Microbial Conversion of Kitchen Waste to Bioenzymes: Promoting Circular Economy and Zero-Waste Initiatives

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Abstract: ***This research delves into the potential of transforming household kitchen waste into bioenzymes via microbial fermentation, assessing their viability as eco-friendly solutions for environmental management and agricultural use. The study aims to showcase how converting organic waste into bioenzymes can mitigate environmental pollution, foster sustainable farming practices, and bolster zero-waste initiatives. The methodology involves fermenting a blend of fruit peels, vegetable scraps, and other organic waste with jaggery and water in a 3: 1: 10 ratio for a duration of 30 to 90 days. Observations of physicochemical changes during fermentation, such as pH reduction and odor alteration, confirmed effective microbial decomposition. Enzymatic activity tests indicated high amylase activity and moderate protease and cellulase activity, highlighting the bioenzyme's potential to enhance soil fertility and aid in composting. Microbial analysis revealed a predominance of beneficial bacteria and yeasts, which contribute to the breakdown of organic matter and improve soil microbial diversity. Application trials on potted plants demonstrated improved growth and soil quality with bioenzyme treatment, supporting its use as a natural biofertilizer. The bioenzyme-treated organic waste decomposed 2–3 times faster than untreated waste, underscoring its potential in waste management and reducing landfill emissions. The production of bioenzymes is economically feasible, particularly in rural and low-income areas, as it utilizes readily available materials and requires minimal infrastructure. This approach encourages community involvement, environmental stewardship, and opportunities for small-scale entrepreneurship. Transforming kitchen waste into bioenzymes aligns with the principles of a circular economy and zero-waste efforts by preventing organic waste from reaching landfills and reducing greenhouse gas emissions. Future research should focus on enhancing fermentation efficiency, standardizing substrate compositions, and expanding production capabilities for broader applications in agriculture, sanitation, and various industries.***

Keywords: Bioenzymes, Kitchen waste, Microbial fermentation, Sustainable agriculture, Environmental sanitation, Composting, Biofertilizer, Waste management, Circular economy, Zero-waste initiatives

1. Introduction

Globally, kitchen waste constitutes a significant portion of municipal solid waste (MSW), often accounting for 50–60% of household trash, particularly in developing nations such as India. This waste comprises fruit and vegetable peels, leftover food, tea leaves, eggshells, and other biodegradable materials with high organic content and moisture. When not disposed properly, kitchen waste leads to environmental and health problems, including greenhouse gas emissions, pollution, and the spread of pests. However, with effective management, kitchen waste can be transformed into a valuable resource through composting, anaerobic digestion, or recycling. These methods help alleviate the pressure on landfills while supporting the circular economy by generating soil enhancers and renewable energy. (Ansar et al.2025)

When organic wastes are dumped in landfills without treatment, they undergo anaerobic decomposition owing to a lack of oxygen. This process produces methane (CH_4), a greenhouse gas that is 25 times more potent than carbon dioxide (CO_2) in terms of global warming potential over a 100-year period (IPCC 2021). This decomposition releases leachate, a toxic liquid that can seep into groundwater, causing environmental harm. (Igwegbe et al.2024) Kitchen waste management plays a crucial role in resource conservation and energy efficiency. By diverting organic waste from landfills, the need for new landfill sites can be reduced and the lifespan of existing landfills extended. The products from kitchen waste recycling, such as compost and biogas, can replace synthetic fertilizers and fossil fuels, leading to reduced carbon emissions and resource depletion. (Meng et al.2022)

The adoption of effective kitchen waste management strategies can yield significant social and economic advantages. These practices can generate employment opportunities in the areas of waste collection, processing, and recycling while also encouraging communities to embrace environmental stewardship. Additionally, transforming kitchen waste into value-added products can boost local economies and support sustainable agriculture.

The United Nations Environment Programme (UNEP) reports that approximately 931 million tons of food waste is produced globally each year, with a large portion not being composted or recycled, ultimately ending up in landfills. In India, the Food and Agricultural Organization (FAO) estimates that about 67 million tonnes of food are wasted annually, with a significant amount coming from households. (Voss et al.2024)

Inadequately managed landfills can release offensive odors, draw in pests, and contribute to the development of ground-level ozone and smog, both of which pose threats to human health and the environment. The cumulative effects of these landfills accelerate climate change, degrade soil and water quality, and place additional pressure on municipal waste-management systems. These sites present significant environmental and health dangers that extend beyond the immediate surroundings. The breakdown of organic waste under anaerobic conditions generates methane, a potent greenhouse gas that intensifies global warming. (Ozbay et al.2021) This process also produces leachate, a toxic liquid that can contaminate groundwater and nearby water bodies if not properly contained. Additionally, the presence of hazardous materials such as electronic waste and chemicals in landfills increases the risk of pollution and releases harmful substances into the surrounding ecosystem.

