



## BIOENZYMES FROM WASTE TO WEALTH

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### ABSTRACT

Life becomes easier when waste is transformed and contributes back to society. The use of organic waste to create bioenzymes has become a sustainable approach in the circular bioeconomy. It transforms common kitchen and agricultural waste into valuable bioproducts. By fermenting fruit peels, vegetable leftovers, and other biodegradable materials, we can produce bioenzymes efficiently and at a low cost. These enzymes offer eco-friendly solutions for various uses, including wastewater treatment, agriculture, cleaning, and industrial processing. They show strong antibacterial, antifungal, and breaking-down properties, making them good alternatives to synthetic chemicals while greatly reducing environmental harm. In addition to environmental advantages, making and selling bioenzymes supports local businesses and community-based waste management, linking economic progress with caring for the environment. There are challenges in standardizing production methods and improving yields. However, ongoing research and technology are broadening the uses and scalability of bioenzyme applications around the world. By viewing waste as a resource for valuable enzyme production, this strategy represents the "waste to wealth" concept and opens doors for new, sustainable development practices.

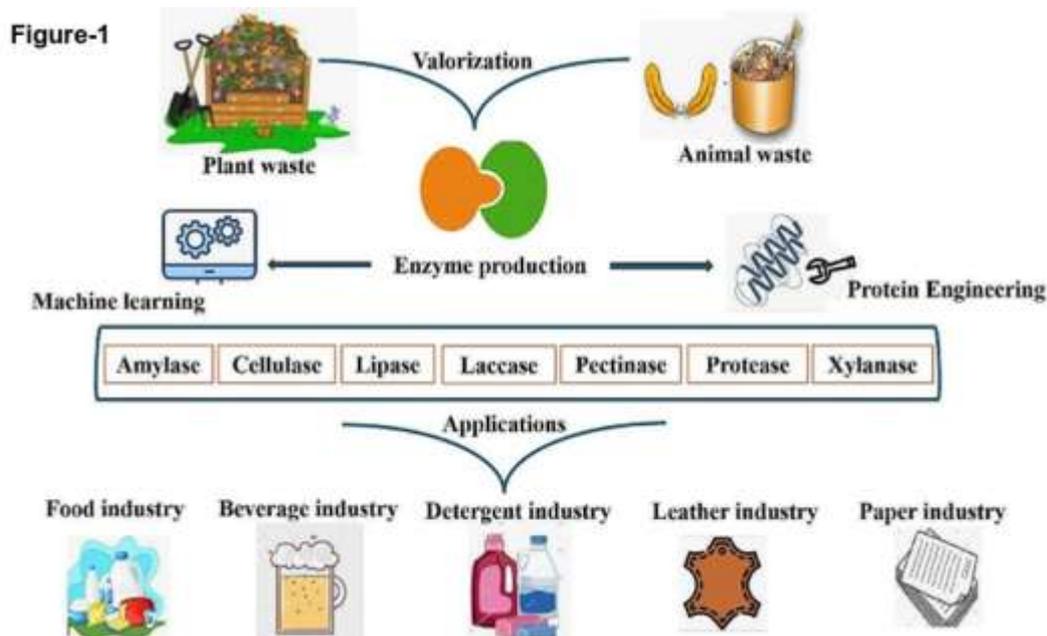
**Keywords:** Bioenzymes, organic waste materials, fermentation, waste management, sustainable development.

### INTRODUCTION

Bioenzymes are complex biochemical mixtures produced primarily through the fermentation of organic residues such as fruit peels, vegetable scraps, and agricultural waste with the help of microbes. These natural enzymes are generated by microorganisms that metabolize the carbon-rich organic matter under anaerobic or controlled aerobic conditions, usually in airtight containers. The fermentation process typically involves mixing organic waste with a sugar source, such as jaggery, molasses, or brown sugar, and water in specific ratios (commonly 1:3:10) and allowing the mixture to undergo microbial activity over a period of about three months [1-2]. During this time, the microbes break down the organic materials, releasing enzyme-rich liquids known as bioenzymes or eco-enzymes. These bioenzymes contain a rich blend of hydrolytic enzymes, secondary metabolites such as alkaloids, flavonoids, and tannins, which confer multiple beneficial properties including antibacterial, antifungal, and anti-inflammatory effects [2]. The

