Iran Agricultural Research (2025) 44(2) 62-78

Shiraz University

Iran Agricultural Research

Journal homepage: https://iar.shirazu.ac.ir/?lang=en

Review Article

Eco-enzymes: A sustainable solution for waste management and agricultural applications

Shno Karimi[a], **Maryam Haghighi**[b*], **Mehdi Sharifani**[b]

[a] Department of Soil Science, College of Agriculture, Isfahan University of Technology, I. R. Iran
[b] Department of Horticulture, College of Agriculture, Isfahan University of Technology, I. R. Iran

ARTICLE INFO

Keywords:
Eco-enzyme
Environmental pollution
Organic waste
Waste management

Received: 16 March 2025
Revised: 13 July 2025
Accepted: 16 July 2025

ABSTRACT- Organic waste is an attractive resource because of its potential to be converted into valuable commodities. It is primarily composed of food scraps, fruit remnants, and other biodegradable materials. When managed properly, composting this waste produces nutrient-rich soil, offering an environmentally friendly approach to waste management while also reducing greenhouse gas emissions. Beyond composting, organic waste can be utilized in other sustainable ways. One option is energy generation through anaerobic digestion, while another is the production of eco-enzymes, an economical and eco-friendly alternative. Eco-enzymes have diverse applications, including use as organic fertilizers, disinfectants, and cleaning agents. Their production process is straightforward, requiring only a carbon source such as sugar or molasses, water, and organic waste. This simple yet effective approach supports a circular economy by reducing the accumulation of organic waste and making use of readily available resources. The development of eco-enzymes represents an important step toward a more sustainable future. By reducing the volume of waste sent to landfills and providing a safe, non-toxic substitute for harmful chemicals, eco-enzymes foster a balance between economic progress and environmental preservation. This article examines the potential of eco-enzymes as a sustainable resource for both agriculture and waste management. Produced through a natural fermentation process, eco-enzymes offer an environmentally friendly alternative to traditional chemical fertilizers and conventional waste disposal methods.

INTRODUCTION

Global economic growth and rising food consumption have significantly increased the generation of organic waste, largely driven by the intensification of agricultural production systems. Agricultural waste encompasses crop residues, animal manure, and byproducts from agro-industrial processes. Globally, approximately 998 million tons of agricultural waste are produced each year, with Asia contributing the largest share due to its highly intensive farming practices (FAO, 2023a; FAO, 2023b). In the United States, agricultural activities generate more than 400 million tons of waste annually, primarily from corn and wheat cultivation (EPA, 2021). In Europe, agricultural systems produce around 700 kilograms of waste per hectare, with cereal straws and sugar beet residues being the most prominent contributors (Eurostat, 2022). In contrast, much of Sub-Saharan Africa's agricultural waste remains underutilized, primarily due to a lack of adequate infrastructure (UNEP, 2022).

ENVIRONMENTAL IMPACT

Unmanaged agricultural waste is a major contributor to greenhouse gas emissions, particularly methane and nitrous oxide, which together account for about 10% of total anthropogenic emissions worldwide (Jamali et al., 2025; IPCC, 2021). Beyond atmospheric impacts, improper disposal of agricultural residues can lead to soil and water contamination through nutrient leaching and pesticide runoff (FAO, 2022; Karimi et al., 2025). At the same time, bio-waste is increasingly recognized as a valuable resource for improving soil health, especially in low- and middle-income countries where soil degradation threatens agricultural productivity. Effective management of organic waste, including bio-waste, is therefore essential not only for maintaining soil fertility but also for promoting sustainable agricultural practices and mitigating the environmental consequences of waste accumulation (Karimi et al., 2024; Roulia, 2024).

*Corresponding Author: Associate professor, Department of Horticultural, College of Agriculture, Isfahan University of Technology, I.R. Iran
E-mail address: mhaghighi@cc.iut.ac.ir
DOI: 10.22099/iar.2025.52732.1679

CHALLENGES AND GAPS IN AGRICULTURAL WASTE MANAGEMENT

Improper waste disposal, particularly food waste, has emerged as a major global environmental concern. Each year, nearly one-third of all food produced worldwide, about 1.3 billion tons, is wasted (FAO, 2020). This loss not only reduces food availability but also represents a significant waste of resources such as water and agricultural land. Globally, food waste accounts for nearly 25% of freshwater consumption and occupies 28% of the world's agricultural land (Jamali et al., 2025; Kummu et al., 2012). The rising demand for food has further intensified the volume of waste generated. Despite these challenges, food waste can serve as a valuable resource. Through composting, it can be converted into organic fertilizers or feedstock, thereby reducing reliance on chemical fertilizers and mitigating the environmental impacts of conventional waste disposal. Moreover, food waste can be reused to produce eco-enzymes via fermentation, a process that also generates biogas for renewable energy production. In this context, eco-enzymes refer to enzymes produced during the fermentation of food waste, offering multiple applications in agriculture and environmental management. This innovative approach not only addresses waste management challenges but also supports sustainable practices in both agriculture and energy systems.

Infrastructural limitations

Developing Nations: Many developing countries face significant challenges in managing organic waste due to the inadequate infrastructure for collection, transportation, and processing. As a result, open dumping and uncontrolled burning are common practices, leading to serious environmental and public health risks (UNEP, 2022). Limited access to modern composting technologies, such as mechanized systems and advanced bioreactors, further constrains the capacity to process large volumes of organic waste and produce high-quality compost (UNEP, 2022). In addition, the absence of effective waste separation systems at the source makes it difficult to isolate organic matter from other waste streams, thereby hindering efficient composting.

High Costs: The establishment of biorefineries for advanced waste utilization remains economically unfeasible in many low-income regions (IEA, 2023). Technologies such as anaerobic digestion and gasification require substantial upfront investment, which poses a major barrier for both low-income regions and small-scale producers. In addition to high capital requirements, ongoing operational expenses, including energy consumption, labor, and maintenance, further increase financial burdens. These costs often make it difficult for small-scale composting and waste management operations to achieve long-term economic viability.

Policy and regulation

In many regions, policy-related barriers hinder the adoption of sustainable waste management practices. For example, subsidies for chemical fertilizers often make compost less economically attractive to farmers, reducing its adoption (FAO, 2022). In addition, the absence of clear regulations governing composting and other waste management practices can result in inconsistent implementation and weak enforcement of environmental standards. Furthermore, government support for the composting industry—through grants, loans, or tax incentives—remains insufficient in several countries, limiting the sector's ability to expand and compete with conventional inputs (FAO, 2022).

Climate change effects

Rising global temperatures accelerate the decomposition of organic matter but can also intensify nutrient losses, thereby reducing the efficiency of microbial degradation processes (IPCC, 2021). Climate change disrupts the delicate balance of microbial communities involved in composting. Shifts in temperature, moisture availability, and oxygen levels may negatively affect microbial activity, ultimately hindering efficient organic matter decomposition (IPCC, 2021).

UTILIZATION METHODS FOR AGRICULTURAL WASTE

Current waste management strategies, which largely focus on collection and disposal, have not sufficiently addressed the ecological challenges associated with agricultural waste (Babazadeh et al., 2020). Innovative approaches are needed to transform bio-waste into valuable resources, particularly for agricultural applications (Mazhandu et al., 2020). Sustainable practices and creative solutions can support more effective and environmentally sound waste management systems (Kominko et al., 2024; Sindhu et al., 2019). Despite challenges such as the bulkiness and unpleasant odor of organic waste, converting it into organic fertilizers offers an efficient solution. Successful conversion depends on adequate organic substrates, the presence of decomposers, and favorable environmental conditions that promote waste transformation into compost or vermicompost (Karimi et al., 2024). Composting, in particular, is widely recognized as one of the most effective methods for managing organic waste, providing both environmental and economic benefits (Roulia, 2024). As illustrated in Fig. 1, the excessive use of chemical fertilizers highlights the urgent need to prioritize sustainable waste management practices. Integrating organic waste recycling into agricultural systems supports the principles of a circular economy, improves soil fertility, and reduces dependence on chemical fertilizers (Oriekhoe et al., 2024; Mapanda et al., 2012).

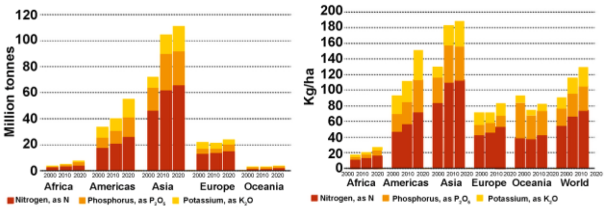

Fig. 1. Inorganic fertilizer use per cropland area by nutrient and region (Rochyani et al., 2020).

Conventional practices

Composting: Composting is one of the most widely used waste management techniques for recovering nutrients from household and agricultural organic waste. Through biological decomposition, organic matter is transformed into nutrient-rich soil amendments. Recognized as a cornerstone of environmentally friendly waste management, composting plays a vital role in advancing sustainable practices (FAO, 2022). Composting methods can be classified into three types, i.e., aerobic, anaerobic, and vermicomposting, depending on the microbial processes involved (Sharma et al., 2023). Globally, an estimated 2 billion tons of organic waste are generated annually, yet only about 25% is composted (Bank, 2022). Europe leads in compost production with over 37 million tons annually, followed by Asia with 30 million tons (Eurostat, 2022). Compost is primarily applied in agriculture (65%), horticulture (20%), and urban landscaping (15%) (EPA, 2021). In regions such as Europe and North America, composting facilities manage over 40% of agricultural waste, making it a key strategy for nutrient recycling (EPA, 2021). Alongside composting, organic household waste can also be processed into eco-enzymes through fermentation of fruit and vegetable residues, thereby reducing waste generation at the source (Benny et al., 2023). Eco-enzymes provide a sustainable and low-cost alternative to composting, offering additional benefits such as reduced environmental impacts and broader applications in agriculture and household use. Unlike composting, eco-enzyme production does not require large land areas or specialized infrastructure; a simple plastic container with a tight lid is sufficient for the fermentation process (Muliarta and Darmawan, 2021). Scaling up eco-enzyme production, which includes ensuring continuous, rapid, and low-cost yields, is particularly important for addressing the growing volumes of industrial organic waste. By complementing composting practices, eco-enzymes contribute to more sustainable waste management systems while promoting circular economy principles.

Ingredients in composting

Crop Residues: These include materials such as wheat straw, rice husks, and corn stover, which constitute approximately 40% of global compost feedstocks (Zhang et al., 2021). Rich in carbon, these materials serve as an energy source for decomposing microorganisms.

Food Waste: Comprising roughly 30% of inputs, especially in urban composting systems, food waste is a significant component (Chen et al., 2022). Rich in nitrogen, food scraps offer vital nutrients that support microbial growth.

Animal Manure: Widely used, particularly in rural areas, animal manure is a valuable source of nitrogen, phosphorus, and potassium. It is often incorporated into compost to enhance nutrient content (FAO, 2023a).

