

Research Article

Harnessing Tomato-based Eco-enzymes for Sustainable Agriculture and Circular Economy Advancement

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Abstract

Agricultural waste constitutes a significant contributor to environmental degradation and food loss within agrarian economies such as Indonesia, where the annual production of organic waste exceeds 25 million tons. Notwithstanding its prevalence, agricultural waste-exemplified by unsold tomatoes-is often improperly managed through incineration or disposal in landfills, resulting in pollution, greenhouse gas emissions, and the forfeiture of economic opportunities. This research investigates the feasibility of utilizing tomato-based agricultural waste for the production of eco-enzymes through fermentation, offering an innovative approach to promote sustainable agricultural practices and circular economy principles. This investigation aimed to assess the nutrient profile and functional characteristics of eco-enzymes derived from tomatoes, with a particular focus on their potential applications as liquid organic fertilizers, natural pesticides, and disinfectants. Employing a fermentation duration of three months, combined with water and sugar, the resultant product was analyzed for its macronutrient content and pH level. Laboratory findings indicated that the eco-enzyme exhibited a stable pH of 3.5, accompanied by nutrient concentrations of 0.53% nitrogen, 1.43% phosphorus, and 7.02% potassium-attributes that are advantageous for soil enhancement and plant health. The results of this study demonstrate that eco-enzymes not only alleviate the burden of agricultural waste but also promote regenerative farming practices, improve resource efficiency, and support rural economies. The research concludes that tomato-based eco-enzymes present a feasible mechanism for converting organic waste into valuable resources, with profound implications for reducing food loss, promoting sustainable land management, and fostering circular value creation within agro-industrial frameworks.

Keywords

Eco-enzyme, Agricultural Waste, Circular Economy, Food Loss, Liquid Organic

1. Background

Agricultural waste is an increasingly urgent environmental challenge [1], especially in countries that rely on the agri-cultural sector as a significant source of income [2]. Based on information from the Food and Agriculture Organization (FAO), around 1.3 billion tons of food are wasted yearly, and about 30% of total agricultural products never reach

con-sumers [3]. This waste comes from unused crops and waste generated during production, processing, and distribution processes [4]. In Indonesia, it is estimated that around 25 million tons of agricultural waste are generated every year, which includes plant residues, fruits that are not suitable for sale, and waste from the food processing process [5].

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This issue is further exacerbated by low awareness and inadequate infrastructure for agricultural waste management [6]. Many farmers still burn their crops' remains, which pollutes the air and reduces soil fertility [7]. This improper management contributes to the loss of potential resources that should be reused in the production process [6]. Therefore, it is crucial to develop a more sustainable strategy for managing agricultural waste, reducing environmental negative impacts, and improving economic efficiency.

1.1. Explanation of the Issue of Agricultural Waste

This issue is further exacerbated by low awareness and inadequate infrastructure for agricultural waste management. Many farmers still burn their crops' remains, which pollutes the air and reduces soil fertility. This improper management contributes to losing potential resources that could be reused in production. Therefore, it is crucial to develop a more sustainable strategy for managing agricultural waste, reducing environmental negative impacts, and improving economic efficiency [6].

1.2. Adverse Effects of Agricultural Waste on the Environment and Economy

Waste from the agricultural sector has a significant impact on the environment, ranging from soil pollution [8] and water [9] to air [10]. For example, burning agricultural waste can release greenhouse gases such as carbon dioxide and methane into the atmosphere, contributing to climate change [11]. In addition, degraded waste in landfills can produce methane gas emissions [12, 13], which has a much greater global warming potential than carbon dioxide [14]. On the other hand, soil and water pollution due to excessive use of fertilizers and pesticides can cause damage to ecosystems and decrease the quality of natural resources [15].

From an economic perspective, agricultural waste also causes considerable losses [16]. According to the Global Food Loss and Waste Protocol report, economic losses due to food waste are estimated to reach around 940 billion US dollars annually worldwide [17]. In Indonesia, the economic impact of agricultural waste is strongly felt, especially by smallholders who depend on their crops [18]. When crops are not used, their income is threatened, and the food security of the community as a whole is threatened. Therefore, effective agricultural waste management is essential to increase productivity and economic sustainability in the agricultural sector.