Mismanaged landfills have negative effects on local communities and urban areas. The release of VOCs and particulate matter from waste decomposition contributes to poor air quality, leading to respiratory issues and health problems in nearby residents. The visual blight of overflowing landfills decreases property values and quality of life in surrounding neighborhoods. Increased truck traffic and road wear further compounds the socio-economic challenges of inadequate waste management. (Meena et al.2020)

Converting kitchen waste into bioenzymes addresses improper organic waste disposal while reducing methane emissions, improving carbon footprint, and promoting a circular economy through waste valorization.

Bioenzymes are organic bioactive substances produced through microbial fermentation of biodegradable organic waste, such as fruit peels, vegetable scraps, and kitchen refuse. These substances contain naturally occurring enzymes, beneficial microorganisms, and metabolic byproducts from the breakdown of organic matter. During fermentation, microbes use sugars and moisture from the waste to produce enzymes such as amylases, proteases, cellulases, and lipases, which accelerate the decomposition of organic compounds into simpler forms. (Jiménez-Moreno et al.2019) The process involves mixing organic waste with sugar and water in a 3: 1: 10 ratio, followed by incubation for 30 to 90 days. During fermentation, pH decreases, microbial populations diversify, and the liquid becomes rich in enzymes and organic acids.

Bioenzymes have attracted interest because of their versatile uses in various industries. In the agricultural sector, they function as natural biofertilizers and biopesticides, promoting plant growth while minimizing the need for chemical input. In the realm of waste management, they facilitate the breakdown of organic waste, thereby decreasing landfill pressures and emissions. Bioenzymes offer a natural substitute for synthetic detergents in household cleaning. Their biodegradability and cost-effectiveness make them particularly suitable for sustainable development, especially in rural areas. The production of bioenzymes supports global initiatives towards a circular economy and environmentally friendly practices, positioning them as crucial components of future green technologies. (C and Vudikala 2025)

Bioenzymes are environmentally friendly and cost-efficient solutions for addressing environmental and agricultural issues. In contrast to synthetic chemicals, which can be hazardous, bioenzymes are naturally sourced and nontoxic. Their application minimizes the environmental footprint associated with chemical fertilizers and waste management. These microbial enzymes decompose organic materials into nutrients without leaving harmful residues, thereby supporting sustainable resource utilization. (Rautela et al.2024)

Bioenzymes provide a cost-effective solution, particularly in rural and low-income regions. Their production requires minimal infrastructure using readily available materials such as kitchen waste and jaggery. These enzymes can replace expensive agrochemicals and cleaning agents, thereby reducing the costs for farmers and households. Because they can be prepared locally, bioenzymes enable communities to participate in sustainable practices.

Bioenzymes are used extensively in various industries. In agriculture, they enhance soil quality, boost microbial activity, and aid seed germination. In the realm of environmental sanitation, they break down pollutants and help to maintain clean drainage systems. Additionally, they are employed in the textile, leather, and food-processing sectors as eco-friendly alternatives. This versatility makes bioenzymes essential for sustainable practices to support health, increase productivity, and protect the environment.

Converting household organic waste into bioenzymes not only benefits the environment but also offers notable economic benefits. This transformation of waste into a valuable asset opens up economic opportunities for local communities and decreases their reliance on imported agricultural supplies. By producing and selling bioenzymes, households and communities can potentially earn income, thereby promoting a grassroots circular economy. Moreover, if bioenzyme production becomes widespread, municipal waste management expenses could be lowered as there would be less organic waste to be collected and processed. (Sulewski et al.2021)

Bioenzymes demonstrate versatility across industries beyond agriculture, including textile processing, bioremediation, and cleaning products. This multi-faceted utility expands their market potential while reducing chemical pollution. As research advances, bioenzymes' role in sustainable development will likely grow, transforming waste management and industrial processes globally. (Bharagava et al.2019)

This research aims to investigate the feasibility of generating bioenzymes from household organic waste via microbial fermentation and to assess their potential as environmentally friendly alternatives for environmental management and agricultural use. The study intends to illustrate how transforming kitchen waste into bioenzymes can help decrease environmental pollution, encourage sustainable farming practices, and advance zero-waste initiatives. Furthermore, the research seeks to evaluate the enzyme activity, practical application, and economic viability of producing bioenzymes at the household level as a viable model for sustainable development.