Optimization of ingredients

The ideal C:N ratio is crucial for efficient composting. Materials with high C:N ratios, such as straw, should be balanced with materials low in C: N, like food scraps, to promote optimal decomposition. The optimal C: N ratio for composting ranges from 25:1 to 30:1, which ensures effective microbial activity and proper odor control (Sharma et al., 2023).

EFFECTIVENESS AND CHALLENGES IN COMPOSTING

By redirecting organic waste from landfills, composting greatly reduces the amount of material that would otherwise be discarded. Studies conducted in Europe have demonstrated a 40% reduction in landfill reliance through effective composting programs (Eurostat, 2022). This not only helps conserve valuable landfill space but also reduces the environmental impact of landfill operations, such as methane emissions. Composting is also essential for reducing greenhouse gas emissions. Methane is a powerful greenhouse gas that is produced in large quantities during the breakdown of organic waste in landfills. Composting facilities are a great way to reduce methane emissions from organic waste. Studies from Europe show that composting initiatives can lead to a 20% reduction in greenhouse gas emissions (Eurostat, 2022). Compost enriches soil by improving its structure, boosting water retention, and enhancing nutrient availability. This results in healthier plant growth, higher crop yields, and a reduced need for synthetic fertilizers. Through composting, organic waste is converted into a valuable resource. The resulting compost can be used as a soil amendment in agriculture, horticulture, and landscaping, fostering sustainable practices and decreasing the demand for synthetic fertilizers (Karimi et al., 2024).

Challenges

While composting offers numerous advantages, several challenges hinder its widespread implementation and effectiveness:

Inconsistent feedstock quality: Variations in the composition of organic waste pose a significant challenge. Fluctuations in moisture content, carbon-to-nitrogen ratios, and the presence of contaminants can negatively impact the composting process. This inconsistency can lead to variable compost quality, hindering its effectiveness as a soil amendment and potentially creating issues such as odor problems or incomplete decomposition (UNEP, 2022).

Infrastructure gaps: In many developing countries, inadequate infrastructure remains a major barrier to widespread composting. The lack of centralized composting facilities, limited access to collection and transportation services, and insufficient investment in composting technologies hinder the development of effective composting programs (Bank, 2022). Establishing viable markets for compost is crucial for the economic sustainability of composting programs. Identifying consistent buyers for compost and developing effective distribution channels can be challenging (Bank, 2022). Raising public awareness about the benefits of composting and encouraging active participation is essential. This involves educating the public on proper composting techniques, promoting the use of compost, and addressing potential concerns regarding odor and aesthetics (Bank, 2022).

FUTURE DIRECTIONS

Innovations in composting

The integration of internet of things (IoT)technologies for real-time monitoring of composting parameters is gaining increasing attention (Chen et al., 2022). Implementing measures to ensure consistent feedstock quality, such as source separation programs, food waste reduction initiatives, and on-site feedstock analysis, is crucial (Chen et al., 2022). Investing in the development of centralized composting facilities, improving collection and transportation infrastructure, and promoting the use of decentralized composting technologies can enhance accessibility. Supporting the development of local and regional markets for compost, exploring innovative marketing strategies, and promoting the use of compost in public spaces can increase demand (Chen et al., 2023).

Policy and education

Raising public awareness and providing subsidies for composting can help increase adoption, particularly in low-income regions (FAO, 2023a). Implementing comprehensive public awareness campaigns, providing educational resources, and organizing community composting initiatives can encourage public participation and promote the benefits of composting.

Emerging technologies

Bioenergy Production: The conversion of agricultural waste into biogas and bioethanol has gained significant momentum, helping to reduce dependence on fossil fuels (IEA, 2023). Harnessing the energy potential of agricultural waste can significantly reduce reliance on fossil fuels such as coal and oil. This shift towards renewable energy sources is essential for combating climate change and ensuring long-term energy security (IEA, 2023).

Main text

Eco-enzymes: Agricultural residues like fruit peels and vegetable scraps are increasingly used to produce eco-enzymes, enhancing waste valorization (Chen et al., 2022). An effective approach to reducing organic waste involves using fruit peels and vegetable scraps to produce eco-enzymes. These eco-enzymes are complex organic liquids that contain a variety of organic enzymes and acids. In a recent study by Selvakumar and Sivashanmugam (2017), eco-enzymes made from a blend of papaya, dragon fruit, and orange peel waste were utilized to lower total suspended solids (TSS) levels and investigate their potential as antibacterial agents (Arun and Sivashanmugam, 2017). This research highlights the versatility and environmental benefits of utilizing eco-enzymes in waste management practices. Eco-enzymes offer a sustainable alternative to typical waste treatment approaches (Arun and Sivashanmugam, 2015a). Fermentation of organic waste, such as fruit and vegetable scraps, creates enzymes, unlike composting. This approach lowers trash at its source and has several environmental advantages (Verma et al., 2019). Eco-enzymes are simple to make, requiring only a plastic container and a fermentation solution. The final products, a suspended residue and a fermented liquid, have a variety of uses (Muliarta and Darmawan, 2021). The residue may be utilized as organic fertilizer, and the liquid can be used to clean, disinfect, as an insecticide, or improve air and water quality (Fadlilla et al., 2023). Eco-enzymes have various benefits over composting. They are created rapidly, cheaply, and take up little space. Furthermore, eco-enzymes have the ability to dissolve insoluble chemical compounds and serve as antifungal, antibacterial, and insecticidal agents (Arun and Sivashanmugam, 2015b). The acidic nature of eco-enzymes also contributes to an unfavorable environment for viruses. The creation of eco-enzymes is a big step toward a more sustainable future. Eco-enzymes help reduce landfill waste and provide a natural alternative to toxic chemicals, promoting a healthy balance between industrial advancement and ecological well-being (Arun and Sivashanmugam, 2015b).

The importance of research

On a global scale, the incorrect handling of food waste is a major environmental problem. The fact that over one-third of all produced food goes to waste exacerbates the loss of food and the resources necessary to generate it. The increasing demand for food has exacerbated this problem. Arun and Sivashanmugam (2018) state that fruit juice companies produce a substantial quantity of wasted fruit. It may be energy- and money-intensive to dispose of this garbage. The creation of eco-enzymes shows promise as a remedy for this issue. Nevertheless, there are ways to turn food scraps into something useful. Composting food scraps can yield organic fertilizers and agricultural feedstock. Also, eco-enzymes made from food scraps may make biogas, which can power homes and businesses. Eco-enzymes are fermented organic solutions that are complicated. Arun and Sivashanmugam (2015b) state that they include a variety of organic acids and enzymes that have numerous uses. Using a wide variety of food scraps, including pineapple, orange, mango, tomato, and cabbage, Arun and Sivashanmugam (2018) created eco-enzymes. Additionally, Mavani et al. (2020) showed that eco-enzymes may be made from waste materials such as pineapple hump, orange peel, and papaya peel. Furthermore, eco-enzyme materials derived from fruit peel waste have shown efficacy. The results show that eco-enzymes have enzyme functions such as amylase, lipase, cellulase, and protease in addition to organic acids like lactate, malate, oxalate, acetate, and citric acid. Because of these components, eco-enzymes have antimicrobial and antifungal characteristics, as well as being useful as cleaning agents and waste processing agents (Arun and Sivashanmugam, 2017). Selvakumar and Sivashanmugam (2017) used eco-enzymes, made from a combination of pomegranate, orange and pineapple peels, to lower total suspended solids levels and investigate their antibacterial potential. This study emphasizes the many uses and positive effects of eco-enzymes in waste management. The study demonstrated that eco-enzyme application resulted in a substantial increase in the levels of essential macronutrients accessible to the plants.

Eco-enzyme production

Eco-enzyme, also known as garbage enzyme, is a multi-functional organic solution produced through the fermentation of organic waste. The typical process involves a 1:3:10 ratio of sugar, organic waste, and water, fermented over three months (Zhang et al., 2021). Eco-enzymes, first formulated by Dr. Rasukan Poompanvong of Thailand, are versatile condensed substances formed by fermenting waste or organic matter, brown sugar or granulated sugar, and water. These enzymes have significant global environmental and economic impacts. The release of methane gas during the fermentation process contributes to the reduction of greenhouse gases and heavy metals in the environment. In addition, the production of nitrate (NO_3) and carbonate (CO_3) gases is crucial in providing vital nutrients for plants in the soil. Time, temperature, pH, carbon and nitrogen supplies, and other variables all affect eco-enzyme fermentation (Hasanah, 2020). Eco-enzymes are typically created by combining sugar, fruit waste, and water. Kitchen waste, particularly vegetable and fruit peels rich in organic acids, is commonly used in the production of these enzymes. Orange and tomato peels are especially good sources of eco-enzymes with bactericidal qualities, which are useful for cleaning aquaculture sludge to increase aerobic digestion and address environmental concerns (Rasit et al., 2019). The final products of eco-enzyme fermentation are suspended residue and a liquid solution. The residue can be used as organic fertilizer, containing essential nutrients like NO_3 and CO_3, while the liquid product finds applications as a disinfectant, insecticide, air and water enhancer, and cleaning agent (Fadlilla et al., 2023). Furthermore, eco-enzymes disrupt environmental health by generating methane gas during fermentation. The enzymes produced, such as protease, amylase, and lipase, efficiently break down proteins, carbohydrates, and fats, making them suitable for applications like waste degradation and pathogen control (Manea et al., 2024). Studies have shown that the optimal pH for enzymatic activity lies between 6.5 and 7.5, which ensures effective organic waste breakdown (Arun and Sivashanmugam, 2017). These eco-enzymes are less expensive than conventional disinfectants while still providing outstanding disinfectant characteristics.

Global statistics

The production of eco-enzymes has been recorded in over 30 countries, including Thailand, India, and Malaysia, which are pioneers in its domestic and industrial applications (FAO, 2021). According to a study by FAO (2021), it is estimated that 1.3 billion tons of organic waste are produced globally each year, presenting significant potential for eco-enzyme synthesis (FAO, 2021). Asia, contributing to over 60% of organic waste globally, leads eco-enzyme production initiatives, followed by Africa and Europe (FAO, 2021). Eco-enzymes derived from citrus peels can promote plant growth and help mitigate the effects of metal-based effluents, organic waste, and heavy metals resulting from industrial processes (Vama and Cherekar, 2020). Furthermore, Hemalatha and Visantini (2020) suggest using eco-enzymes derived from different citrus peels to clean wastewater in rivers, thereby reducing pollution and improving water quality. In recent years, eco-enzymes have gained significant attention for their ability to treat various wastewater streams, including greywater, residential wastewater, food waste, dairy waste-activated sludge, and landfill leachate.

