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ENZYMATIC BIODEGRADATION OF AGRICULTURAL WASTE IN NIGERIA: ADVANCES AND FUTURE PROSPECTS

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ABSTRACT

Nigeria generates enormous volumes of agricultural waste annually, including cassava peels, rice husk, sugarcane bagasse, corn cobs, palm empty fruit bunches, and sorghum stalks. Inefficient disposal of these residues contributes to greenhouse gas emissions, soil degradation, and public health burdens. Enzymatic biodegradation offers a sustainable and cost-effective strategy for the valorisation of these lignocellulosic materials into fermentable sugars, biofuels, pharmaceutical precursors, and other high-value products. This review critically examines the advances in the enzymatic biodegradation of agricultural waste in Nigeria, with emphasis on key enzyme systems, cellulases, hemicellulases, laccases, lignin peroxidases, and manganese peroxidases, and the microorganisms responsible for their production. The role of solid-state fermentation (SSF) and submerged fermentation (SmF) as platforms for enzyme production is discussed, along with physicochemical parameters influencing enzyme activity and yield. The biotechnological applications of these enzymatic processes, particularly bioethanol production, bioremediation, and the synthesis of pharmaceutical-grade compounds, are highlighted. Current challenges, including high enzyme production costs, substrate recalcitrance, and limited scale-up infrastructure in Nigeria, are identified, alongside emerging strategies such as enzyme engineering, consolidated bioprocessing (CBP), and the circular bioeconomy model. This review identifies critical gaps in Nigerian-specific enzyme biotechnology research and recommends targeted policy, investment, and translational pathways to unlock the full potential of the country's agricultural waste biomass.

Keywords: Enzymatic biodegradation; Agricultural waste; Lignocellulosic biomass; Nigeria; Cellulase; Laccase; Biofuel; Circular bioeconomy; Solid-state fermentation; Biorefinery.

1. INTRODUCTION

Nigeria, with a population exceeding 220 million people and an agricultural sector contributing approximately 24% of gross domestic product (GDP), is one of Africa's foremost agrarian economies.[1] Major food and industrial crops, including cassava (Manihot esculenta), maize (Zea mays), rice (Oryza sativa), sorghum (Sorghum bicolour), sugarcane (Saccharum officinarum), and oil palm (Elaeis guineensis), are cultivated across the country's diverse agroecological zones. The processing and harvesting of these crops generate staggering quantities of residual biomass. Nigeria is the world's largest producer of cassava, producing over 59 million tonnes annually, and

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the second-largest maize producer in Africa. [2,3] The waste streams from these value chains, comprising peels, husks, stalks, bagasse, and cobs, represent a largely untapped reservoir of lignocellulosic biomass.

Conventional disposal methods such as open burning and unregulated dumping of agricultural residues exacerbate air pollution, greenhouse gas emissions, and environmental contamination.[4] Against this backdrop, the concept of enzymatic biodegradation has emerged as a transformative approach, facilitating the breakdown of complex polymeric structures in biomass through the catalytic action of specific enzyme systems. Cellulases, hemicellulases, laccases, lignin peroxidases (LiP), and manganese peroxidases (MnP) constitute the principal enzyme classes involved in the deconstruction of cellulose, hemicellulose, and lignin, the three major structural components of plant cell walls.[5]

Enzymatic processes offer distinct advantages over chemical hydrolysis, including greater substrate specificity, milder operating conditions, reduced generation of toxic inhibitory by-products, and compatibility with downstream fermentation processes.[6] In the pharmaceutical and biotechnology industries, enzymes derived from agricultural waste bioconversion are increasingly recognised as precursors for bioactive molecules, drug-delivery excipients, and speciality chemicals.[7]

Despite a growing body of research on enzymatic biodegradation in West Africa, systematic documentation of advances specifically within Nigeria, the region's dominant agricultural producer, remains limited. This review synthesises current knowledge on enzymatic biodegradation of agricultural waste in Nigeria, covering the biochemical basis of enzyme action, microbial sources, fermentation strategies, value-chain applications, and prospects. Special attention is drawn to research conducted by Nigerian institutions and to the translational challenges unique to low- and middle-income country (LMIC) settings.