2. Materials and Methods

This section delineates the sequential procedures employed in the production, fermentation, and evaluation of bioenzymes derived from household kitchen waste. The methodology was crafted to ensure cost-effectiveness, reproducibility, and minimal infrastructure requirements, rendering it suitable for household or small-scale community implementation.

2.1 Materials Required

1) Organic Waste (Substrate Source): Fruit Peels: Banana, orange, mango, papaya, and pineapple peels, which are rich in sugars, vitamins, and cellulose.
2) Vegetable Scraps: Cabbage leaves, spinach stalks, onion skins, and carrot ends, which contain cellulose and minerals.
3) Other Organic Waste: Used tea leaves and eggshells, which serve as a calcium source, as well as overripe fruits. These materials were collected fresh from household kitchens, rinsed, and chopped into small pieces (~2–3 cm).
4) Sugar Source (Fermentable Carbon Source):
5) Jaggery (unrefined cane sugar) serves as a substrate for fermenting microorganisms.
6) Water: Clean, potable water was utilized, having been boiled and subsequently cooled to remove any chlorine or microbial contaminants that might interfere with the fermentation process.
7) Fermentation Containers:
   Containers made of airtight plastic or glass, equipped with either screw caps or flip lids, and having a capacity of 5–10 liters, were meticulously cleaned and sterilized using hot water prior to use.
8) Supplementary Equipment and Tools
   - Stirring rods for consistent mixing.
   - Muslin cloth or a fine sieve for filtering.
   - A digital pH meter to observe changes in acidity during fermentation.
   - A weighing balance for precise measurement of waste and jiggery.

2.2. Preparation of Bioenzyme Solution

1) Sorting and Chopping:
The collected kitchen waste was sorted to eliminate any non-biodegradable items. The organic material was then cut into small, uniform pieces to increase the surface area and promote microbial activity.

2) Weighing and Mixing:
The standard ratio used was: 3 parts chopped kitchen waste: 1 part jaggery: 10 parts water (by volume)
For instance, 300 g of organic waste + 100 g of jaggery + 1 liter of water.

3) Fermentation Process:
The components were thoroughly combined and placed into a fermentation vessel. The lid was either loosely secured or equipped with a small valve to permit the escape of carbon dioxide (CO_2) while limiting oxygen exposure. The container was marked with the preparation date and stored in a dark, well-ventilated area with a temperature range of 25–35°C. The mixture was stirred every three days using a clean wooden stick or plastic spatula to ensure uniform fermentation and to prevent mold from forming on the surface. The fermentation process spanned 30 to 90 days, influenced by the ambient temperature and the composition of the raw materials.

4) Filtration and Storage:
Upon completion of the fermentation process, as indicated by a vinegar-like odor, a pH value of less than 4, and a decrease in bubbling activity, the mixture was filtered using a muslin cloth. The resulting bioenzyme liquid was collected and stored in clean, dry bottles, preferably amber-colored to prevent light exposure. The remaining residue, referred to as fermentation sludge, was either composted or utilized as a soil amendment.

2.3. Physicochemical and Microbial Analysis

1) pH Monitoring:
pH measurements were conducted on Day 0, Day 15, Day 30, and the final day (either Day 60 or Day 90) utilizing a digital pH meter. This procedure facilitated the evaluation of the fermentation process and the progression of acidity over time.

2) Enzyme Activity Testing:
- Amylase Activity: Evaluated through the starch hydrolysis technique. The bioenzyme was placed on a starch agar plate and left to incubate. The appearance of a clear zone after applying iodine signified amylase activity.
- Protease Activity: Assessed by casein digestion. The enzyme was introduced to a milk protein solution, and the breakdown of cloudiness was observed.
- Lipase Activity: Determined using olive oil emulsions. The formation of clear zones indicated the activity of fat-degrading enzymes.
- Cellulase Activity: Analyzed by the degradation of filter paper in a liquid medium, monitored by observing a reduction in fiber structure.