enzyme solution resulting from this natural fermentation serves a broad spectrum of practical applications. It is widely used as an effective natural cleaning agent that reduces chemical usage in homes and industries. Additionally, bioenzymes act as powerful soil conditioners and biofertilizers, enhancing soil fertility by promoting microbial activity and nutrient availability [3-4]. Beyond agricultural uses, bioenzymes play a significant role in environmental remediation. They are applied in wastewater treatment to degrade organic pollutants, reducing contamination and helping to recycle water safely. This eco-friendly approach provides a cost-effective and sustainable alternative to conventional chemical treatments that often produce harmful by-products [5-6]. The ability to transform organic waste into valuable bioproducts exemplifies the concept of "waste to wealth," aligning with global efforts toward sustainable waste management and circular economy practices. In summary, bioenzymes produced from organic waste represent a multifaceted solution contributing to waste reduction, environmental sustainability, and resource recovery (Figure-1) [7]. Their production harnesses microbial fermentation to convert otherwise discarded

materials into enzyme-rich solutions with extensive applications spanning cleaning, agriculture, and environmental health [1,3-4, 8].



### BIOENZYME PRODUCTION FROM WASTE

Bioenzyme production primarily involves a fermentation process, which is widely practiced for converting organic waste into valuable bioactive enzyme solutions. This process typically combines organic waste, a carbon source such as jaggery or sugar, and water in an airtight container for a prolonged period, usually around three months. During fermentation, microorganisms act on the organic matter, breaking it down to release a complex mixture of enzymes, organic acids, and other bioactive compounds. These bio-enzymes include hydrolases like amylase, cellulase, lipase, and protease, which catalyze various biochemical reactions beneficial for environmental and agricultural applications [9-10]. The fermentation is an anaerobic process, meaning it occurs in the absence of oxygen, which is crucial for the efficiency of enzyme production. Jaggery or similar sugars serve as a fermentation catalyst and carbon source, fueling microbial growth and enzymatic action. Regular agitation during the fermentation period helps distribute microbes and enzymes evenly. After fermentation, the solution is strained to separate the clear enzyme-rich liquid from the solid residues. The resulting bioenzyme solution exhibits valuable properties, including antimicrobial effects and pollutant degradation capabilities, making it useful in

both domestic cleaning and agricultural waste management [5, 11]. Beyond their cleaning and antimicrobial roles, these bioenzymes contribute to sustainable waste management by reducing organic waste volume, minimizing landfill methane emissions, and providing a cost-effective alternative to chemical fertilizers and pesticides. This approach aligns with global sustainability goals by promoting recycling of kitchen and household organic waste into eco-friendly, multipurpose bioenzyme solutions [10-12].

### CLASSIFICATION OF BIOENZYMES

Bioenzymes are specialized protein molecules produced by living organisms that catalyze biochemical reactions [13]. They can be classified based on their source, function, and underlying biochemical activity, which is crucial for formulating applications in biotechnology, cleaning, agriculture, and environmental management [14].

#### Main Types of Bio enzymes:

Bioenzymes are categorized in tabular form, according to the standardized Enzyme Commission (EC) classification (Table-1), which divides enzymes into six major classes based on the type of reaction they catalyze [15].



**Table-1:** Category of bio enzymes according to Enzyme Commission (EC) classification

Enzyme Class	EC Number	Reaction Type	Examples and Applications
Oxidoreductases	EC 1	Oxidation & reduction	Dehydrogenases for metabolism
Transferases	EC 2	Transfer functional groups	Kinases in phosphorylation
Hydrolases	EC 3	Hydrolysis of bonds	Proteases, amylases for waste treatment
Lyases	EC 4	Addition/removal of groups	Decarboxylases in biosynthesis
Isomerases	EC 5	Isomerization	Racemases for amino acid synthesis
Ligases	EC 6	Bond formation with ATP	DNA ligases in molecular biology

Many common bioenzymes used in daily life and industrial applications are hydrolases (e.g., proteases, cellulases, amylases, pectinases), which break down large molecules like proteins, carbohydrates, and fats, facilitating processes such as cleaning, wastewater treatment, and composting [16].

#### SOURCE-BASED CLASSIFICATION

Plant-derived bioenzymes: Orange, hibiscus, ginger, tamarind, soapnut, and neem bioenzymes are produced by fermenting plant materials. They are widely used for cleaning and as fertilizers due to their antimicrobial and enzymatic properties [17].