2. TYPES AND VOLUMES OF AGRICULTURAL WASTE IN NIGERIA

Nigeria's diverse agricultural production generates a heterogeneous portfolio of residual biomass that constitutes the primary feedstock for enzymatic bioconversion processes. Table 1 below summarises the major agricultural wastes, their approximate annual generation volumes, biochemical compositions, and the dominant enzymatic targets associated with each substrate.

Table 1. Major agricultural wastes in Nigeria: composition and enzymatic targets

Agricultural Waste	Source Crop	Approx. Annual Volume (Nigeria)	Main Biochemical Components	Dominant Enzyme Target
Cassava peels	Cassava (M. esculenta)	~6 million t/year	Starch (40–60%), Cellulose (10–20%), Pectin	Amylase, Cellulase, Pectinase
Rice husk/straw	Oryza sativa	~1.8 million t/year	Cellulose (35–40%), Silica (15–	Cellulase, Xylanase

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Agricultural Waste	Source Crop	Approx. Annual Volume (Nigeria)	Main Biochemical Components	Dominant Enzyme Target
			20%), Hemicellulose	
Sugarcane bagasse	Saccharum officinarum	~300,000 t/year	Cellulose (40–50%), Hemicellulose (25%), Lignin (20%)	Cellulase, Laccase, MnP
Corn cob/stover	Zea mays	~4 million t/year	Hemicellulose (35–40%), Cellulose (30%), Lignin (15%)	Xylanase, Cellulase, LiP
Palm fruit empty bunches	Elaeis guineensis	~1.4 million t/year	Cellulose (44%), Hemicellulose (27%), Lignin (17%)	Cellulase, Laccase
Groundnut shells	Arachis hypogaea	~600,000 t/year	Cellulose (35%), Hemicellulose (18%), Lignin (30%)	LiP, MnP, Cellulase
Sorghum stalks	Sorghum bicolor	~3 million t/year	Cellulose (32%), Hemicellulose (27%), Lignin (18%)	Cellulase, Xylanase, Laccase

MnP = manganese peroxidase; LiP = lignin peroxidase.

Sources: Compiled from references [3,7,8,9,10]

Cassava peels constitute the largest single category of agricultural biomass waste, attributable to Nigeria's status as the global leading producer.[3] Rice residues, including husk and straw, are generated across the rice-producing belts of Ebonyi, Niger, and Kebbi states. Sugarcane bagasse, a by-product of sugar milling concentrated in Sokoto, Adamawa, and Kogi states, contains 40–50% cellulose and 20–25% lignin, rendering it a tractable substrate for both cellulolytic and ligninolytic enzymes.[7,8] Corn cob, generated in large quantities in Kano, Kaduna, and Benue states, is particularly enriched in hemicellulose and constitutes an excellent substrate for xylanase production.[9] The oil palm sector, centred in Rivers, Akwa Ibom, and Cross River states, generates empty fruit bunches (EFBs) rich in cellulose (44%), making them commercially relevant for cellulase-mediated saccharification.[10] Figure 1 presents the Schematic representation of the major agricultural waste streams in Nigeria and their enzymatic biodegradation pathways into

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value-added products.