3) Microbial Population Assessment:
A 1 mL sample of bio- enzyme underwent serial dilution and was subsequently plated on both nutrient agar and selective media. Incubation was conducted at 30°C for a duration of 24 to 48 hours. Colony Forming Units (CFU/mL) were enumerated to assess the microbial load. Gram staining and simple microscopy techniques were employed to identify prevalent beneficial bacteria and yeasts.

2.4. Application Trials

1) Soil Application (Bio- fertilizer Use):
A solution of bio- enzyme and water in a 1: 10 ratio was prepared and applied to pots with spinach and fenugreek plants. Control pots were given only water. Over the course of three weeks, data on shoot height, leaf number, and soil moisture were collected.

2) Organic Waste Decomposition Test:
Fresh vegetable peels were evenly divided into two separate piles: one was treated with a bioenzyme, and the other was left untreated. The decomposition process was tracked and recorded on a daily basis. Weight reduction and visual signs of breakdown served as the indicators.

3) Odor and Cleaning Efficiency (Optional Study):
Bioenzyme was utilized to clean greasy kitchen surfaces and drains, and its performance was evaluated against synthetic cleaners based on scent, cleaning efficiency, and user satisfaction.

3. Results

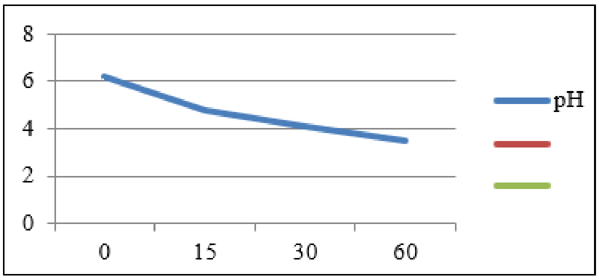
This section details the results obtained from the fermentation process, enzyme activity evaluations, microbial analyses, and trials involving the use of bioenzymes in agriculture and waste breakdown. Data were systematically collected throughout the fermentation and experimental phases.

3.1 Fermentation Progress and Physicochemical Changes

The fermentation process was monitored for changes in physical parameters such as pH, odor, color, and CO_2 release.

Table 1: Physicochemical Properties of Fermenting Bioenzyme

Parameter	Day 0	Day 15	Day 30	Day 60
pH	6.2	4.8	4.1	3.5
Odor	Mild fruity	Sweet-sour	Vinegary	Fermented acidic
Color	Light yellow	Brownish	Dark brown	Dark brown
Gas Production	None	High (bubbling)	Moderate	Minimal



Graph 1: pH Reduction During Fermentation Process

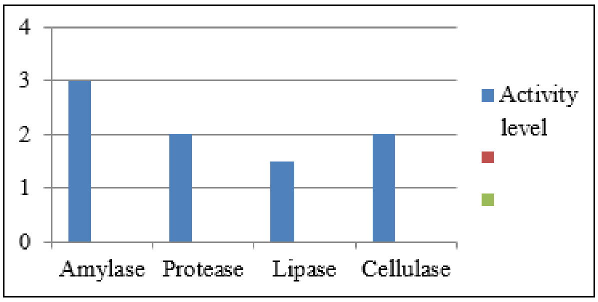
pH decreases steadily from 6.2 → 3.5 over 60 days.

3.2. Enzyme Activity Test Results

Different enzymatic activities were observed in the bioenzyme solution using standard substrate breakdown methods

Table 2: Enzymatic Activity Observed in Bioenzyme

Enzyme	Test Method	Observation (Qualitative)	Activity Level
Amylase	Starch Agar (Iodine test)	Clear halo zone (20 mm diameter)	High
Protease	Casein Hydrolysis	Cloudiness disappeared	Moderate
Lipase	Olive oil emulsion	Light clearing zone (10 mm)	Low to Moderate
Cellulase	Filter paper breakdown	Visible breakdown after 5 days	Moderate



Graph 2: Relative Enzyme Activity (Qualitative Scale)

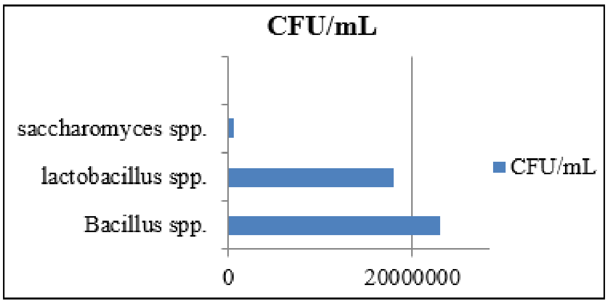
Bar chart with enzyme types on X-axis and Activity Level (Low, Moderate, High) on Y-axis:

3.3. Microbial Load Assessment

The total viable microbial count was estimated using standard plating techniques.