Progress in research and development

Studies by Zhang et al. (2021) highlight the optimization of fermentation conditions, such as temperature and pH, to enhance enzyme yield (Zhang et al., 2021). Innovations include the use of microbial inoculants to accelerate fermentation and increase the spectrum of enzymatic activity (Chen et al., 2022). The development of eco-enzymes not only reduces landfill waste but also serves as a natural alternative to synthetic chemicals detrimental to human health and the environment. Given the growing emphasis on sustainable technology, eco-enzymes provide a promising solution for integrating industrial progress with ecological preservation. Production involves cultivating enzymes in controlled environments using natural substrates like molasses, enhancing their biocatalytic efficacy (Patil et al., 2023). By reducing the need for conventional, energy-intensive waste management methods, eco-enzymes exemplify a sustainable innovation, addressing global challenges like resource depletion and environmental degradation (Das et al., 2024; Villalba et al., 2020).

Environmental and economic benefits

Quantitative reduction in organic waste diverted from landfills has been demonstrated in Malaysia, with eco-enzyme applications reducing landfill dependency by 25% (Das et al., 2021). Cost-benefit analyses indicate that eco-enzyme production could reduce waste management costs by 30% compared to traditional methods. The environmental benefits of eco-enzymes are significant. A study by Das et al. (2021) highlighted that the adoption of eco-enzyme technology could reduce landfill waste by approximately 30%, decreasing greenhouse gas emissions by over 25% compared to traditional waste management methods. Furthermore, food waste represents 8-10% of global greenhouse gas emissions, with eco-enzyme solutions presenting a viable method to mitigate these emissions (IPCC, 2022). The production of eco-enzymes, which requires low-cost raw materials such as molasses or brown sugar, enhances its accessibility and scalability for communities worldwide (Mandal et al., 2024). In addition to environmental advantages, eco-enzymes reduce reliance on synthetic chemicals that contribute to soil and water contamination (Das et al., 2024). For example, industrial cleaning solutions replaced by eco-enzymes have reduced chemical runoff by up to 40% in pilot projects (Prihanto et al., 2024). Economically, eco-enzyme production represents a cost-effective strategy. Studies report that the production cost of eco-enzymes is 50-70% lower than that of conventional chemical cleaning agents (Wikaningrum et al., 2022). The integration of eco-enzymes into waste management systems has proven successful in regions like Southeast Asia, where community-driven initiatives have demonstrated a 15% reduction in municipal solid waste through eco-enzyme adoption (Yang et al., 2024). Furthermore, large-scale industrial applications have shown potential to process over 500 tons of organic waste annually, reducing operational costs for waste treatment plants by 20% (Villalba et al., 2020). Nazim and Meera (2017) were pioneers in utilizing waste enzymes extracted from vegetable and fruit peels to treat synthetic greywater. Their study, which examined concentrations ranging from 5% to

50%, revealed that a 10% concentration of eco-enzyme was most effective in reducing nutrients, biochemical oxygen demand (BOD), and chemical oxygen demand (COD). However, one weakness of their study was the lack of characterization of the individual enzyme contents. Building on this work, Arun and Sivashanmugam (2015) created trash enzymes from pineapple and orange peels, effectively optimizing the activity of amylase, lipase, and protease within these enzymes. They then used these enzymes to remediate waste activated sludge. Eco-enzymes may help minimize contaminants and improve overall water quality (Nalladiyil et al., 2023). Duran and Esposito (2000) did a thorough study of phenol oxidases like laccase and oxidative enzymes from bacteria, fungi, and plants, as well as how they can be used to clean wastewater. Furthermore, pancreatic lipase was shown to be efficient in hydrolyzing and reducing the size of fat particles in slaughterhouse effluent (Masse et al., 2001). Extracellular enzymes, sometimes known as “garbage enzymes” (eco-enzyme), might serve as potential biological catalysts to solve the limits of traditional wastewater treatment systems, especially in the pretreatment phase (Joseph et al., 2021). Based on the search method used in this paper, two studies have looked into how eco-enzymes made through fermentation can be used to clean up wastewater (Rasit and Mohammad, 2018; Nazim and Meera, 2013). Table 1 describes the most major applications of eco-enzymes. The application of eco-enzymes to plants can result in a 7.82% increase in soil pH, a 1.82% boost in nitrogen absorption, a 7.33% rise in leaf count, a 1.47% increase in fresh weight, and a 1.64% increase in dry weight. Its application may also raise the pH of the soil by 1.94%, boost the number of leaves by 15.33%, increase the fresh weight by 23.15%, improve the dry weight by 2.39%, and increase the absorption of nitrogen by 9.87%. Fresh weight may increase by 23.37%, dry weight by 4.86%, nitrogen absorption by 23.57%, soil pH by 10.02%, and leaf count by 37.52% when the concentration and application technique of liquid organic fertilizer are combined. A 1:1 ratio of watering to spraying, or 75 mL of eco-enzyme combined with 25 mL of water, is the ideal treatment combination (Rasit and Mohammad, 2018).

Eco-enzyme uses

Applications in daily life

Eco-enzymes are widely used as cleaning agents due to their antibacterial properties (Chaudhary et al., 2022). In wastewater treatment, they degrade organic pollutants, reducing BOD and COD levels by up to 80% (Zhou et al., 2022). The production of eco-enzymes has a positive impact on the world economy and ecology (Hasanah, 2020). Environmentally, the fermentation process emits ozone gas (O_3), which helps to mitigate greenhouse gases and heavy metals in the atmosphere. Furthermore, eco-enzymes generate emission gases such as NO_3 and CO_3, which are vital nutrients for plants and soil. From an economic standpoint, eco-enzymes seem to be very adaptable as multifunctional cleansers, plant fertilizers, and insect repellents, therefore showcasing their considerable potential for many commercial applications. The several advantages and uses of eco-enzymes across a range of sectors have been investigated (Vama and Cherekar, 2020; Hemalatha and Visantini, 2020). The acidic properties of eco-enzymes enable the efficient separation of extracellular enzymes from organic wastes during fermentation, therefore aiding in the mitigation or total elimination of infections. Acetobacter bacteria catalyze the breakdown of glucose into pyruvic acid, which subsequently transforms into ethanol and acetic acid. This process significantly improves the antibacterial characteristics of eco-enzymes.

Role in environmental sustainability

The use of eco-enzymes in municipal solid waste management has reduced landfill dependency by 25% in countries like Thailand (Noviana et al., 2024). Reduction in greenhouse gas emissions from organic waste decomposition is another critical benefit (FAO, 2022). Eco-enzymes include a variety of active enzymes and secondary metabolites that demonstrate a wide array of uses, such as ecological remediation, aromatherapy, mitigation of environmental toxicity in agriculture, and functioning as liquid plant fertilizers. The use of eco-enzymes blended with water as organic fertilizers for plants has shown beneficial outcomes on plant development. The observed enhancements in height, stem diameter, leaf breadth, and color vibrancy in chili plants, compared to those without eco-enzyme fertilizer, support this (Ramadani et al., 2022).

Table 1. Applications and uses of eco-enzyme area of activity applications usage

Area of Activity	Application	Usage
Household	Household cleaner, detergent, body care, natural liquid soap	Eliminate impurities on surfaces, providing a non-toxic cleaning alternative (Wen et al., 2021)
	Air purification	Removes odors and dissolved toxic substances, improving indoor air quality (Salvi, 2024)
	Food preservation	Prevents the growth of microorganisms, extending shelf life of foods by up to 30% (Galintin et al., 2021)
Environmental	Insecticide, organic fertilizer, and pesticides	Keeps farms free from insects and infections, promoting sustainable agriculture (Hemalatha and Visantini, 2020)
		Increases crop yields by 20-30% without chemical pollution (Ratiani et al., 2024)
Treatment	Catalyst	Decomposes, composes, and transforms organic matter, enhancing composting efficiency (Wijaya and Laila, 2024)
		Speeds up reactions within treatment processes, reducing treatment time by 50% (Hemalatha and Visantini, 2020)
	Absorbent	Absorbs pollutants from polluted water, effectively reducing BOD and COD levels (Salvi, 2024)

Advanced applications

The development of eco-enzymes not only reduces landfill waste but also serves as a natural alternative to synthetic chemicals detrimental to human health and the environment. Given the growing emphasis on sustainable technology, eco-enzymes provide a promising solution for integrating industrial progress with ecological preservation. Production involves cultivating enzymes in controlled environments using natural substrates like molasses, enhancing their biocatalytic efficacy (Patil et al., 2023). By reducing the need for conventional, energy-intensive waste management methods, eco-enzymes exemplify a sustainable innovation, addressing global challenges like resource depletion and environmental degradation (Das et al., 2024; Villalba et al., 2020). Eco-enzymes have been applied in biogas production, enhancing methane yield by 15-20% (Natasya et al., 2023). In textile industries, eco-enzymes aid in reducing dye toxicity during wastewater treatment (Sharma et al., 2023). Table 1 shows applications and uses of eco-enzyme area, usage in households as a household cleaner, detergent, body care, and natural liquid soap that eliminates impurities on the surface. It assists in air purification, removes odor and dissolves toxic air. It acts as a food preservation, prevents the growth of microorganisms to preserve foods, serves as an environmental insecticide, organic fertilizer and pesticide. It keeps farms free from insects and infections, increases crop yields, acts as a catalyst, and transforms organic matter. It speeds up reactions within the treatment absorbent and facilitates the absorption of pollutants from polluted water.

Role of microorganisms in agricultural waste management

Microbial decomposition

Microbial consortia, comprising bacteria and fungi, are essential in breaking down complex organic matter. Trichoderma species and *Bacillus subtilis* are commonly employed to accelerate decomposition (Sharma et al., 2023). *Firmicutes*, *Proteobacteria*, *Actinobacteriota*, and *Cyanobacteria* were the four dominant phyla that made up the majority of the initial bacterial community in the composting of tomato straw organic waste. These four phyla together accounted for almost 98% of the overall bacterial abundance. The breakdown of organic waste was significantly aided by the large relative abundance of lignocellulolytic-capable *Firmicutes* and *Actinobacteriota* (Qi et al., 2021; Hu et al., 2019), which likely contributed to the observed decrease in pH during the early stages of fertilization (Xu et al., 2021). Notably, *Firmicutes* exhibit a high degree of resilience to adverse environmental conditions, enhancing their ability to facilitate compost decomposition even under challenging circumstances (Hartmann et al., 2014). Proteobacteria play a crucial role in lignin degradation and nitrogen fixation (Takaku et al., 2006), primarily driving the breakdown of organic matter such as proteins and starches during the early stages of composting.