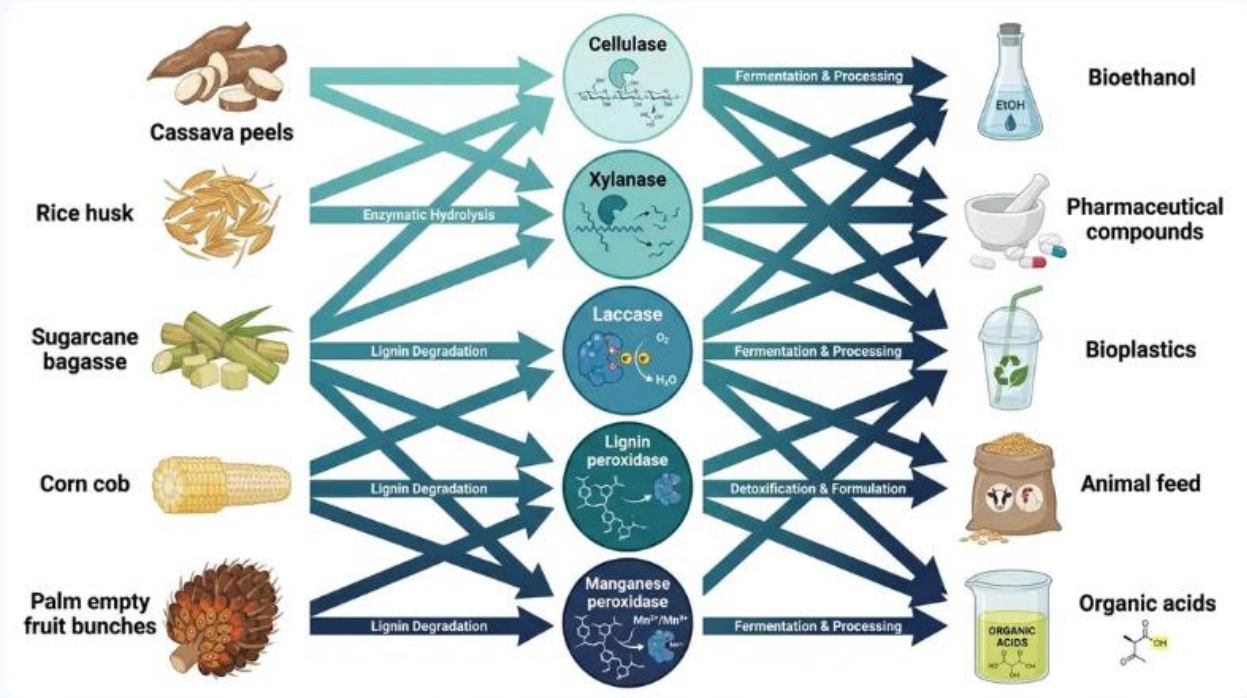


Figure 1. Schematic representation of the major agricultural waste streams in Nigeria and their enzymatic biodegradation pathways into value-added products.

Caption: A detailed scientific infographic diagram showing a flowchart of Nigeria's major agricultural waste types (cassava peels, rice husk, sugarcane bagasse, corn cob, palm empty fruit bunches) on the left side, with arrows leading through central icons representing key enzymes (cellulase, xylanase, laccase, lignin peroxidase, manganese peroxidase) in the middle, connecting to value-added products on the right (bioethanol, pharmaceutical compounds, bioplastics, animal feed, organic acids).

Sources: Created with reference to data from [4] and [7].

3. KEY ENZYMES INVOLVED IN AGRICULTURAL WASTE BIODEGRADATION

3.1 Cellulases

Cellulases are a synergistically acting enzyme complex comprising endoglucanases (EC 3.2.1.4), cellobiohydrolases (EC 3.2.1.91 and EC 3.2.1.176), and β-glucosidases (EC 3.2.1.21).[5] Endoglucanases randomly cleave internal β-1,4-glycosidic bonds in the amorphous regions of cellulose chains, generating shorter chain oligosaccharides. Cellobiohydrolases (exoglucanases) attack from the reducing and non-reducing ends of cellulose chains, releasing cellobiose units, while β-glucosidases complete saccharification by hydrolysing cellobiose to glucose. [11] In Nigeria, Aspergillus niger isolates from sugarcane bagasse and corn cob substrates have demonstrated cellulase activities of 205–302 IU/mL under optimised solid-state fermentation conditions at pH 5 and 50°C. [7] Trichoderma reesei remains the global reference organism for commercial cellulase production, though engineering efforts to enhance its β-glucosidase activity are ongoing.[12]

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3.2 Hemicellulases

Hemicellulose, the second most abundant polysaccharide in lignocellulosic biomass, is heterogeneous in structure, comprising xylan, glucuronoxylan, arabinoxylan, and glucomannan polymers depending on the biomass source.[13] Xylanases (EC 3.2.1.8) and β-xylosidases (EC 3.2.1.37) are the most industrially relevant hemicellulases for the deconstruction of the xylan backbone abundant in corn cob and rice straw. Pectinases degrade pectin-rich wastes such as cassava and citrus peels. Co-production of xylanase and cellulase by Aspergillus niger strains on sugarcane bagasse and brewery spent grain substrates has been demonstrated with promising yields under both SSF and SmF conditions. [14]