1.3. The Importance of Agricultural Waste Management in the Context of Sustainability

Good agricultural waste management is important in

achieving sustainability goals [19]. By implementing environmentally friendly management practices, we can reduce the negative impact of agricultural waste while harnessing its potential [16]. One promising approach is using eco-enzymes, natural enzymes that can help decompose organic waste into valuable compost [20]. Eco-enzymes accelerate the decomposition process, increase soil fertility, and support plant growth [21].

In the context of a circular economy, agricultural waste management can contribute to the creation of added value [16]. By turning waste into valuable products, such as organic fertilizers or industrial raw materials, we can reduce our dependence on non-renewable resources and create new jobs. For example, several initiatives in Indonesia have successfully converted agricultural waste into biogas, which can be used as an alternative energy source [22]. Thus, agricultural waste management contributes to environmental sustainability and provides significant economic benefits to the community. Overall, agricultural waste management must be a priority in the sustainable development agenda.

We can create more sustainable and efficient agricultural systems by utilizing innovative technologies and practices, such as eco-enzymes. This will reduce the negative impact on the environment and improve food security and the community's economic well-being. Therefore, collaboration between the government, academia, and the private sector is needed to develop practical solutions for agricultural waste management.

2. Literature Review

2.1. Definition and Concept of Circular Economy

Circular economy (CE) is an innovative economic model that is in stark contrast to traditional linear economies, which typically follow a "take-make-" pattern [23]. The circular economy is also considered a concept that aims to create a regenerative system to minimize agricultural waste, industry, emissions, and energy leakage [24, 25] by designing products that are durable and improve resource efficiency. This concept has gained traction globally, supported by initiatives such as the World Economic Forum and the European Union, which aim to integrate CE principles into corporate policies and strategies [26, 27].

This is achieved through remanufacturing, refurbishing, and material recycling [27, 28]. In a circular economy, products are designed to be reusable, recycled, or converted into new products, forming a closed-loop system that reduces the need for new resources and the environmental impact [29]. The concept of a circular economy also involves several pillars, such as regenerative design, industrial ecology, and reverse logistics, all of which contribute to a more sustainable system [30]. In various industrial sectors, the circular

economy encourages sustainable practices and resource optimization, significantly reducing waste and environmental impacts [31].

Through business models that go hand in hand with digitalization, the circular economy targets environmental issues and improves economic and social performance in the digital era [32]. Overall, the circular economy can create positive economic, social, and environmental synergies by promoting more sustainable consumption and production than traditional linear models [28].

A circular economy represents an economic framework that aspires to reduce waste generation by reconfiguring the production and consumption paradigm to extend the life of products, materials, and resources [24, 33]. The main goal of the circular economy is to revolutionize management strategies from traditional linear models, which typically include resource extraction, product fabrication, and ultimately waste disposal, to systems that aim to reuse, minimize, and recycle every component in the production continuum [21].

Circular economy principles in the context of waste management include waste mitigation strategies through methodologies such as recycling [34], reprocessing of materials by producers [35], as well as product engineering that guarantees materials can be retrieved and reused [36]. This paradigm goes beyond the mere increase in waste streams; it has to do with the basic design of a product to reduce its ecological footprint after the end of its functional life [23, 37].

In sustainable agriculture, the circular economy is poised to significantly impact [38]. The circular economy facilitates sustainable agricultural practices by allowing the reuse of agricultural waste as a viable resource, manifesting in the form of organic fertilizers or energy sources [38, 39]. In this context, the concept of a circular economy helps to reduce dependence on industrially produced agricultural inputs [40], reduce waste generation, and improve the efficiency of agricultural resources [31, 41]. In addition, this concept encourages farmers and stakeholders in the agricultural sector to re-evaluate and optimize the utility of by-products that may have previously been considered waste. A more prudent management of this aspect can contribute to realizing goals centered around environmentally sustainable agricultural practices [42].

2.2. Eco-enzymes

Eco-enzyme is the fermentation of organic matter, which can be used as an alternative in waste management, especially agricultural waste. Making eco-enzymes generally involves residual organic matter such as fruits, vegetables, and other agricultural waste fermented with sugar and water. This fermentation process results in a liquid rich in beneficial enzymes and microorganisms, which can increase soil fertility, reduce odors, and facilitate waste decomposition [43, 44].