Bioaugmentation

Studies show that introducing microbial inoculants to composting systems enhances nutrient availability and reduces harmful pathogens (Chen et al., 2023). Inoculating exogenous microbial agents can boost the population and activity of functional microorganisms, thereby accelerating the biodegradation of organic pollutants, aiding nutrient recycling, and enhancing the humification process during composting (Gou et al., 2017). For example, the addition of 0.5% *Bacillus subtilis* reduced the relative abundances (RAs) of antibiotic resistance genes (ARGs), mobile genetic elements (MGEs), and pathogens during composting (Duan et al., 2019). It has been shown that inoculated composts improve nitrogen storage by promoting the succession of microbial communities (Yang et al., 2018; Mao et al., 2018). A two-stage inoculation procedure increased the amount of total nutrients and humic substances (HS) by 5.9% and 10.5%, respectively, during the composting of rice straw and cow dung, according to Zhu et al. (2021). According to Guo et al. (2020), adding bentonite and bacterial agents improved nitrogen retention and ammonia oxidation while lowering emissions of nitrous oxide (N_2O) and ammonia (NH_3). Furthermore, successful composting may be greatly enhanced by effective microorganisms (EM), such as filamentous bacteria, lactic acid bacteria, yeast, photosynthetic bacteria, and Gram-positive actinomycetes (Guo et al., 2020). With elimination efficiencies of 77.2% for absolute abundance and 64.5% for relative abundance, Cao et al. (2020) showed that the application of EM microbial agents greatly decreased the overall abundance of antimicrobial resistance genes (ARGs) (Cao et al., 2020).

Role of microorganisms in composting

Key microbial agents

Microorganisms, such as bacteria (e.g., *Bacillus subtilis*, *Pseudomonas aeruginosa*), fungi (e.g., *Aspergillus niger* and *Trichoderma reesei*), and *actinomycetes*, play essential roles in the degradation of organic matters (Chen et al., 2023). Table 2 presents a selection of microorganisms commonly employed in composting and eco-enzyme production, along with their respective roles in these bioprocesses.

Microbial effectiveness

Studies show that inoculating compost piles with microbial consortia accelerates decomposition by 20-30% while enhancing nutrient retention (Singh et al., 2021). Biodegradation is the primary process responsible for removing estrogens, influencing their transport and ultimate fate (Abdellah et al., 2022). Estrogen-degrading bacteria aid in the breakdown of estrogens during composting, and microorganisms assist in this process. Numerous bacterial strains have been shown to be capable of breaking down estrogens, and their conversion processes have been described. These strains include *Sphingomonas, Novosphingobium, Comamonas, Rhodococcus, Pseudomonas,* and *Deinococcus.* A variety of habitats, including soil, composts, wastewater, and activated sludge, were used to isolate and screen these strains (Abdellah et al., 2022).

Table 2. Use of different microorganisms for improving the quality of composting and eco-enzymes

Microorganism	Effect	Reference
Lactobacillus, Yeast, Bacillus, Actinomycetes, Photosynthetic Bacteria	Enhanced composting efficiency through increased temperature and extended high-temperature phase	(Xu et al., 2024)
Lactic Acid Bacteria, Bacillus, Photosynthetic Bacteria, Yeast, Actinobacteria, Acetobacter	Significant influence on estrogen content through the degradation of Acinetobacter, Bacillus, and Pseudomonas	(Li et al., 2023)
Bacillus megaterium, Saccharomyces cerevisiae, Lactobacillus plantarum	Promoted the survival of beneficial bacteria, facilitated the metabolism of amino acids, carbohydrates, and lipids, suppressed energy metabolism and the tricarboxylic acid (TCA) cycle, and increased the complexity of the bacterial network	(Liu et al., 2023)

Future directions

Innovations in microbial technology

Harnessing genetically modified microorganisms for enhanced enzyme production and waste degradation shows promise (Singh et al., 2021). Abdellah et al. (2022) reported that microbial diversity has increased and bacterial structure has been modified, both of which encourage the synthesis of HS. The breakdown of polymers may be facilitated by the introduction of a varied microbial population, which can promote the development of different polymer depolymerases (Jia et al., 2023). An inoculation experiment used pig dung and straw compost, along with microbial strains such as *Acinetobacter pittii*, *Bacillus altitudinis*, and *Bacillus subtilis* subsp. stercoris (Li et al., 2021). Precursors were effectively produced by this microbial mixture's efficient degradation of organic waste, and the polymerases that were released helped to further convert these precursors into HS. Composting is sped up, composting time is shortened, and unpleasant smells are decreased by using effective microorganisms (EMs), which comprise a range of functional microorganisms (Ney et al., 2020). Nevertheless, according to some research, EM microbial agents are not very efficient in breaking down compost substrates (Jia et al., 2023).

Circular economy integration

Developing integrated waste-to-resource frameworks can transform agricultural waste into biofertilizers, reducing dependency on synthetic inputs (UNEP, 2022). Table 2 illustrates the use of microbial species in the synthesis of eco-enzymes. Rasit et al. (2019) reported that eco-enzymes are distinguished by their elevated propionic acid concentration, which efficiently suppresses microbial proliferation. Furthermore, the presence of acetic acid facilitates organism eradication, while increased concentrations of nitrate (NO_3) and carbonate (CO_3) may speed up the decomposition, composition, and transformation of organic compounds into simpler forms. Based on these results, Wen et al. (2021) proposed that eco-enzymes function in a similar manner as enzymes, thereby promoting a faster and more thorough breakdown process. Moreover, eco-enzymes include a significant quantity of metal ions that function as cofactors, facilitating the catalysis of diverse chemical processes. To effectively manufacture citrus eco-enzymes, it is essential to implement ideal conditions for continuous fermentation. Typically, this entails a three-month fermentation period at ambient temperature. Due to the generation and emission of gases during fermentation, people often store the solution in plastic vessels. The inclusion of yeast can effectively regulate the fermentation process. The preparation method for eco-enzymes is illustrated in Fig. 2, which emphasizes the various components involved in the production of citrus eco-enzymes (Nazim and Meera, 2013). Fermenting fresh kitchen waste, such as fruit and vegetable peels, along with sugar (whether brown sugar, jaggery, or molasses) and water, results in the production of eco-enzymes, a complex solution. The components are mixed in a precise proportion of 1:3:10, resulting in a liquid of dark brown color with a unique aroma of sweet and sour fermentation. The first month of fermentation is characterized by gas production, necessitating daily pressure release to avoid container breakage (Rani et al., 2020). It is advisable to occasionally plunge the skins of fruits or vegetables downwards. Producers keep the containers in a cold, dry, and well-ventilated environment for three months to achieve optimal enzyme production. Following fermentation, the solution undergoes separation into a brownish liquid and solid subphases. Both solutions go through filtration to extract the enzymes. The appearance of a white mold on the surface may suggest the existence of a yeast B complex and vitamin C. The resultant enzyme solution has a pale brownish yellow color and is suitable for storage in a plastic container. Crucially, eco-enzymes are not subject to an expiry date, and their effectiveness increases over time, particularly when mixed with water. It is important to bear in mind that eco-enzymes are designed only for external use (Nazim and Meera, 2013).

Fig. 2. Eco-enzyme production process.

Eco-enzyme in agriculture

Soil health improvement

Eco-enzymes enrich soil microbiota, improving nutrient cycling and organic matter decomposition. Parengkoan (2023) reported a 20-30% increase in crop yield when eco-enzyme-treated fertilizers were used (Sharma et al., 2023). Narang et al. (2024) evaluated the effect of eco-enzymes on the composting process and subsequent plant growth. Their studies demonstrated that traditional composting procedures are typically sluggish and ineffective, prompting the development of faster approaches. Eco-enzymes have emerged as a viable alternative for speeding the breakdown of solid wastes. The current study aimed to utilize eco-enzymes derived from kitchen waste to decompose agricultural residues and produce compost that could serve as a soil conditioner and fertilizer for various plant species. Eco-enzyme was applied to each composting batch at different concentrations (10%, 15%, and 20%, v/v) once a week. The final compost exhibited a near-neutral pH range of 6.51 ± 0.03 to 7.88 ± 0.50 across all samples. Notably, the compost with a 10% eco-enzyme concentration demonstrated the most significant growth-promoting effects for *Phaseolus vulgaris*. Table 3 presents the macronutrient composition at various eco-enzyme concentrations.

Crops such as rice and shallots can benefit from the efficient use of eco-enzymes, which are adaptable liquid organic fertilizers. These enzymes are produced through a three-month fermentation process, utilizing kitchen waste, water, and a sweetener like molasses or palm sugar in anaerobic conditions. The specific combination of ingredients affects the scent, pH, and color of the resulting eco-enzyme. When eco-enzyme is applied to shallot plants at a concentration of 1.75 mL per liter of water, it promotes root growth and enhances leaf production, demonstrating its potential as a valuable agricultural input. Ichsan et al. (2024) examined how to improve soil fertility and sorghum yields by combining eco-enzymes, soil amendments, and NPK fertilization. Three replications were included in the experiment, which used a factorial randomized block design with a split-split plot arrangement and a 3 × 2 × 2 structure. Ten kilograms of Ultisol soil were utilized in each of the 108 pots. The sub-plots received NPK treatments (600 and 900 kg ha^{-1}), the split-split plots received eco-enzyme treatments (sprayed once or twice a week), while the main plots received various soil amendments (no amendment, charcoal, and compost). The results indicated that both eco-enzymes and soil amendments significantly influenced soil pH and NPK levels. Furthermore, it was discovered that the nitrogen (N), phosphorous (P), and potassium (K) content, as well as the yield potential, were impacted by the interactions among soil amendments, NPK treatments, and eco-enzymes. Additionally, the pH of the soil, electrical conductivity (EC), and chlorophyll content in sorghum leaves were significantly impacted by NPK treatments and eco-enzyme sprays. The research found that using soil amendments, NPK, and eco-enzymes together increased sorghum yields and Ultisol fertility, supporting attempts to diversify the food supply. The utilization of eco-enzymes and oyster mushroom media waste (bag-log waste) as growing media for celery microgreens was examined by Titisari (2023). Two factors were examined: the concentration of eco-enzymes (0.5, 15, or 25 mL L^{-1}) and the quantity of bag-log trash (0.50, 100, or 150 g/tray). A factorial design that was fully randomized was used. Fresh weight, fresh economic weight, root length, root volume, moisture content, vitamin C, magnesium, and calcium levels were among the variables evaluated in the study. Across all tested parameters, the findings showed a substantial interaction between bag-log waste and eco-enzymes. The combination of 150 g of bag-log waste per tray and 25 mL L^{-1} eco-enzyme proved to be the most successful treatment. Both eco-enzymes and bag-log waste positively impacted all tested metrics, suggesting their potential as effective growth media for celery microgreen cultivation. Defiani and Astarini (2023) assessed the impact of eco-enzymes on the growth of various rice varieties. The experiment began with seed germination in a medium consisting of soil, compost, and manure in a 1:1:1 ratio. Three rice cultivars, i.e., red rice 'Jatiluwih', red rice 'Pulagan', and white rice 'Mentik Susu' were grown using two treatments: a commercial liquid organic fertilizer (LOF) at 10% and eco-enzyme at 0.1%. Both treatments resulted in high germination rates of 90–95% after four days. Red rice 'Jatiluwih' treated with eco-enzyme exhibited a 25% increase in plant height compared to the LOF treatment. Similarly, 'Pulagan' red rice and 'Mentik Susu' white rice showed improvements of 10% and 5%, respectively, after eco-enzyme application. Additionally, rice treated with eco-enzyme was harvested 2–3 weeks earlier than those treated with conventional liquid organic fertilizer. 'Mentik Susu' white rice responded particularly well to eco-enzyme treatment, producing more tillers and increasing harvest yield. The application of eco-enzymes may enhance plant growth by boosting soil enzyme activity, thereby improving nutrient availability for root uptake. Table 4 presents the effects of varying eco-enzyme concentrations on plant development.