Table 3: Microbial Load in Bioenzyme (Day 60)

Microorganism Type	CFU/mL (approximate)	Identified Microbes	Microorganism Type
Bacteria	$2.3*10^7$ $1.8*10^7$	Bacillus spp., Lactobacillus spp.	Bacteria
Yeasts	$6.1*10^5$	Saccharomyces spp.	Yeasts
Total Aerobic Microbes		Mixed colonies	Total Aerobic Microbes



Graph 3: Microbial Population in Bioenzyme (CFU/mL)

3.4. Application Trials

a) Agricultural Use on Potted Plants (Spinach & Fenugreek)
Pots were treated with diluted bioenzyme and monitored for growth parameters.

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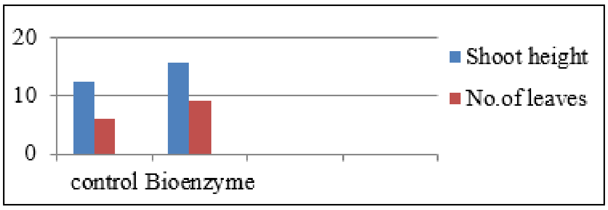
Table 4: Effect of Bioenzyme on Plant Growth (After 3 Weeks)

Treatment Type	Avg. Shoot Height (cm)	Avg. No. of Leaves	Soil Moisture Retention
Control (Water only)	12.3	6	Low
Bioenzyme-treated	15.8	9	Moderate to



Graph 4: Comparison of Plant Growth with and Without Bioenzyme

Table 5: Degradation Time Comparison

Treatment Type	Time for Visible Decomposition	Odor Level
Control (No treatment)	12 days	Strong and foul
Bioenzyme-treated	4 days	Mild acidic (no foul)

Bar chart with two groups:-Shoot height: Control (12.3 cm), Bioenzyme (15.8 cm) and - Leaf number: Control (6), Bioenzyme (9)

3.5. Summary of Key Findings

The pH of the solution dropped significantly from 6.2 to 3.5, indicating active fermentation.

High amylase and moderate protease/cellulase activity were confirmed, supporting use as composting accelerators and plant tonics.

Microbial analysis showed dominance of beneficial bacteria and yeast.

Plant trials confirmed enhanced growth and soil quality with bioenzyme.

Decomposition of organic waste was accelerated 2–3 times with bioenzyme treatment compared to control.

4. Discussion

The findings of this research strongly endorse the idea that household kitchen waste can be successfully transformed into versatile bioenzymes through microbial fermentation. This eco-friendly process not only alleviates the environmental impact of improper organic waste disposal but also produces a valuable product for use in agriculture, sanitation, and environmental management.

4.1 Fermentation and Physicochemical Transformation

The drop in pH from 6.2 to 3.5 during fermentation indicates the establishment of an anaerobic microbial ecosystem. The increased acidity results from microbes—particularly lactic acid bacteria and yeasts—breaking down sugars into organic acids. This acidification prevents pathogenic growth and enhances enzyme stability. A vinegar-like odor and CO_2 production between Day 3 and Day 15 validate effective fermentation. These findings confirm the microbial community transformed kitchen waste into a stabilized, enzyme-rich liquid under household conditions.

4.2 Enzyme Activity and Biocatalytic Potential

The enzymatic activity tests showed high amylase and moderate protease and cellulase activity, demonstrating the bioenzyme's potential. Amylase breaks down starch into sugars, while protease hydrolyzes proteins and cellulase degrades plant matter, enhancing soil fertility and composting. The lower lipase activity, due to limited fat in waste inputs, can aid in waste treatment applications.