Microbial bioenzymes: Produced by bacteria and fungi (e.g., *Bacillus*, *Sporosarcina*, *Clostridium*), these are utilized in soil improvement and biodegradation processes [18].

Animal-derived bioenzymes: Though less common, these include those used in medical or laboratory contexts—such as digestive enzymes like pepsin and trypsin [19].

#### FUNCTIONAL-BASED CLASSIFICATION

Antimicrobial bioenzymes: Exhibit antibacterial, antifungal, and antiviral properties, making them suitable for cleaning and sanitation [20].

Catalysts in Sustainable Chemistry: Used in green chemistry for environmentally friendly processes due to their biodegradability and renewability [21].

Agricultural and Environmental Use: Decompose waste and improve soil health through accelerating organic matter breakdown [22].

#### APPLICATIONS: FROM WASTE TO WEALTH

Bioenzymes from organic waste are increasingly recognized as pivotal agents in the circular economy, offering a transformative path from waste to wealth. These natural catalysts, derived via fermentation of fruit peels, molasses, and other household or municipal organic wastes, convert low-value refuse into marketable products while substantially reducing waste management costs and chemical pollution [23]. In agriculture, bioenzymes serve as fertilizers and soil conditioners that improve nutrient cycling, enhance plant growth, and increase yields, with the added

benefit of reducing the input of synthetic chemicals [24-25]. The deployment of these eco-friendly formulations across rural communities demonstrates the scalability and resilience of such circular approaches, particularly in biodiversity hotspots where traditional farming coexists with modern sustainability practices [26]. Bioenzymes have emerged as powerful tools in domestic and municipal wastewater treatment. They efficiently lower chemical oxygen demand (COD) and biological oxygen demand (BOD) in wastewater streams, meanwhile neutralizing pathogens, thanks to their natural enzymatic and microbial pathways [27]. Unlike conventional treatments that rely on harsh chemicals, bioenzyme treatments are cost-effective, scalable, and sustainable, making decentralized and rural wastewater management feasible. The field of biorefinery has begun to exploit bioenzymes and waste-derived substrates—such as agro-industrial residues and cyanobacterial cultivation environments—to synthesize bioethanol, biopolymers, and other high-value products [28]. These integrated technological platforms offer not just bioenergy, but also a suite of products with industrial and commercial applications, advancing the circular bio-economy. Household and industrial applications of bio-enzymes continue to expand. They are now incorporated into natural cleaning agents, textile processing, and even paper recycling, providing an eco-friendly substitute for chemical treatments while reducing environmental toxicity [29]. The versatility of bio-enzymes extends to their use in bioremediation, where they facilitate the breakdown of heavy metals and hydrocarbons in contaminated soils. The "waste to wealth" concept is best illustrated by bio-enzymes, which transform organic waste into useful resources for industry, agriculture, and environmental cleanup. This is in line with international initiatives to reduce pollution and increase the value of waste.

### **ECONOMIC AND ENVIRONMENTAL IMPACT**

Several case studies demonstrate the dual impact of bioenzyme production—not only mitigating pollution and maximizing resource recovery but also creating economic opportunities for communities through the sale of bioenzyme products. For instance, innovative approaches have used wastewater and solid wastes like poultry litter and cow dung for cultivating microorganisms that produce bioenzymes while simultaneously bioremediating the waste. This reduces harmful contaminants such as nitrites, nitrates, and

organic carbon, yielding cleaner water and reduced environmental pollution. Moreover, the biomass produced can be converted into valuable co-products including bioethanol and biopolymers, enhancing overall resource valorization by up to 61% [30]. The "waste to wealth" paradigm in bioenzyme technology supports sustainable development by promoting circular economy principles. Agro-industrial waste residues serve as inexpensive raw materials for producing industrially important enzymes, which can be utilized across sectors such as agriculture, pharmaceuticals, and biofuels. This creates localized economic benefits by enabling rural and marginalized communities to generate income from waste-derived bioenzyme products while reducing dependency on conventional disposal methods [31-32]. The alignment of these approaches with global objectives for zero-waste and resource efficiency contributes to environmental conservation and climate action [33]. Additionally, the scalability of these models has been demonstrated, converting household organic waste into enzyme-rich fertilizers that improve soil health and crop yields, further driving economic upliftment in agricultural communities [34]. By fostering an ecosystem where waste streams are converted into valuable bio-products, bioenzyme technologies exemplify how scientific innovation can generate both economic returns and ecological benefits, embodying the sustainable "waste to wealth" vision.