The use of eco-enzymes in agricultural waste management

has many benefits. First, eco-enzymes can help reduce the volume of agricultural waste that often contributes to waste disposal problems. Through the fermentation process, these organic ingredients are reduced in quantity and transformed into more beneficial products. In addition, eco-enzymes can accelerate the decomposition of organic matter in the environment, improving soil quality and reducing the need for chemical fertilizers [43, 44].

Second, eco-enzymes also contribute to the management of food loss. In this context, eco-enzymes can be introduced as a solution to utilize food and agricultural waste that would usually be wasted, thus maximizing the use of available resources and reducing the losses caused by waste. According to Herlina [45], education and socialization regarding the use of eco-enzymes and organic waste management need to be improved to provide understanding to the public about effective ways to recycle waste and reduce environmental pollution resulting [45].

Furthermore, the application of eco-enzymes in agriculture can have a positive impact on environmental sustainability. The use of eco-enzymes helps create more sustainable agricultural practices by reducing reliance on synthesizer-based chemicals, which can often damage ecosystems. In addition, coenzymes can be used to fertilize plants more naturally and safely [44, 46].

In implementing eco-enzymes, strategies involving the community are essential. Education and active participation in the manufacture and use of eco-enzymes can raise awareness of the importance of waste as a valuable resource, as well as encourage better waste management through the 3R (Reduce, Reuse, Recycle) principle [46, 47]. This awareness can be integrated into people's daily practices, encouraging them to not only produce waste but also contribute to its effective management.

Overall, eco-enzymes provide many benefits in agricultural waste management, helping to reduce food loss, convert waste into more valuable products, and support environmental sustainability through more environmentally friendly agricultural practices.

3. Methodology

3.1. Approach Used

This study uses an experimental approach to explore the manufacture of eco-enzymes made from tomatoes, one of the abundant agricultural waste types. Eco-enzymes are fermented products produced from organic waste, such as unused tomato fruits [48]. According to research by Xingzhu [49], eco-enzymes can improve soil fertility and reduce the use of chemical fertilizers, thus contributing to more sustainable agricultural practices. In this experiment, tomatoes unsuitable for sale will be fermented using water and sugar as additives to produce eco-enzymes. This fermentation process is carried out for 3 months and is expected to produce a solution rich in enzymes, organic acids, and other

nutrients that are beneficial to plants.

3.2. Data Collection Techniques

The data collection technique in this study involves experiments and case studies. Manufacturing eco-enzymes from tomato fruit raw materials involves systematic and measurable stages. The process begins with the collection of organic raw materials, especially tomatoes and vegetables, which are mixed with brown sugar or molasses and water with a precise ratio of 1: 3: 10, where one part sugar is mixed with three parts fruit, rest and ten parts water [50, 51]. At this stage, it is essential to choose fresh tomatoes so that the fermentation process can occur properly and produce quality eco-enzymes.

After collecting raw materials, the next stage is the mixing and placement process. This mixture is put in a clean, sealable container but not completely tight so that fermentation can take place optimally. The fermentation process generally takes about 90 to 120 days at the appropriate temperature, and during this time, the mixture needs to be stirred periodically to ensure even distribution [50, 52].

3.3. Data Analysis

3.3.1. PK Content Testing Method in Eco-enzymes

Testing the of NPK (Nitrogen, Phosphorus, and Potassium) within eco-enzymes is imperative for ascertaining their efficacy as fertilizers. The precise quantification of these essential nutrients is instrumental in evaluating the capacity of eco-enzymes to promote plant growth and productivity, akin to conventional fertilizers. An array of methodologies and research endeavors have been undertaken to analyze the NPK content in fertilizers, which can be extrapolated to eco-enzymes to validate their effectiveness. This examination is crucial for refining fertilization methods and improving nutrient utilization efficiency. [53].

3.3.2. PH Measurement

To accurately assess the pH of an eco-enzyme solution using an electrometer, it is essential to understand the fundamental principles governing electrochemical pH measurement, as well as the impact of pH on the bioavailability of soil nutrients and the functionality of microbial communities. The methodology involves diluting the eco-enzyme with water at a 1: 5 ratio to facilitate precise measurements. This dilution is of paramount importance as it serves to stabilize the ionic strength of the solution, an essential factor for accurate pH determination. The pH of a solution can significantly influence the accessibility of nutrients and the metabolic activities of soil microorganisms, thereby affecting the overall health and productivity of the soil ecosystem [54].