3.3 Ligninolytic Enzymes: Laccases and Peroxidases

Lignin, constituting 15–30% of lignocellulosic biomass, poses the greatest challenge to enzymatic deconstruction owing to its complex cross-linked aromaticity. Three principal ligninolytic enzyme families are recognised: (i) laccases (EC 1.10.3.2), multi-copper oxidases that catalyse the oxidation of phenolic subunits using molecular oxygen as the terminal electron acceptor; (ii) lignin peroxidases (LiP, EC 1.11.1.14), high-redox-potential heme glycoproteins that oxidise both phenolic and non-phenolic lignin units; and (iii) manganese peroxidases (MnP, EC 1.11.1.13), which operate through the oxidation of Mn^{2+} to Mn^{3+} as a diffusible oxidant.[15,16] Nigerian isolates of Trametes polyzona (WRF03) have been purified and characterised as novel laccase-producing white-rot fungi with significant biotechnological promise.[11] Versatile peroxidases (VP), which combine the catalytic features of both LiP and MnP, have also been identified in Bjerkandera and Pleurotus species recoverable from Nigerian compost and agricultural soils.[17]

4. MICROBIAL PRODUCERS OF BIODEGRADATIVE ENZYMES IN NIGERIA

A wide diversity of fungi and bacteria isolated from Nigerian soil, compost, rumen, and decaying agricultural residues serve as prolific producers of biodegradative enzymes. Table 2 summarises key microorganisms identified in the literature alongside their substrates and enzyme profiles.

Table 2. Key microbial producers of biodegradative enzymes and their agricultural waste substrates in Nigeria and related contexts

Microorganism	Substrate Used	Enzyme Produced	Fermentation Mode	Reference
Aspergillus niger	Sugarcane bagasse, corn cob	Cellulase	SmF	[7]
Trametes polyzona WRF03	Lignocellulosic waste	Laccase	SmF	[11]
Trichoderma reesei	Rice straw, wheat bran	Cellulase cocktail (EG, CBH, BGL)	SmF	[13]
Phanerochaete chrysosporium	Groundnut shells, sawdust	LiP, MnP	SSF / SmF	[16]

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Microorganism	Substrate Used	Enzyme Produced	Fermentation Mode	Reference
Streptomyces lazureus	Sawdust (lignocellulosic)	Cellulase, Ligninase	SmF	[10]
Aspergillus tubingensis	Palm empty fruit bunches	Cellulase, Xylanase	SSF + SmF	[15]
Bacillus subtilis strains	Cassava peels, rice bran	Amylase, Protease	SmF	[20]
Pleurotus ostreatus	Corn stover, cassava peels	Laccase, MnP	SSF	[17]

SmF = submerged fermentation; SSF = solid-state fermentation; LiP = lignin peroxidase; MnP = manganese peroxidase.

Sources: Compiled from references [10,17,18,19,20]

Filamentous fungi, particularly Aspergillus, Trichoderma, Penicillium, and Pleurotus species, dominate the literature as the principal enzyme producers. White-rot basidiomycetes such as Trametes versicolor and Phanerochaete chrysosporium are the primary industrial sources of ligninolytic enzymes globally, and related species have been isolated from Nigerian forest litter and agricultural compost.[17,18] Among bacteria, Bacillus, Streptomyces, and Cellulomonas species are notable producers of extracellular cellulases and amylases utilising local agricultural substrates, including cassava peels and rice bran.[10,19] The rumen microbiome, accessible from cattle and buffalo rumen contents, represents a particularly rich, underexplored source of synergistic cellulolytic and ligninolytic enzyme consortia adapted to plant biomass digestion.[20] Figure 2 shows the Electron micrograph-style illustration of key enzyme-producing fungal microorganisms.