Table 3. Nutrient contents using different concentrations of eco-enzyme

Eco-enzyme concentration	N (%)	C-organic (%)	C/N ratio (%)	P (%)	K (%)	Reference
Control	1.811	8.04	4.44	0.053	0.291	(Fadlilla et al., 2023)
20 (mL)	0.95	11.43	12.03	0.067	0.33	(Fadlilla et al., 2023)
40 (mL)	0.501	6.82	13.61	0.042	0.388	(Fadlilla et al., 2023)
Control	0.28	1.39	9	0.028	0.16	(Narang et al., 2024)
Eco-enzyme (10%)	1.02	18.05	18	0.015	2.25	(Narang et al., 2024)
Eco-enzyme (20%)	0.6	5.64	10	0.076	1.61	(Narang et al., 2024)
Without dilution	0.02	1.33	66.5	0.01	0.06	(Fadlilla et al., 2023)
Eco-enzyme/water (1:1500)	0.01	0.01	1	0.000009	0.000133	(Fadlilla et al., 2023)
Eco-enzyme/water (1:1000)	0.01	0.01	1	0.000008	0.000008	(Fadlilla et al., 2023)
Eco-enzyme/water (1:500)	0.01	0.01	1	0.000008	0.000008	(Fadlilla et al., 2023)

Table 4. Effect of different concentrations of eco-enzymes on plant growth

Type of plant	Height of plant (cm)	Height of plant (cm)	Reference
Chili	Control: 2.90	Eco-Enzyme: 5.00	(Hemalatha and Visantini, 2020)
Aloe Vera	Control: 17.2	Eco-Enzyme: 18.6	(Hemalatha and Visantini, 2020)
Indian mustard (*Brassica juncea*)	Control: 3.5	Eco-Enzyme: 5.7	(Selvakumar and Sivashanmugam, 2017)
Soybean	Control: 15.81	Eco-Enzyme: 22.82	(Gustina, 2024)
Onion	Control: 17.5	Eco-Enzyme: 22.1	(Siswanto et al., 2023)

Deepa and Malladadavar (2020) found that using a cocopeat-based growth medium combined with 15 mL of eco-enzyme produced the highest chlorophyll content and the lowest bacterial contamination in wheatgrass microgreens. Typically, the suggestion is to maintain a high degree of sterility while reducing fungal or bacterial contamination in the growth medium. Mar'ah and Farma (2021) investigated how eco-enzymes derived from discarded papaya and pineapple skin affected the development of ground kale (*Ipomoea reptans*). Their research revealed a positive impact of eco-enzyme treatment on plant height, leaf count, and fresh weight, suggesting its potential as a growth booster. Eco-enzymes are a dark liquid with a distinct scent (Utpalasari and Dahliana, 2020). They include soil-friendly nutrients such as acetic acid, nitrate, and carbon trioxide (Janarthanan et al., 2020). Researchers have found that eco-enzymes improve plant development, while acetic acid may kill insects and pests (Nazim and Meera, 2013).

Eco-enzymes may help soybean plants produce more. One liter of eco-enzyme mixed with 100 liters of water is suggested as a treatment (Joseph et al., 2021). Studies have shown that applying eco-enzymes at concentrations of up to 10 mL L^{-1} significantly influences shallot growth and yield (Joseph et al., 2021). However, research into the impact of eco-enzymes on soybean plants, especially mutant lines such as 'Kipas Putih', is scarce. Research indicates that eco-enzymes exhibit natural pesticidal properties, reducing reliance on chemical pesticides by 15-25% in controlled studies (Ningrum et al., 2024). Eco-enzymes promote drought-resistant crop growth by improving water retention in the soil (FAO, 2023a). Their application mitigated soil salinity and acidity while enhancing crop adaptability to stress conditions (UNEP, 2022).

Assessment of waste in the world and application of eco-enzyme synthesis

Current waste statistics

As reported by the World Bank (2022), global waste generation is expected to increase to 3.4 billion tons by 2050. Organic waste constitutes 44% of global waste streams, predominantly from agriculture and households (FAO, 2023a). Effective waste management strategies are crucial for addressing the significant challenges posed by the growing volume of solid waste produced globally. Cities, in particular, must emphasize effective waste management solutions to reduce negative environmental and public health consequences. Furthermore, Fig. 3 highlights the significant quantity of food waste created worldwide, which accounts for more than half of the total solid waste produced in several years. This frightening trend emphasizes the critical need for novel solutions, such as the eco-enzyme approach, to decrease waste and improve sustainability. Growing populations and urbanization have resulted in significant increases in waste generation, posing major challenges to solid waste management systems. These issues include a rapid urban population increase, poor strategic planning, insufficient disposal facilities, a shortage of skilled personnel, a lack of technical skills, and insufficient financial resources. Often, the primary focus of limited resources is on collection costs, leaving minimal funds for safe final disposal. Effective solid waste management is crucial for reducing public health hazards and environmental deterioration.

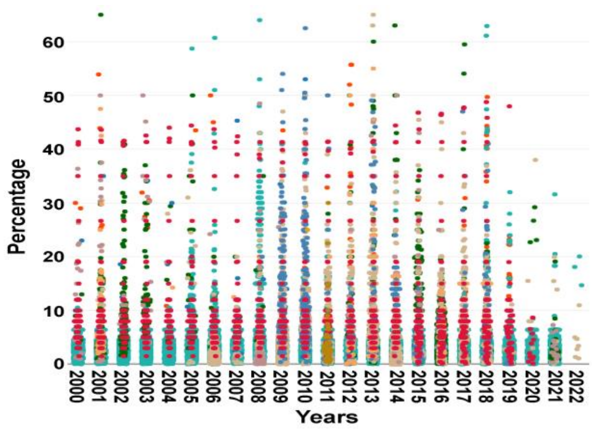

Fig. 3. Food loss as a percentage of domestic production in the world (World Bank, 2022).

Strategies for application

Large-scale eco-enzyme production from agricultural waste is being piloted in Brazil and the Philippines, aiming to recycle 10-20% of crop residues annually (Sangeeta et al., 2024). In Europe, municipal waste composting facilities are integrating eco-enzyme synthesis as part of circular economy initiatives (UNEP, 2022). Waste reduction strategies provide a long-term solution to global warming and resource conservation (Nordin et al., 2020). Food waste constitutes a major portion of global waste production, with approximately 30% of cereals, 20% of oilseeds, and 40–50% of root crops being discarded (Corrado and Sala, 2018). Per capita food waste differs significantly across regions, with consumers in Europe and North America discarding 96-120 kg per year, whereas in South Asia and Sub-Saharan Africa, the waste amounts to only 7-13 kg per year. In less developed countries, food waste is more common at the early stages of the food value chain, primarily due to the financial and technological limitations in harvesting, storage, and refrigeration.

Innovative applications

Using eco-enzymes in landfill leachate treatment has reduced environmental contamination by 35% (Zhou et al., 2024). Pilot projects in zero-waste cities in Asia have successfully incorporated eco-enzyme production into urban sustainability models (FAO, 2022). Researchers have studied the potential applications of lignocellulosic waste from food production, such as phytochemical extraction, biodiesel generation, enzyme manufacture, and wastewater treatment. These initiatives seek to address the environmental and economic consequences of food waste, as well as to investigate long-term waste management and resource usage strategies. The poor execution of current regulations reduces the system's flexibility in addressing gaps and enhancing overall waste management procedures. To create a more sustainable waste management system in Iran, concentrated efforts must be made to develop environmental regulations, upgrade legal frameworks, and improve implementation techniques. Kitchen waste, such as leftover vegetables, fruits, and peels, may be reused for eco-enzyme synthesis, providing a dual advantage of reducing waste management difficulties while also finding uses in agriculture, animal husbandry, home cleaning, and other fields (Muliarta et al., 2023). Eco-enzymes not only help minimize waste-related methane emissions, but they also save money (Muliarta et al., 2023). Eco-enzymes may help plants develop and produce more efficiently (Muliarta et al., 2023). Furthermore, eco-enzyme synthesis has several benefits, including enhanced organic waste management and a wide range of uses in different industries (Kerkar and Salvi, 2020). Eco-enzymes have been widely used in sewage treatment, notably for sewage sludge treatment, with considerable increases in pH levels and organic content decreases (Wikaningrum et al., 2022). Furthermore, eco-enzymes have the potential to prevent microbial growth in liquid waste and digest metal-based waste, increasing their value.

Challenges for eco-enzymes production

Standardization issues

Challenges in setting global production standards have limited scalability (Singh et al., 2021). Variability in raw material quality affects enzyme consistency and potency (Chen et al., 2022). The rapid growth in population and urbanization has resulted in a significant increase in trash creation, posing severe disposal issues in both rural and urban locations. Developing nations, in particular, confront severe waste management challenges owing to insufficient procedures in collection, separation, treatment, and disposal (Chen et al., 2022).

Technological barriers

Limitations in fermentation technology for large-scale adoption remain a key barrier (Lee et al., 2020). Incorporating AI and automation in production could improve efficiency, but high costs are a constraint (UNEP, 2022). Solid waste management in developing countries is significantly more challenging than in developed nations due to the absence of proper documentation and effective procedures for waste assessment and disposal. This lack of control adds to environmental degradation, exposure to harmful compounds, and associated health hazards. Additionally, the issue is made worse by a lack of funding for cutting-edge waste treatment equipment and inadequate funds for waste disposal. The lack of a defined procedure complicates eco-enzyme synthesis, resulting in longer production periods and restricted industrial usage.

Policy and regulation

Current policies promoting or hindering eco-enzyme production vary widely between regions (FAO, 2021). Recommendations for global frameworks to support eco-enzyme industries include tax incentives and subsidies for sustainable practices (UNEP, 2022). There is limited research on the mechanism of action of eco-enzymes in component reduction, which needs more exploration in order to overcome these limitations and realize their potential in a variety of applications. While the aforementioned issues have significantly influenced eco-enzyme production, they may be solved by good management methods and enhanced field expertise.

