–42. https://doi.org/10.17957/IJAB/15.2173

Rosita, R., Imran, Z., Eris, D. D., Widayanti, S., Ayu, R., Purnajaya, A., Bayuaji, D. Y., Dewi, A. C., & Fitra, A. (n.d.). Effects of Storage Time and Mixing Technique on the Nutrient Content of Biopos Compost.

Saidi, D., Setyaningrum, T., & Akbar, B. M. 2023. Effect of Types of Bioactivators and Organic Waste on the Quality of Organic Fertilizer.ISSN,7(8).

Saypariya, D. C., Singh, D., Dikshit, A. K., & Dangi, M. B. 2024. Composting of organic fraction of municipal solid waste in a three-stage biodegradable composter. Heliyon, 10(17).

Sokra, in, & Somaly, S. 2025.Microbial Consortia in Composting: A Review of Functional Roles, Synergies, and Optimization Strategies for Efficient Biodegradation. Journal of Agriculture and Technology. https://doi.org/10.5281/ZENODO.17949820

Solihin, M. A., & Fitriatin, B. N. 2017. Sebaran mikroba tanah pada berbagai jenis penggunaan lahan di kawasan Bandung Utara. soilrens,15(1).

Sudarmaji, I., Saepuloh, D., Sabur, A., Fahmi, R., & Ramdani, H. C. 2025. Solusi Berkelanjutan untuk Lingkungan Bersih melalui Pengelolaan Limbah Organik Rumah Tangga. Jurnal Pengabdian Masyarakat Ilmu Pendidikan, 4(2), 326-342.

Sukmawati, F. N., Irna, A., Pramudya, Y., Sukarji, S., Pamungkas, S. S. T., Rahmat, A., Rozaki, Z., & Hanum, F. F. 2024. Quality analysis of coffee waste compost with the addition of cassava tapai local microorganism (LMO) bioactivator. Applied Research in Science and Technology,3(2), 72–85. https://doi.org/10.33292/areste.v3i2.46

Suryadi, H., Judono, J. J., Putri, M. R., Eclessia, A. D., Ulhaq, J. M., Agustina, D. N., & Sumiati, T. 2022. Biodelignification of lignocellulose using ligninolytic enzymes from white-rot fungi. Heliyon,8(2), e08865. https://doi.org/10.1016/j.heliyon.2022.e08865

Susilowati, L. E., Mahrup, M., Arifin, Z., & Sutriono, R. 2023. Effectiveness of Bio Activator of Phosphate Solubilizing Bacteria Consortium on Composting Bag-log Waste Incorporated with Cow Dung.Jurnal Penelitian Pendidikan IPA,9(2), 788–795. https://doi.org/10.29303/jppipa.v9i2.2755

Sutrisno E, B Zaman. I.W Wardhana, L Simbolon, and R Emeline. 2020. Are bioactive vectors from Vegetables Waste are Applicable in Composting Systems? IOP Conf. Series: Earth and Environmental Science 448: 012033

Walpajri, F., Siregar, F. W., Ilyosa, A. N., & Wiyaga, M. 2023. Effectiveness of Various Types Bio-Activators to Speed Up The Composting Process And Quality Of Compost Fertilizer. International Journal of Progressive Sciences and Technologies (IJPSAT), 36(2), 630-636.

Widyabudiningsih, D., Rinaldi, K., Firdaus, F. M., Fauzi, R. R., & Hulupi, M. 2025. EM4 Effect on Macronutrients and Microbial Growth in Liquid Organic Fertilizer from Cibogo Market Waste. Fluida,18(1), 23–30. https://doi.org/10.35313/fluida.v18i1.6050

Wikurendra, E., Nurika, G., Herdiani, N., & Lukiyono, Y. T. 2022. Evaluation of the Commercial Bio-Activator and a Traditional Bio-activator on Compost Using Takakura Method.Journal of Ecological Engineering,23(6), 278–285. https://doi.org/10.12911/22998993/149303

Witasari, W. S., Sa'diyah, K., Istianah, N., & Hidayatulloh, M. 2022. Composting Time Effect of the Activated Sludge from Bioethanol Solid Waste by Orgadec Bio-activator to the Compost Characteristics. Jurnal Teknik Kimia Dan Lingkungan,6(1), 53–61. https://doi.org/10.33795/jtkl.v6i1.285

Yang, H., Zhang, H., Qiu, H., Anning, D. K., Li, M., Wang, Y., & Zhang, C. 2021. Effects of C/N Ratio on Lignocellulose Degradation and Enzyme Activities in Aerobic Composting. Horticulturae,7(11), 482. https://doi.org/10.3390/horticulturae7110482

Yang, M., Guo, Y., Yang, F., Wang, J., Gao, Y., Wang, M., Liang, X., & He, S. 2024. Dynamic changes in and correlations between microbial communities and physicochemical properties during the composting of cattle manure with *Penicillium oxalicum*. BMC Microbiology,24(1), 301. https://doi.org/10.1186/s12866-024-03449-4

Youssef, S. M., Shaaban, A., Abdelkhalik, A., Abd El Tawwab, A. R., Abd Al Halim, L. R., Rabee, L. A., Alwutayd, K. M., Ahmed, R. M. M., Alwutayd, R., & Hemida, K. A. 2023. Compost and Phosphorus/Potassium-Solubilizing Fungus Effectively Boosted Quinoa's Physio-Biochemical Traits, Nutrient Acquisition, Soil Microbial Community, and Yield and Quality in Normal and Calcareous Soils. Plants,12(17), 3071. https://doi.org/10.3390/plants12173071

Yusi, Y., Zubaidah, T., & Haris, A. 2025. Accelerating Composting of Hospital Organic Waste Using EM-4 Bioactivator: A Controlled Trial in South Kalimantan, Indonesia. Global Health & Environmental Perspectives, 2(1), 245-257.

Zhan, Y., Wei, Y., Zhang, Z., Zhang, A., Li, Y., & Li, J. 2021. Effects of different C/N ratios on the maturity and microbial quantity of composting with sesame meal and rice straw biochar. Biochar, 3(4), 557–564. https://doi.org/10.1007/s42773-021-00110-5.