3.3.3. Nitrogen Content

Kjeldahl Method with Spectrophotometer: The Kjeldahl method is a thoroughly esteemed and extensively used analytical protocol primarily employed for the accurate determination of nitrogen concentration in various samples. This intricate procedure requires the digestion of the sample in the presence of concentrated sulfuric acid, which effectively facilitates the transformation of nitrogen compounds into ammonium sulfate. This compound is then meticulously quantified using a spectrophotometer, an instrument that measures the intensity of light absorbed by the solution. Ultimately, this sophisticated methodology provides a reliable estimation of the total nitrogen content present within the eco-enzyme, thereby contributing valuable data for further environmental and biochemical analyses [55].

3.3.4. Phosphorus and Potassium Content

Dry Isolation and Digestion with HNO₃: The process of dry ashing, followed by the digestion of the sample using nitric acid (HNO₃), is a widely accepted methodology for accurately determining phosphorus and potassium concentrations within various matrices. Initially, the sample undergoes a smoking procedure at elevated temperatures, which serves the critical function of effectively eliminating organic matter, thereby ensuring that only the inorganic components remain for further analysis. After this, the residual minerals are subjected to dissolution in nitric acid (HNO₃). The quantification of phosphorus and potassium concentrations can be achieved through the application of exact and sophisticated analytical techniques, including but not limited to atomic absorption spectroscopy or inductively coupled plasma analysis (ICP), both of which provide reliable and reproducible results in the context of trace element analysis.[56].

3.4. Data Analysis to Be Carried Out

The data analysis to be carried out includes testing the content of NPK (Nitrogen, Phosphorus, Potassium). These tests are important to determine eco-enzymes' effectiveness in increasing soil fertility and supporting plant growth. The analysis method used is spectrophotometry to measure the concentration of NPK in soil samples. In addition, statistical analysis will be carried out to compare the growth results of plants that are treated with eco-enzymes with those that do not. Research by Hardiyanti [57] shows that increasing NPK content in soil can contribute significantly to plant growth, so the results of this analysis are expected to provide a clear picture of the benefits of eco-enzymes in the context of circular economy and food loss mitigation [58].

4. Esults and Discussion

4.1. Esults of Research Findings

In this study, producing eco-enzymes takes about three

months to produce a liquid, with many advantages [59]. The resulting eco-enzyme liquid has an intense brown color, emits an aroma reminiscent of fermented alcohol, smells good, and has a pH of 3.5. There is a mushroom-like layer on a small part of the surface, but it does not harm its quality, often called Mama Enzyme. The term “Mama Enzyme” refers to the specific layer of fungi involved in the Eco-Enzyme process, highlighting the important role of fungi in biocatalysis and

enzyme production. This layer of fungi occurs occasionally during ecoenzyme production and offers a wide range of applications, such as face masks, wound care, and fever reduction. Next, the eco-enzyme solution undergoes laboratory testing to assess its macronutrient composition. The research physical and chemical attributes of eco-enzymes are presented comprehensively in [58, 60] see Table 1.

Table 1. Eco-Enzyme Macronutrient Content Test.

No.	Parameters	Result of Ecoenzymes Characters (A)	Result of Ecoenzymes Characters (B)
1.	Fermentation Age	5 Months	3 Months
2.	Liquid Color	Strong Brown	Strong Brown
3.	Ph	3, 5	3, 5
4.	Viscosity Level	Not thick	Not thick
5.	The presence of fungi or bacteria	There was not	There was not
6.	Aroma	Smells Good, Alcoholic, typical of fermentation	Slightly Acidic, Alcoholic, typical of fermentation
7.	The Content of		
	Nitrogen/N	0, 53%	0.02 mg/l
	Phosphorus/P ₂ O ₅	1, 43%	0.00025 mg/l
	Potassium/K ₂ O	7, 02%	0.0012 mg/l

The findings derived from the laboratory pH assessment of the eco-enzyme showed a measurement of 3.5. This value is considered appropriate, per the quality standards set out in the eco-enzyme manufacturing module (2011), which confirms that eco-enzyme fermentation is considered optimal when the pH level ≤ 4.0 . The organic acids in the eco-enzyme result from a fermentation process that lasts for three months, which is consistent with the findings. The pH level of the eco-enzyme is anticipated to decrease due to the concentration of organic acids it contains, as noted by the Contents you mentioned indicating the concentration of macronutrients in the eco-enzyme. These elements are essential for the growth and development of organisms, including microorganisms [61, 62].