CONCLUSION

Waste management is a pressing global challenge that demands innovative solutions, particularly in industries that generate substantial volumes of waste. One promising strategy for mitigating environmental impacts is community-based initiatives, such as the transformation of organic waste into eco-enzymes. Eco-enzymes are multifunctional products with diverse applications, including cleaning, food preservation, air purification, plant fertilization, and pest control. Their production supports sustainable practices by reducing waste streams while contributing to environmental conservation. The adoption of eco-enzyme production by waste-generating sectors reflects a strong commitment to the principles of reduction, reuse, and recycling. Collaborative efforts to repurpose waste materials can foster the development of eco-friendly products, moving societies closer to achieving zero or near-zero waste goals. This integrated approach is vital for advancing a more sustainable, responsible, and environmentally conscious waste management system.

FUNDING

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

Conceptualization: Shno Karimi; Methodology: Shno Karimi; Software: Shno Karimi; Validation: Shno Karimi; Formal analysis: Shno Karimi; Investigation: Shno Karimi; Resources: Shno Karimi; Data curation: Shno Karimi; Writing—original draft preparation: Shno Karimi; Writing—review and editing: Maryam Haghighi and Mehdi Sharifiani; Visualization: Shno Karimi; Supervision: Maryam Haghighi; Project administration: Maryam Haghighi and Mehdi Sharifiani; Funding acquisition: Maryam Haghighi.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

ETICAL STATEMENT

Not applicable.

DATA AVAILABILITY

Not applicable.

ACKNOWLEDGMENTS

The authors thank the anonymous reviewers for their valuable comments and suggestions.

REFERENCES

Abdellah, Y. A. Y., Shi, Z. J., Sun, S. S., Luo, Y. S., Yang, X., Hou, W. T., & Wang R. L. (2022). An assessment of composting conditions, humic matters formation and product maturity in response to different additives: A meta-analysis. *Journal of Cleaner Production, 366*, 132953. https://doi.org/10.1016/j.jclepro.2022.132953

Arun, C., & Sivashanmugam, P. (2018). Enhanced production of biohydrogen from dairy waste activated sludge pre-treated using multi hydrolytic garbage enzyme complex and ultrasound-optimization. *Energy Conversion and Management*, *164*, 277-287. https://doi.org/10.1016/j.enconman.2018.02.095

Arun, C., & Sivashanmugam P. (2017). Study on optimization of process parameters for enhancing the multi-hydrolytic enzyme activity in garbage enzyme produced from preconsumer organic waste. *Bioresource Technology, 226*, 200-210. https://doi.org/10.1016/j.biortech.2016.12.029

Arun, C., & Sivashanmugam, P. (2015a). Identification and optimization of parameters for the semi-continuous production of garbage enzyme from pre-consumer organic waste by green RP-HPLC method. *Waste Management*, *44*, 28-33. https://doi.org/10.1016/j.wasman.2015.07.010

Arun, C., & Sivashanmugam, P. (2015b). Investigation of biocatalytic potential of garbage enzyme and its influence on stabilization of industrial waste activated sludge. *Process Safety and Environmental Protection*, *94*, 471-478. https://doi.org/10.1016/j.psep.2014.10.008

Babazadeh, T., Nadrian, H., Mosaferi, M., & Allahverdipour, H. (2020). Challenges in household solid waste separation plan (HSWSP) at source: A qualitative study in Iran. *Environment Development and Sustainability*, *22*, 915-930. https://doi.org/10.1007/s10668-018-0225-9

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050 (Overview booklet). Washington, DC: World Bank. License: Creative Commons Attribution CC BY 3.0 IGO. https://doi.org/10.1596/978-1-4648-1329-0

Benny, N., Shams, R., Dash, K. K., Pandey, V. K., & Bashir, O. (2023). Recent trends in utilization of citrus fruits in production of eco-enzyme. *Journal of Agriculture and Food Research, 13*, 100657. https://doi.org/10.1016/j.jafr.2023.100657

Cao, R., Ben, W., Qiang, Z., & Zhang, J. (2020). Removal of antibiotic resistance genes in pig manure composting influenced by inoculation of compound microbial agents. *Bioresource Technology, 317*, 123966. https://doi.org/10.1016/j.biortech.2020.123966

Chaudhary, P., Chaudhary, A., Bhatt, P., Kumar, G., Khatoon, H., Rani, A., Kumar, S., & Sharma, A. (2022). Assessment of soil health indicators under the influence of nanocompounds and Bacillus spp. in field condition. *Frontiers in Environmental Science, 9*, 769871. https://doi.org/10.3389/fenvs.2021.769871

Chen, L., Chen, Y., Li, Y., Liu, Y., Jiang, H., Li, H., Yuan, Y., Chen, Y., & Zou, B. (2023). Improving the humification by additives during composting: A review. Waste management, *158*, 93-106. https://doi.org/10.1016/j.wasman.2022.12.040

Chen, L., He, Z., Yang, L., Wang, L., Li, Y., & Chen, T., et al. (2022). Optimal utilization of solid residue from phase-separation pretreatment before food waste anaerobic digestion. *Journal of Cleaner Production*, *372*, 133795. https://doi.org/10.1016/j.jclepro.2022.133795

Corrado, S., & Sala, S. (2018). Food waste accounting along global and European food supply chains: State of the art and outlook. *Waste Management*, *79*, 120-131. https://doi.org/10.1016/j.wasman.2018.07.032

Das, S. C., Khan, O., Khadem, A. H., Rahman, M. A., Bedoura, S., Uddin, M. A., & Islam, M. D. S. (2024). Evaluating the biocatalytic potential of fruit peel-derived eco-enzymes for sustainable textile wastewater treatment. *Results in Engineering, 21*, 101898. https://doi.org/10.1016/j.rineng.2024.101898

Das, S., Wadud, A., & Khokon, M. A. R. (2021). Evaluation of the effect of different concentrations of organic amendments and botanical extracts on the mortality and hatching of Meloidogyne javanica. *Saudi Journal of Biological Sciences, 28*(7), 3759-67. https://doi.org/10.1016/j.sjbs.2021.03.041

Deepa, N., & Malladadavar, D. (2020). Microgreens: the treasure of nutrients. *International Journal of Current Microbiology and Applied Sciences, 9*(2), 18-23. https://doi.org/10.20546/ijcmas.2020.902.004

Defiani, M., & Astarini, I. (2023). Eco-enzyme enhanced the growth of rice cultivars. IOP Conference Series: Earth and Environmental Science; IOP Publishing. https://doi.org/10.1088/1755-1315/1255/1/012007

Duan, M., Zhang, Y., Zhou, B., Wang, Q., Gu, J., Liu, G., Qin, Z., & Li, Z. (2019). Changes in antibiotic resistance genes and mobile genetic elements during cattle manure composting after inoculation with *Bacillus subtilis*. *Bioresource Technology, 292*, 122011. https://doi.org/10.1016/j.biortech.2019.122011

Duran, N., & Esposito, E. (2000). Potential applications of oxidative enzymes and phenoloxidase-like compounds in wastewater and soil treatment: A review. *Applied Catalysis B: Environmental, 28*(2), 83-99. https://doi.org/10.1016/S0926-3373(00)00168-5

Environmental Protection Agency (EPA). (2021). *Agricultural waste management in the United States.* Washington, DC. Environmental Protection Agency.

Eurostat. (2022). European composting statistics. Brussels, Belgium.

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

FAO. (2023a). The State of Food and Agriculture 2023. Revealing the true cost of food to transform agrifood systems. Rome. https://doi.org/10.4060/cc7724en

FAO. (2023b). *Global waste assessment.* Rome, Italy: FAO Publishing. Retrieved from: https://www.fao.org. 2023

FAO. (2022). The State of Food and Agriculture 2022. Leveraging automation in agriculture for transforming agrifood systems. Rome, FAO. https://doi.org/10.4060/cb9479en

FAO. (2021). Food Waste Index Report. Retrieved from: https://www.fao.org/platform-food-loss-waste/food-loss/food-loss-reduction/en

FAO. (2020). Food wastage footprint and climate change. Retrieved from: https://openknowledge.fao.org/server/api/core/bitstreams/7fffcaf9-91b2-4b7b-bceb-3712c8cb34e6/content

Galintin, O., Rasit, N., & Hamzah, S. (2021). Production and characterization of eco enzyme produced from fruit and vegetable wastes and its influence on the aquaculture sludge. *Biointerface Research in Applied Chemistry, 11*(3), 10205-10214. https://doi.org/10.33263/BRIAC113.1020510214

Gou, C., Wang, Y., Zhang, X., Lou, Y., & Gao, Y. (2017). Inoculation with a psychrotrophic-thermophilic complex microbial agent accelerates onset and promotes maturity of dairy manure-rice straw composting under cold climate conditions. *Bioresource Technology*, *243*, 339-346. https://doi.org/10.1016/j.biortech.2017.06.097

Guo, H., Gu, J., Wang, X., Nasir, M., Yu, J., Lei, L., Wang, J., Zhao, W., & Dai, X. (2020). Beneficial effects of bacterial agent/bentonite on nitrogen transformation and microbial community dynamics during aerobic composting of pig manure. *Bioresource Technology, 298*, 122384. https://doi.org/10.1016/j.biortech.2019.122384

Gustina, L. (2024). Effect of eco-enzymes on vegetative and generative growth in several kipas putih soybean (*Glycine max* (L) Merr.) mutant lines. IOP Conference Series: Earth and Environmental Science; IOP Publishing. https://doi.org/10.1088/1755-1315/1297/1/012061

Hartmann, M., Niklaus, P. A., Zimmermann, S., Schmutz, S., Kremer, J., Abarenkov, K., Lüscher, P., Widmer, F., & Frey, B. (2014) Resistance and resilience of the forest soil microbiome to logging-associated compaction. *The ISME Journal, 8*(1), 226-244. https://doi.org/10.1038/ismej.2013.141

Hasanah, Y. (2020). Eco enzyme and its benefits for organic rice production and disinfectant. *Journal of Saintech Transfer*, *3*(2), 119-28. https://doi.org/10.32734/jst.v3i2.4519

Hemalatha, M., & Visantini, P. (2020). Potential use of eco-enzyme for the treatment of metal based effluent. IOP Conference Series: Materials Science and Engineering; IOP Publishing. https://doi.org/10.1088/1757-899X/716/1/012016

Hu, T., Wang, X., Zhen, L., Gu, J., Zhang, K., Wang, Q., Ma, J., Peng, H., Lei, L., & Zhao, W. (2019). Effects of inoculating with lignocellulose-degrading consortium on cellulose-degrading genes and fungal community during co-composting of spent mushroom substrate with swine manure. *Bioresource Technology*, *291*, 121876. https://doi.org/10.1016/j.biortech.2019.121876

Ichsan, C., Qadri, L., Nurahmi, E., Kurniawan, T., & Santi, I. (2024). Improvement of ultisol fertility and sorghum yield by applying soil amendments, npk, and eco enzymes to support food diversification. IOP Conference Series: Earth and Environmental Science; IOP Publishing. https://doi.org/10.1088/1755-1315/1290/1/012056

International Energy Agency (IEA). (2023). *Biochar and biofuel integration in composting*. Paris, France. Retrieved from: https://www.iea.org/energy-system/low-emission-fuels/biofuels

Intergovernmental Panel on Climate Change (IPCC). (2022). Climate Change and Land. Geneva, Switzerland. Retrieved from: https://www.ipcc.ch/report/ar6/wg2/

Intergovernmental Panel on Climate Change (IPCC). (2021). Climate change and land. Geneva, Switzerland. Retrieved from: https://www.ipcc.ch/srccl/

Jamali, M., Yazdian, H., Bahman, G., & Eslamian, S. (2025). Water agriculture nexus a system dynamics approach for the next three decades. *Scientific Reports*, *15*(1), 5946.