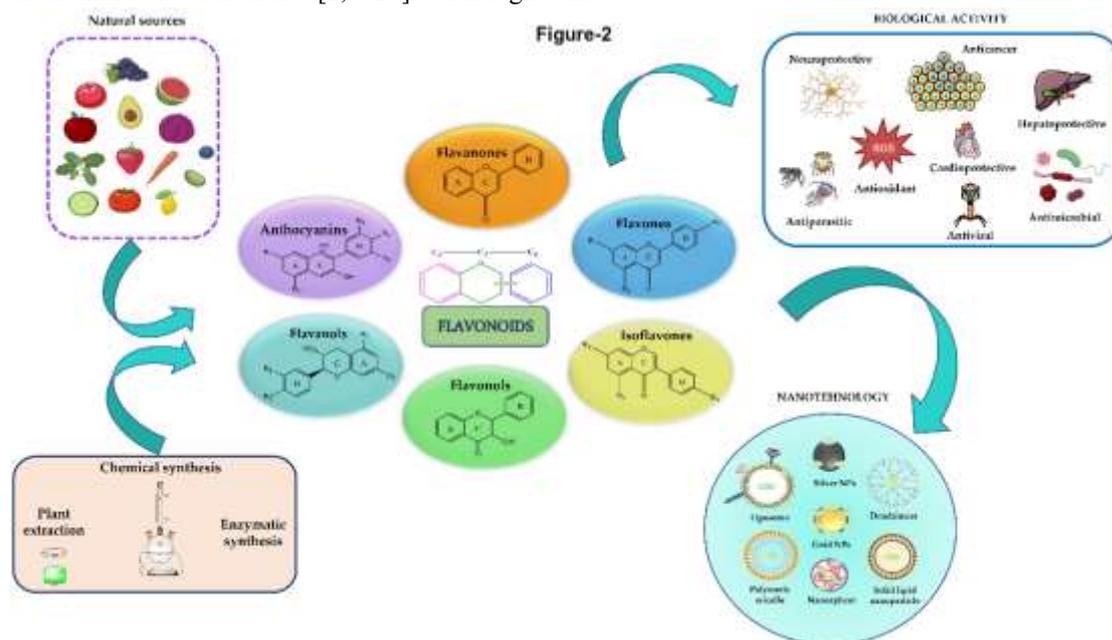
### **BIOLOGICAL POTENTIALS OF BIOENZYMES**

Bioenzymes, often derived from natural organic sources through fermentation processes, exhibit diverse biological potentials that have garnered significant interest in various fields including medicine, agriculture, and environmental management. These enzymes contain secondary metabolites (Figure-2) [35] such as alkaloids, flavonoids, tannins, quinones, saponins, and cardenolides, which are known for a spectrum of bioactivities including antibacterial, antifungal, antiviral, anti-inflammatory, insecticidal, and antioxidant properties [2]. This biochemical diversity enables bioenzymes to be effective in applications ranging from wound healing to soil stabilization and waste treatment. In the medical domain, bioenzymes demonstrate potential for enhanced therapeutic applications. For instance, bioenzyme-based nanomedicines have been innovatively used to target cancer treatments through mechanisms like direct induction of cancer cell death, modulation of the tumor microenvironment, and degradation of tumor extracellular matrix components.



These multifaceted biological activities allow bioenzymes to enhance the efficacy of treatments such as chemotherapy and immunotherapy [36]. Similarly, bioenzymes derived from Mosambi peel exhibit wound-healing capabilities in animals by promoting rapid blood clotting and normal tissue repair processes while also serving as natural fly repellents, offering cost-effective alternatives to antibiotics and addressing issues of antibiotic resistance [37]. Beyond medical uses, bioenzymes contribute to sustainable agricultural and environmental practices. They have proved efficient in soil improvement and stabilization by facilitating biochemical reactions that enhance soil structure and fertility without the use of harmful chemicals [38-39]. Additionally, bioenzymes play a critical role in the biodegradation of organic waste and wastewater treatment, leveraging their catalytic activity to break down pollutants and reduce environmental toxicities [2, 27]. Through the