4.2. Interpretation of Eco-enzyme Test Results

Laboratory test results for eco-enzymes show the following nutrient content: Nitrogen (N) in character (B) shows 0.53%, indicating that eco-enzyme provides moderate Nitrogen. The Nitrogen concentration of 0.02 mg/L is relatively low, indicating that the eco-enzyme provides minimal Nitrogen [63]. This low nitrogen content can be attributed to denitrification and ammonification, which are influenced by anaerobic bac-

teria in producing eco-enzymes. This level can still be used to support the growth of base crops, but it may need to be supplemented with additional nitrogen sources for plants with high nitrogen requirements. Because Nitrogen is an essential nutrient for plant growth, it is mainly responsible for developing leaves and stems. It is a key component of chlorophyll, which is essential for photosynthesis.

Although eco-enzyme nitrogen can contribute to providing nucleic acids and bio-enzymes, its main benefit as an organic fertilizer often lies in reducing dependence on inorganic fertilizers and their potential environmental pollution. Research on eco-enzymes also includes studies of their characteristics and their ability to reduce nitrite levels in the water, although the direct impact on the nitrogen content in the eco-enzyme itself is a different consideration [48, 64, 65]

Phosphorus (P₂O₅) is essential for plant energy transfer, root development, and flowering. It is a component of ATP, which is the cell's energy. The Phosphorus content is 1.43%, indicating that eco-enzymes can effectively support root development and flowering [66]. Phosphorus is important in stimulating early growth and developing an extensive and robust root system, allowing plants to explore more soil for nutrients and moisture [67]. Flowering and Reproduction: Phosphorus is indispensable for flowering, fruit production,

and seed formation, as it is involved in energy transfer and respiration reactions within plants. Although eco-enzymes are often considered organic and environmentally friendly, their phosphorus content directly contributes to the vital functions of these plants, thus benefiting plant productivity [55, 67, 68].

The Potassium (K₂O) content is 7.02%; the content of this magnitude can be said to be relatively high, which shows that the eco-enzyme is very effective in increasing plant resistance and stress tolerance [63]. This high potassium level is beneficial for improving the quality of fruits and vegetables, which [69] directly affects the attributes of fruit and vegetable quality, including taste, firmness, color, and shelf life [70]. This is because potassium is essential for the overall health of plants, improving disease resistance, water regulation, and enzyme activation. It helps in the synthesis of proteins and starches [71]. This makes the plant more resistant to challenging environmental conditions, such as drought or disease.

Increased Productivity: Besides quality, adequate potassium levels contribute to higher yields and overall crop productivity.

Photosynthetic Activity: Research shows that potassium can have a positive impact on photosynthetic activity in plants, such as lemon trees, which further contributes to their growth and strength [72, 73].

4.2.1. Potential Application of Eco-enzymes in Agricultural Waste Management

Eco-enzymes, including those made from organic waste such as tomatoes, show potential as insecticides due to their active compounds. The acetic acid in eco-enzymes can de-destroy harmful organisms, making them suitable as insecticides or pesticides. As an innovative solution in the agricultural and household sectors, it significantly benefits sustainable practices. These enzymes come from the fermentation of organic waste, such as fruits, vegetables, and other organic matter, resulting in a liquid with many uses. According to Hasanah, ecoenzymes have three main functions: increasing agricultural productivity through liquid organic fertilization and pest control, contributing to household hygiene through disinfectants and cleaning agents, and even acting as an alternative to traditional soaps and detergents. This multi-function underscores eco-enzymes’ potential to reduce dependence on synthetic chemicals, encouraging an environmentally friendly approach to agriculture and home care [55, 74, 75].

Creating eco-enzymes addresses waste management challenges by transforming organic waste into valuable products and supporting economic sustainability for farmers

and businesses. Research conducted by Andhini et al. highlights how the 3R (Reduce, Reuse, Recycle) waste management approach can encourage the production of eco-enzymes in cafes, effectively reducing landfill waste while generating additional income through valuable by-products. This shows that farmers and small business owners can use waste streams to create eco-enzymes, improving their economic position and environmental footprint [76].