Janarthanan, M., Mani, K., & Raja, S. R. S. (2020). Purification of contaminated water using eco enzyme. IOP Conference Series: materials science and engineering; IOP Publishing. https://doi.org/10.1088/1757-899X/955/1/012098

Jia, P., Wang, X., Liu, S., Hua, Y., Zhou, S., & Jiang, Z. (2023). Combined use of biochar and microbial agent can promote lignocellulose degradation and humic acid formation during sewage sludge-reed straw composting. *Bioresource Technology*, *370*, 128525. https://doi.org/10.1016/j.biortech.2022.128525

Joseph, A., Joji, J. G., Prince, N. M., Rajendran, R., & Nainamalai, D. M. (2021). Domestic wastewater treatment using garbage enzyme, presented at Roceedings of the International Conference on Systems, Energy & Environment (ICSEE), Kerala, India, GCE Kannur Publishing. https://dx.doi.org/10.2139/ssrn.3793057

Karimi, S., Raza, T., & Mechri, M. (2024). Composting and vermitechnology in organic waste management. In Kumar, V., Bhat, S. A., Kumar, S., & Verma, P. (Ed.), Environmental engineering and waste management: recent trends and perspectives (pp. 449-70). Cham: Springer Nature Switzerland. http://dx.doi.org/10.1007/978-3-031-58441-1_16

Karimi, S., Kolahchi, Z., Zarrabi, M., Nahidan, S., & Raza, T. (2025). From invasive species to agricultural resource: evaluation of Phragmites australis from Zarivar Lake as an organic amendment for the release of phosphorus, potassium, micronutrients and toxic metals. Discover Applied Sciences, 7(2), 100. https://doi.org/10.1007/s42452-025-06525-0

Kerkar, S., & Salvi, S. (2020). Application of eco-enzyme for domestic waste water treatment. *International Journal for Research in Engineering Application and Management*, *5*(11), 114-116. http://dx.doi.org/10.35291/2454-9150.2020.0075

Kominko, H., Gorazda, K., & Wzorek, Z. (2024). Sewage sludge: A review of its risks and circular raw material potential. *Journal of Water Process Engineering*, *63*, 105522. https://doi.org/10.1016/j.jwpe.2024.105522

Koya, C. M. (2017). Comparison of treatment of greywater using garbage and citrus enzymes. *International Journal of Innovative Research in Science, Engineering and Technology*, *6*(4), 49-54.

Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., & Ward, P. J. (2012). Lost food, wasted resources: Global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. *Science of the Total Environment*, *438*, 477-489. https://doi.org/10.1016/j.scitotenv.2012.08.092

Lee, R. P., Meyer, B., Huang, Q., & Voss, R. (2020). Sustainable waste management for zero waste cities in China: Potential, challenges and opportunities. *Clean Energy*, *4*(3), 169-201. https://doi.org/10.1093/ce/zkaa013

Li, C., Li, H., Yao, T., Su, M., Ran, F., Li, J., He, L., Chen, X., Zhang, C., & Qiu, H. (2021). Effects of swine manure composting by microbial inoculation: Heavy metal fractions, humic substances, and bacterial community metabolism. *Journal of Hazardous Materials*, *415*, 125559. https://doi.org/10.1016/j.jhazmat.2021.125559

Li, Y., Zeng, D., Jiang, X. L., He, D. C., Hu, J. W., Liang, Z. W., Wang, J. C., & Liu, W. R. (2023). Effect comparisons of different conditioners and microbial agents on the degradation of estrogens during dairy manure composting. *Chemosphere*, 345, 140312. https://doi.org/10.1016/j.chemosphere.2023.140312

Liu, X., Zubair, M., Kong, L., Shi, Y., Zhou, H., Tong, L., Zhu, R., Lv, Y., & Li, Z. (2023). Shifts in bacterial diversity characteristics during the primary and secondary fermentation stages of bio-compost inoculated with effective microorganisms agent. *Bioresource Technology*, *382*, 129163. https://doi.org/10.1016/j.biortech.2023.129163

Manea, E. E., Bumbac, C., Dinu, L. R., Bumbac, M., & Nicolescu, C. M. (2024). Composting as a sustainable solution for organic solid waste management: Current practices and potential improvements. *Sustainability, 16*(15), 6329. https://doi.org/10.3390/su16156329

Mandal, S., & Verma, D. (2024). Effect of eco-enzyme on growth, yield and quality characters of different cultivars of radish (*Raphanus sativus* L.). *Asian Journal of Microbiology Biotechnology and Environmental Sciences. 26*, 1-7. https://doi.org/10.53550/ajmbes.2024.v26i01.001

Mao, H., Lv, Z., Sun, H., Li, R., Zhai, B., Wang, Z., Awasthi, M. K., Wang, Q., & Zhou, L. (2018). Improvement of biochar and bacterial powder addition on gaseous emission and bacterial community in pig manure compost. *Bioresource Technology, 258*, 195-202. https://doi.org/10.1016/j.biortech.2018.02.082

Mapanda, F., Wuta, M., Nyamangara, J., & Rees, R. (2012). Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe. *Nutrient Cycling in Agroecosystems, 93*, 85-96. http://dx.doi.org/10.1007/s10705-012-9528-7

Mar'ah, S., & Farma, S. A. (2021). Making and utilizing organic waste into bio eco-enzyme as an indicator of organic plant fertilizer. *Prosiding Semnas Bio, 1*, 689-699. https://doi.org/10.24036/prosemnasbio/vol1/89

Masse, L., Kennedy, K. J., & Chou, S. P. (2001). The effect of an enzymatic pretreatment on the hydrolysis and size reduction of fat particles in slaughterhouse wastewater. *Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental & Clean Technology, 76*(6), 629-635. http://dx.doi.org/10.1002/jctb.428

Mavani, H. A. K., Tew, I. M., Wong, L., Yew, H. Z., Mahyuddin, A., Ahmad Ghazali, R., & Pow, E. H. N. (2020). Antimicrobial efficacy of fruit peels eco-enzyme against Enterococcus faecalis: An in vitro study. *International Journal of Environmental Research and Public Health, 17*(14), 5107. https://doi.org/10.3390/ijerph17145107

Mazhandu, Z. S., Muzenda, E., Mamvura, T. A., Belaid, M., & Nhubu, T. (2020). Integrated and consolidated review of plastic waste management and bio-based biodegradable plastics: Challenges and opportunities. *Sustainability, 12*(20), 8360. https://doi.org/10.3390/su12208360

Muliarta, I. N., & Darmawan, I. K. (2021). Processing household organic waste into eco-enzyme as an effort to realize zero waste. *Agriwar Journal, 1*(1), 6-11. https://doi.org/10.22225/aj.1.1.2021.6-11

Muliarta, I. N., Sudita, I. D. N., & Situmeang, Y. P. (2023). The effect of eco-enzyme spraying on suwung landfill waste, denpasar, on changes in leachate characteristics. *Journal of Environmental Health, 15*(1), 56-66. http://dx.doi.org/10.20473/jkl.v15i1.2023.56-66

Nalladiyil, A., Prakash, P., & Babu, G. S. (2023). Garbage enzyme-mediated treatment of landfill leachate: A sustainable approach. *Bioresource Technology, 385*, 129361. https://doi.org/10.1016/j.biortech.2023.129361

Narang, N., Hussain, A., & Madan, S. (2024). 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), 1-11. http://dx.doi.org/10.1007/s11356-023-27168-x

Natasya, N., Fadilah, M., Fitri, R., Farma, S. A., & Simwela, M. (2023). Analysis of eco-enzyme quality based on differences in plant tissue. *Journal Biota, 9*(1), 45-53. https://doi.org/10.19109/BIOTA.V9I1.13166

Nazim, F., & Meera, V. (2017). Comparison of treatment of greywater using garbage and citrus enzymes. *International Journal of Innovative Research in Science, Engineering and Technology, 6*(4), 49-54.

Nazim, F., & Meera, V. (2013). Treatment of synthetic greywater using 5% and 10% garbage enzyme solution. *Bonfring International Journal of Industrial Engineering and Management Science, 3*(4), 111.

Ney, L., Franklin, D., Mahmud, K., Cabrera, M., Hancock, D., Habteselassie, M., Newcomer, Q., & Dahal, S. (2020). Impact of inoculation with local effective microorganisms on soil nitrogen cycling and legume productivity using composted broiler litter. *Applied Soil Ecology, 154*, 103567. https://doi.org/10.1016/j.apsoil.2020.103567

Ningrum, R. S., Karima, R., Renjana, E., Ramadani, A. H., Umarudin, U., Istiqomah, N., & Aminingsih, T. (2024). Investigation of eco-enzyme from pineapple (*Ananas comosus* (L.) Merr.) waste: Chemical composition, antibacterial activity, and molecular docking approach. *Waste and Biomass Valorization, 15*(8), 1-13. http://dx.doi.org/10.1007/s12649-024-02492-6

Nordin, N., Kaida, N., Othman, N., Akhir, F., & Hara, H. (2020). Reducing food waste: Strategies for household waste management to minimize the impact of climate change and contribute to Malaysia's sustainable development. IOP Conference Series: Earth and Environmental Science; IOP Publishing. https://doi.org/10.1088/1755-1315/479/1/012035

Noviana, N., Johan, H., Mayub, A., & Firdaus, M. L. (2024). Determination of organic content and the use of eco-enzyme solutions in reducing organic levels in water samples from Cukuh Raya Beach, Kaur Regency, Bengkulu Province, Indonesia. *Aquatic Science & Management, 12*(1), 1-6. http://dx.doi.org/10.35800/jasm.v12i1.54930

Oriekhoe, O. I., Ashiwaju, B. I., Ihemereze, K. C., Ikwue, U., & Udeh, C A. (2024). Review of technological advancements in food supply chain management: A comparative study between the US and Africa. *International Journal of Management & Entrepreneurship Research, 6*(1), 132-49. https://doi.org/10.51594/ijmer.v6i1.713