degradation of organic matter and toxic compounds, bioenzymes embody an eco-friendly approach to environmental management and waste valorisation. Despite these promising potentials, challenges remain in the clinical and industrial translation of bioenzymes. These include the need for comprehensive evaluation of enzyme immunogenicity, catalytic activity stability under varying conditions, and methods to achieve targeted delivery and controlled release [40]. Moreover, large-scale production and regulatory approval are ongoing hurdles that require innovative manufacturing processes and thorough safety assessments. To sum up, bioenzymes offer a flexible biological toolkit with potential uses in environmental sustainability, agriculture, and healthcare. To fully utilize the biological potential of bioenzymes, future research aimed at resolving clinical and production issues will be essential.



### CHALLENGES AND FUTURE DIRECTIONS

Bioenzymes represent a promising frontier in converting waste into wealth, but several critical challenges must be addressed to realize their full potential. Current obstacles include scalability, where transitioning from laboratory-scale to industrial-level production demands significant advancements in process optimization to enhance efficiency and cost-effectiveness [41-42]. Additionally, regulatory standards for bioenzyme products remain inconsistent across regions, posing barriers to widespread adoption

and commercialization [43]. Maintaining consistent product quality is also a key challenge due to variability in waste feedstocks and fermentation conditions, which requires standardized protocols and quality control measures [44]. Advances in protein engineering hold promise for creating more robust and efficient bioenzymes tailored to target waste substrates, enhancing bioconversion processes [45]. Integration of multiple technologies, including microbial bioconversion, nanotechnology, and multiomics platforms, is expected to improve process yields and

enable the valorization of diverse waste streams into high-value products [22,46]. Furthermore, improved waste collection and segregation systems are crucial to providing consistent and high-quality raw materials for bioenzyme production, which will also minimize contamination risks [47]. The future direction of bioenzymes lies in their deeper integration into green chemistry and sustainable industry practices to foster circular economies that minimize waste and maximize resource recovery [48]. Emphasizing bioenzyme applications across agriculture, wastewater treatment, and industrial cleaning can reduce reliance on chemical fertilizers and harsh solvents, promoting eco-friendly alternatives that support environmental and human health [49]. Continued research, policy support, and public awareness will be vital to overcoming existing challenges and expanding bioenzyme technologies' reach and effectiveness, thereby advancing sustainability goals.

## DISCUSSION

Converting organic residues into bioenzymes through microbial fermentation offers an eco-friendly and economical approach with applications across multiple sectors. These bioenzymes, generated from the fermentation of fruit and vegetable wastes with sugar sources, possess hydrolytic enzymes and bioactive compounds that exhibit antimicrobial and degradative effects [1-2]. These properties render bioenzymes viable alternatives to synthetic chemicals for applications in wastewater treatment, agriculture, cleaning, and industrial processes, significantly reducing environmental pollution [5]. Their use fosters circular economy principles by converting waste into valuable resources while supporting local economies through entrepreneurship and community-driven waste management [31, 50]. However, challenges remain in scaling production efficiently, standardizing quality across variable feedstocks, and navigating regulatory frameworks, which require advances in process optimization, protein engineering, and integrated technologies [33]. Furthermore, bioenzymes exhibit diverse biological potentials, including roles as biopesticides and nanomedicines, extending their impact from environmental remediation to healthcare [36,37]. The ongoing research and technological innovations are critical to overcoming production and application constraints and unlocking the broad utility of bioenzymes in sustainable development.

**Conclusion:** Bioenzymes derived from organic waste exemplify the "waste to wealth" concept by

transforming discarded biomass into multifunctional bioproducts that promote environmental sustainability, economic development, and health benefits. Through microbial fermentation, bioenzymes offer effective, eco-friendly solutions for pollution reduction, soil fertility enhancement, pest management, and industrial applications, aligning with circular bioeconomy objectives. Despite production and regulatory challenges, continued advances in biotechnology and integrated waste management promise to expand their scalability and commercial viability. Future efforts focused on optimizing fermentation processes, ensuring product quality, and fostering supportive policies will be essential to fully realize bioenzymes' potential as sustainable alternatives to synthetic chemicals and contributors to global sustainability goals.

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## CONFLICT OF INTEREST

Authors have no conflict of interest.

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