Furthermore, the integration of eco-enzymes into agricultural practices is closely aligned with the principles of eco-logical sustainability. The bioremediation capabilities of these enzymes can help with soil health and pest control, which promotes a more balanced ecosystem. Barathi et al. discuss the importance of various biological interventions in sustaining eco-agriculture by supporting plant growth and managing environmental stressors [77]. This synergy between eco-enzymes and microbial activity promotes healthier crops while minimizing the adverse effects of conventional agricultural inputs.

In addition to the agricultural benefits, eco-enzymes offer a viable alternative to conventional cleaning products. The transition to environmentally friendly disinfectants helps maintain cleanliness in households and public spaces without contributing to environmental degradation. Ecoenzymes are effective cleaning agents that can replace harsher chemical alternatives, reducing pollution and promoting safer living conditions. This is reinforced by findings that show the positive implications of using environmentally friendly substances for environmental health and sustainability, as discussed by [74].

Developing and utilizing eco-enzymes ultimately presents transformative opportunities for sustainable agricultural practices and environmentally conscious products. By empowering farmers and businesses to turn waste into valuable resources, eco-enzymes contribute to economic sustainability and a healthier planet. The intersection between waste management and organic agriculture related to eco-enzymes illustrates the potential for innovation in achieving environmental goals while supporting the local economy.

4.2.2. Comparative Analysis of the Benefits of Eco-enzymes

The following Table 2, provides a comparative analysis of the economic benefits, environmental impacts, and social benefits of ecoenzymes, supported by insights from relevant research papers.

Table 2. Comparison of Economic Benefits, Environmental Impacts, and Social Benefits of Eco-enzymes.

Economic Benefits	Environmental Impact	Social Benefits
Cost reduction through organic fertilizers	Reduction of greenhouse gas emissions	Empowerment of rural communities

Economic Benefits	Environmental Impact	Social Benefits
New revenue streams through value-added products	Minimizing environmental pollution	Increased knowledge and skills in waste management
Job creation in rural areas	Promotion of sustainable agriculture	Increased participation in sustainable practices
Increased market competitiveness	Contribution to global climate action	Improvement of the socio-economic status of agricultural households

4.2.3. Implications of Eco-enzymes for the Circular Economy

The use of ecoenzymes has a significant impact on advancing the circular economy. By facilitating the recycling of organic waste, eco-enzymes align with circular economy principles, such as waste minimization, resource optimization, and value generation from waste. This section discusses the extensive implications of eco-enzymes for the circular economy, supported by findings from related scientific articles.

1) Waste Reduction and Resource Efficiency

The primary benefit of eco-enzymes in the circular economy is their ability to reduce waste and enhance resource efficiency. The eco-enzyme production process converts organic waste, such as fruit and vegetable residues, into nutrient-dense liquid products, thereby reducing landfill waste and transforming it into a resource beneficial for agriculture, households, and industry [78, 79]. In addition, waste reduction plays a crucial role in reducing environmental pollution. The decomposition of organic waste in landfills produces methane, a potent greenhouse gas; therefore, the conversion of waste into eco-enzymes limits methane emissions, thereby helping to mitigate climate change [79, 80].

2) Creating Value from Waste

Eco-enzymes embody the principle of a circular economy, deriving value from waste. By transforming organic waste into a multifunctional product, eco-enzymes demonstrate the potential to view waste as a resource, rather than a burden. This methodology not only reduces the economic and environmental impacts associated with waste disposal but also fosters new income opportunities for farmers, households, and companies [79, 81]. The diverse applications of eco-enzymes further enhance the potential to generate value from waste. These applications include their role as organic fertilizers, pesticides, household cleaning agents, and industrial bioproducts, highlighting the significant contribution of eco-enzymes across various sectors in the circular economy [79, 82, 83].

3) Promotion of Sustainable Agriculture

The application of eco-enzymes promotes sustainable agriculture, a key component of the circular economy. By minimizing chemical inputs, eco-enzymes improve soil health, biodiversity, and ecosystem services. This methodol-

ogy not only increases agricultural productivity but also ensures the long-lasting sustainability of agricultural systems [83, 84]. Additionally, the integration of eco-enzymes aligns with growing consumer demand for organic and sustainably produced agricultural products. Farmers who use environmental enzymes can differentiate themselves as environmentally conscious producers, attracting environmentally conscious consumers and premium markets [85, 86].