Parengkoan, F. N. (2023). The Identification of Lactobacillus Bacteria and Yeast Isolated from Fermented Food Waste Eco-Enzyme Harvested at Different Times and Its Possibility for Synthetic Wastewater Treatment (Doctoral dissertation, Indonesia International Institute for Life Sciences). http://repository.i3l.ac.id/jspui/handle/123456789/834

Patil, P., Sharara, M., Shah, S., Kulesza, S., & Classen, J. (2023). Impacts of utilizing swine lagoon sludge as a composting ingredient. *Journal of Environmental Management, 327*, 116840. https://doi.org/10.1016/j.jenvman.2022.116840

Prihanto, J. B., Suprapto, N., Winarsih, W., Iriani, S. S., Hariyono, E., Rizki, I. A., & Vebianawati, E. (2024). Water and sustainable development: implementation and impact of eco-enzyme flushing program in green universities. *International Journal of Sustainable Development & Planning, 19*(2), 567-576. http://dx.doi.org/10.18280/ijsdp.190214

Qi, H. S. Z. Y., Wang, X., Wei, Z., Zhang, X., Wu, J. Q. X., Kang, K., Yang, H., Shi, M., Su, X., Zhang, C., & Wu, Z. (2021). Manganese dioxide driven the carbon and nitrogen transformation by activating the complementary effects of core bacteria in composting. *Bioresource Technology, 330*, 124960. https://doi.org/10.1016/j.biortech.2021.124960

Rani, A., Negi, S., Hussain, A., & Kumar, S. (2020). Treatment of urban municipal landfill leachate utilizing garbage enzyme. *Bioresource Technology, 297*, 122437. https://doi.org/10.1016/j.biortech.2019.122437

Ramadani, A. H., Karima, R., & Ningrum, R. S. (2022). Antibacterial activity of pineapple peel (Ananas comosus) eco-enzyme against acne bacterias (*Staphylococcus aureus* and *Prapionibacterium acnes*). *Indonesian Journal of Chemical Research*, *9*(3), 201-207. https://doi.org/10.30598//ijcr.2022.9-nin

Rasit, N., Hwe Fern, L., & Ab Karim Ghani, W. A. W. (2019). Production and characterization of eco enzyme produced from tomato and orange wastes and its influence on the aquaculture sludge. *International Journal of Civil Engineering and Technology, 10*(3), 967-980. Retrieved from: https://ssrn.com/abstract=3456453

Rasit, N., & Mohammad, F. S. (2018). Production and characterization of bio catalytic enzyme produced from fermentation of fruit and vegetable wastes and its influence on aquaculture sludge. *International Journal of Science and Technology, 4*(2), 12-26. http://dx.doi.org/10.20319/mijst.2018.42.1226

Ratiani, S. I., Amir, R., Shapira, S. B., & Wahyuni, N. S. (2024). Utilization of eco-enzyme technology from tomato waste as raw material for making hand sanitizer and testing its inhibitory power against staphylococcus aureus bacteria, presented at Proceeding International Conference on Religion, Science and Education, Indonesia, Universitas Islam Negeri Sunan Kalijaga Publishing.

Roulia, M. (2024). Sustainable utilization of humic substances and organic waste in green agriculture. *Agriculture*, *14*(1), 115. https://doi.org/10.3390/agriculture14010115

Salvi, S. (2024). Innovative use of eco-enzymes for domestic wastewater purification. *Journal of Environmental Nanotechnology, 13*(3), 435-439. http://dx.doi.org/10.13074/jent.2024.09.242771

Sangeeta, S., Rai, S., Ramachandran, P., Yadav, P., & Chandola, G. (2024). *Value addition of spices processing industrial waste.* Wealth out of Food Processing Waste: CRC Press.

Selvakumar, P., & Sivashanmugam, P. (2017). Optimization of lipase production from organic solid waste by anaerobic digestion and its application in biodiesel production. *Fuel Processing Technology, 165*, 1-8. https://doi.org/10.1016/j.fuproc.2017.04.020

Sharma, P., Sharma, S., Singh, J., Singh, A., & Katnoria, J. K. (2023). Characterization of *Tectona grandis* leaf litter compost: An ecological approach for converting leaf litter waste into organic product using composting. *Biomass Conversion and Biorefinery, 15(2),* 2145-2160. http://dx.doi.org/10.1007/s13399-023-04309-3

Sindhu, R., Gnansounou, E., Rebello, S., Binod, P., Varjani, S., Thakur, I. S., Nair, R. B., & Pandey, A. (2019). Conversion of food and kitchen waste to value-added products. *Journal of environmental management, 241*, 619-630. https://doi.org/10.1016/j.jenvman.2019.02.053

Singh, A., Tiwari, R., & Chandrahas Dutt, T. (2021). Augmentation of farmers' income in India through sustainable waste management techniques. *Waste Management & Research*, *39*(6), 849-859. https://doi.org/10.1177/0734242x20953892

Siswanto, Y., Sumartono, I., & Ilman, M. (2023). Effectiveness of eco enzyme administration and rhizobium isolation against the growth and production of onions red (*Allium ascolonicum* L). *World Journal of Advanced Research and Reviews*, *17*(3), 688-705. http://dx.doi.org/10.30574/wjarr.2023.17.3.0450

Takaku, H., Kodaira, S., Kimoto, A., Nashimoto, M., & Takagi, M. (2006). Microbial communities in the garbage composting with rice hull as an amendment revealed by culture-dependent and-independent approaches. *Journal of Bioscience and Bioengineering, 101*(1), 42-50. https://doi.org/10.1263/jbb.101.42

Titisari, P. W. (2023). Eco-enzyme and mushroom bag-logs waste stimulate production and nutrients content of celery microgreen (*Apium graveolens* L.). *Journal Agronomi Indonesia*, *51*(3), 334-345. http://dx.doi.org/10.24831/jai.v51i3.49588

United Nations Environment Programme (UNEP). (2022). Circular economy. Retrieved from: https://www.unepfi.org/wordpress/wp-content/uploads/2024/07/PRB_CE-Nexus_Guidance-Doc

Utpalasari, R. L., & Dahliana, I. (2020). Analisis hasil konversi eco enzyme menggunakan nenas (*Ananas comosus*) dan pepaya (*Carica papaya* L.). *Journal Redoks*, *5*(2), 135-140. http://dx.doi.org/10.31851/redoks.v5i2.5060

Vama, L., & Cherekar, M. N. (2020). Production, extraction and uses of eco-enzyme using citrus fruit waste: wealth from waste. *Asian Journal of Microbiology, Biotechnology & Environmental Sciences*, *22*(2), 346-51.

Verma, D., Singh, A., & Shukla, A. (2019). Use of garbage enzyme for treatment of waste water. *International Journal of Scientific Research and Review, 7*(7), 201-5.

Villalba, L., Donalisio, R. S., Basualdo, N. E. C., & Noriega, R. B. (2020). Household solid waste characterization in Tandil (Argentina): Socioeconomic, institutional, temporal and cultural aspects influencing waste quantity and composition. *Resources, Conservation and Recycling*, *152*, 104530. https://doi.org/10.1016/j.resconrec.2019.104530

Wen, L. C., Ling, R. L. Z., & Teo, S. S. (2021). Effective microorganisms in producing eco-enzyme from food waste for wastewater treatment. *Applied Microbiology: Theory & Technology*, *2*(1), 28-36. http://dx.doi.org/10.37256/amtt.212021726

Wijaya, D. P., & Laila, N. (2024). Potential for eco-enzyme development as entrepreneurship in river ecotourism and mangrove conservation. *Indonesian Tourism Journal*, *1*(2), 131-145. http://dx.doi.org/10.69812/itj.v1i2.39

Wikaningrum, T., Hakiki, R., Astuti, M. P., Ismail, Y., & Sidjabat, F. M. (2022). The eco enzyme application on industrial waste activated sludge degradation. *Indonesian Journal of Urban and Environmental Technology*, *5*(2), 115-133. http://dx.doi.org/10.25105/urbanenvirotech.v5i2.13535

Xu, P., Shu, L., Yang, Y., Kumar, S., Tripathi, P., Mishra, S., Qiu, C., Li, Y., Wu, Y., & Yang, Z. (2024). Microbial agents obtained from tomato straw composting effectively promote tomato straw compost maturation and improve compost quality. *Ecotoxicology and Environmental Safety*, *270*, 115884. https://doi.org/10.1016/j.ecoenv.2023.115884

Xu, Z., Qi, C., Zhang, L., Ma, Y., Li, J., Li, G., & Luo, W. (2021). Bacterial dynamics and functions for gaseous emissions and humification in response to aeration intensities during kitchen waste composting. *Bioresource Technology*, *337*, 125369. https://doi.org/10.1016/j.biortech.2021.125369

Yang, L., Gu, J., Yang, Y., Yang, Y., Shan, C., & Shen, F. (2024) The effects of postfire regeneration patterns on soil microbial metabolic limitation based on eco-enzyme stoichiometry in the boreal forest of China. *Forest Ecology and Management*, *568*, 122129. https://doi.org/10.1016/j.foreco.2024.122129

Yang, L., Jie, G., She Qi, Z., Long-Xiang, S., Wei, S., Qian, X., Man-Li, D., Ya-Nan, Y., & Xiao-Juan, W. (2018). Effects of adding compound microbial inoculum on microbial community diversity and enzymatic activity during co-composting. *Environmental Engineering Science*, *35*(4), 270-278. http://dx.doi.org/10.1089/ees.2016.0423

Zhang, J., Cook, J., Nearing, J. T., Zhang, J., Raudonis, R., Glick, B. R., Langille, M. G. I. & Cheng, Z. (2021). Harnessing the plant microbiome to promote the growth of agricultural crops. *Microbiological Research*, *245*, 126690. https://doi.org/10.1016/j.micres.2020.126690

Zhou, X., Luo, X., Liu, K., Zheng, T., Ling, P., Huang, J., Chen, W., & Huang, Q. (2024). Importance of soil ecoenzyme stoichiometry for efficient polycyclic aromatic hydrocarbon biodegradation. *Chemosphere*, *359*, 142348. https://doi.org/10.1016/j.chemosphere.2024.142348

Zhou, Q., Sun, H., Jia, L., Wu, W., & Wang, J. (2022). Simultaneous biological removal of nitrogen and phosphorus from secondary effluent of wastewater treatment plants by advanced treatment: A review. *Chemosphere*, *296*, 134054. https://doi.org/10.1016/j.chemosphere.2022.134054

Zhu, N., Zhu, Y., Kan, Z., Li, B., Cao, Y., & Jin, H. (2021). Effects of two-stage microbial inoculation on organic carbon turnover and fungal community succession during co-composting of cattle manure and rice straw. *Bioresource Technology*, *341*, 125842. https://doi.org/10.1016/j.biortech.2021.125842