4.3 Microbial Community and Bioproduct Formation

The microbial profile showed predominant beneficial microbes including Bacillus spp., Lactobacillus spp., and Saccharomyces spp., known for biodegradation, enzyme production, and pathogen suppression. Their presence enhances organic matter degradation and improves soil microbial diversity. The high microbial load (2.3×10^7 CFU/mL) indicates healthy fermentation and biological activity, contributing to secondary metabolites that enhance the bioenzyme's multifunctionality.

4.4 Agricultural Applications and Plant Growth Promotion

The bioenzyme application to spinach and fenugreek plants showed significant improvement in shoot height, leaves, and soil moisture versus controls, due to bioavailable nutrients and beneficial microbes that enhance soil structure. These findings support bioenzymes as natural biofertilizers, improving nutrient cycling and microbial diversity while reducing synthetic fertilizer dependency for sustainable agriculture.

4.5 Waste Decomposition and Environmental Sanitation

The bioenzyme-treated organic waste decomposed within 3-5 days, compared to 10-14 days for untreated waste. This acceleration occurs due to enzymes and microbes that break down complex organic compounds. The bioenzyme's antimicrobial and deodorizing effects reduce foul odors during decomposition, making it suitable for household and municipal waste management while helping reduce landfill loads and emissions.

4.6 Economic and Social Implications

From an economic perspective, the production of bioenzymes is highly feasible, particularly in rural and low-income urban areas. This process employs readily accessible materials, such as kitchen waste and jaggery, does not necessitate advanced equipment, and yields a value-added product with diverse applications. Households and communities can independently produce bioenzymes, thereby decreasing dependence on expensive agrochemicals, fertilizers, and cleaning products.

Socially, this practice fosters community involvement in waste management, enhances environmental consciousness,

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and generates opportunities for small-scale entrepreneurship. The participation of local stakeholders in the production and distribution of bioenzymes can contribute to grassroots environmental stewardship and the promotion of a circular economy.

4.7 Environmental Impact and Circular Economy Relevance

Transforming kitchen waste into bioenzymes supports the concepts of a circular economy and zero-waste efforts. This process prevents organic waste from ending up in landfills, cuts down on greenhouse gas emissions, especially methane, and results in a biodegradable, non-toxic, and versatile product. Incorporating such eco-friendly technologies into municipal solid waste management can greatly diminish environmental pollution and carbon emissions.

Moreover, the use of bioenzymes in various fields—such as agriculture, sanitation, waste management, and potentially industries like textiles and food processing—demonstrates its scalable and adaptable role within broader sustainable development strategies.

4.8 Limitations and Future Scope

1) The study showed promising results, but several limitations were observed:
- The fermentation duration is quite lengthy, reaching up to 60 days, which may not be practical for applications that require rapid outcomes.
- The activity of enzymes can vary with changes in the waste composition and environmental conditions. Furthermore, due to the unavailability of laboratory-grade equipment, the quantitative measurement of enzyme activity (U/mL) was not performed.
2) Future research should focus on:
- Enhancing fermentation time by employing microbial inoculants or enzymatic accelerators.
- Establishing standardized substrate compositions to achieve uniform enzyme quality.
- Expanding production capabilities for institutional or industrial use.
- Measuring enzyme kinetics and examining purification techniques.

Conflict of Interest Statement:
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability Statement:
All data generated or analyzed during this study are included in this published article. Additional datasets and raw data related to fermentation progress, enzyme activity, and application trials are available from the corresponding author upon reasonable request.

5. Conclusion

Research showed that kitchen waste from households, abundant in biodegradable organic material, can be transformed into bioenzymes through a simple, cost-effective microbial fermentation method. These bioenzymes displayed significant enzymatic activities, especially amylase and protease, and contained beneficial microbial communities, including Bacillus, Lactobacillus, and Saccharomyces species.

The physicochemical changes during fermentation, including pH reduction and odor transformation, confirmed effective microbial decomposition. The bioenzyme showed significant benefits in agriculture by promoting plant growth and improving soil conditions. In environmental sanitation, it reduced odor and accelerated waste degradation, indicating potential as a natural alternative to synthetic cleaners.

This approach fosters sustainable waste valorization by requiring minimal resources and providing maximum utility. It minimizes waste, decreases landfill reliance, and advances circular economy goals by converting waste into valuable bio-based products.

Generating bioenzymes from kitchen waste offers an environmentally friendly and cost-effective approach to sustainable farming. With increased awareness, this method can expand to household and community scales, providing a model for zero-waste living.

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