4) Empowering Rural Communities

The cultivation and application of eco-enzymes promises to empower rural communities, especially in developing areas. By offering training and capacity-building initiatives, the program can equip farmers and households with the skills necessary for producing and applying eco-enzymes. This process not only supports technical expertise but also fosters ownership and engagement in sustainable development [87, 88]. The empowerment of rural communities is also facilitated by the formation of new income streams through the production of eco-enzymes. It can improve the socio-economic status of agricultural households and advance rural development. For example, in Indonesia, community service initiatives have enabled women to produce ecoenzymes from household waste, thereby promoting environmental sustainability and economic empowerment [87, 89].

5) Contribution to Global Climate Action

Eco-enzymes contribute to global climate action by reducing greenhouse gas emissions and minimizing the impact of waste. Their production process produces ozone, increasing the sustainability of the atmosphere [79]. Additionally, eco-enzymes significantly reduce methane emissions from the decomposition of organic waste in landfills, aligning with global climate change initiatives and the Paris Agreement [79, 80].

6) Policy and Institutional Support for the Circular Economy

Recognizing the potential of ecoenzymes for a circular economy necessitates robust policies and institutional support. Governments and organizations are crucial in encouraging eco-enzyme production through training, financial incentives, and market initiatives, as demonstrated in Indonesia [85, 89]. Furthermore, incorporating eco-enzymes into waste management and sustainable agriculture policies can facilitate their adoption, supported by safety and efficacy stand-

ards [85, 86].

7) Challenges and Limitations

Despite the significant potential of ecoenzymes, various challenges and limitations must be overcome. The primary issue is the limited awareness and knowledge among farmers regarding the production and application of ecoenzymes, which hinders their widespread adoption [78, 90]. In addition, the need for specific inputs, such as sugar and water, is a barrier for some farmers; However, alternative substrates, such as molasses, have been identified to reduce costs and improve accessibility [91, 92].

5. Conclusions and Suggestions

5.1. Conclusion

This study confirms that utilizing eco-enzymes derived from agricultural waste, particularly from tomatoes that are unsuitable for sale, is an innovative and sustainable approach to managing organic waste. The fermentation results indicate that eco-enzymes contain essential nutrients, including nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O), at varying levels, making a significant contribution to soil fertility and plant growth. In addition, the acidic properties (pH 3.5) and distinctive fermentation aroma indicate an optimal decomposition process.

Eco-enzymes not only function as liquid organic fertilizers but also have the potential to be natural insecticides, disinfectants, and environmentally friendly household products. This approach directly contributes to reducing food loss, supports circular economy principles, and increases the economic value of previously untapped waste. These findings strengthen the eco-enzymes' position as a multifunctional solution in sustainable agricultural systems, transforming waste management towards a more responsible production and consumption paradigm.

5.2. Suggestions and Directions for Further Research Development

5.2.1. Increased Nutrient Content

To improve nutritional quality, especially for plants with high nitrogen requirements, an eco-enzyme formula with nitrogen-rich additives and nitrogen-fixing microorganisms needs to be developed.

5.2.2. Field-scale Effectiveness Tests

To test the effectiveness of eco-enzymes practically and holistically, including their effect on productivity and crop quality, follow-up experiments on agricultural land with various types of crops and agroclimatic conditions are necessary.

5.2.3. Economic Studies and Business Models

Further research can explore eco-enzyme-based business models that are feasible for farmers and MSME actors, including their marketing potential, partnership schemes, and integration into the green supply chain.

5.2.4. Integration of Digital Technology and IoT

The development of digital tools or applications for real-time fermentation monitoring and standardization of eco-enzyme quality will drive systematic replication and production scalability.

5.2.5. Participatory and Educational Social Approach

Engaging local communities in the participatory production and utilization of eco-enzymes can expand the social impact and build collective awareness about sustainable waste management at the grassroots level.

Abbreviations

CE	Circular Economy
NPK	Nitrogen, Phosphorus, and Potassium
FAO	Food and Agriculture Organization
ICP	Inductively Coupled Plasma
MSME	Micro, Small, and Medium Enterprises
3R	Reduce, Reuse, Recycle
POC	Liquid Organic Fertilizer

Conflicts of Interest

The authors declare no conflicts of interest.

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