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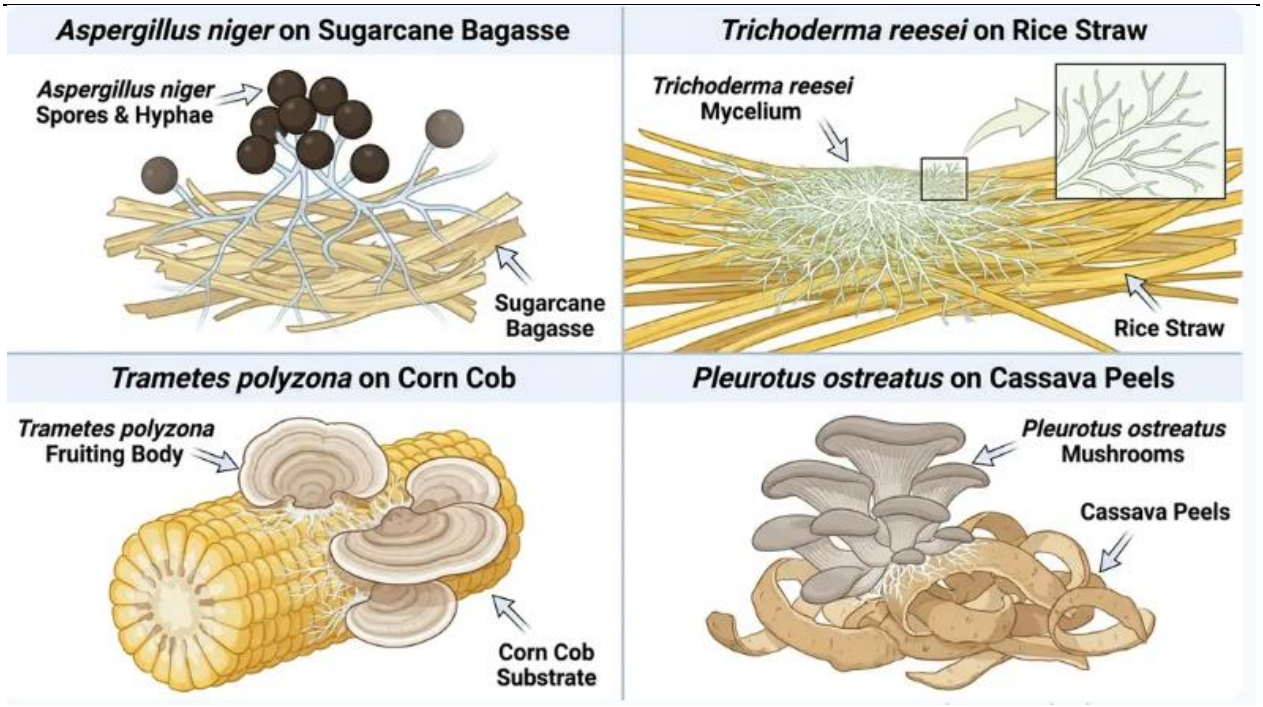


Figure 2. Electron micrograph-style illustration of key enzyme-producing fungal microorganisms (Aspergillus niger, Trichoderma reesei, Trametes polyzona, Pleurotus ostreatus) alongside their preferred Nigerian agricultural waste substrates.

Caption: A high-quality scientific illustration panel showing four quadrants, each depicting a key enzyme-producing microorganism used in Nigerian agricultural waste biodegradation: (1) Aspergillus niger spores and hyphae on sugarcane bagasse substrate, (2) Trichoderma reesei mycelium on rice straw, (3) Trametes polyzona mushroom fruiting body on corn cob, (4) Pleurotus ostreatus on cassava peels.

Sources: Created with reference to [11] and [15].

5. FERMENTATION STRATEGIES FOR ENZYME PRODUCTION

The two principal fermentation systems employed for the production of biodegradative enzymes from agricultural waste are solid-state fermentation (SSF) and submerged fermentation (SmF). Each platform confers distinct advantages in the context of Nigerian waste valorisation.

SSF involves the growth of microorganisms on moist solid substrates in the absence of free water, closely mimicking the natural habitat of filamentous fungi on decaying plant matter. SSF is particularly advantageous for ligninolytic enzyme production: laccase activities in SSF systems have been reported at 26,247 U/g, a value orders of magnitude greater than those achievable in SmF.[15] Furthermore, SSF requires less water, generates smaller effluent volumes, and lends itself to low-technology implementation, making it economically attractive in resource-limited Nigerian settings. The inherent structure of agricultural waste substrates such as rice husk and corn cob provides the necessary porosity and surface area for fungal colonisation without requiring pre-emulsification.[8]

SmF, by contrast, offers superior control over process parameters, temperature, pH, dissolved oxygen, and agitation, which are critical determinants of enzyme activity and selectivity. The

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production of cellulase by A. niger from sugarcane bagasse under SmF at optimised conditions of pH 5 and 50°C achieved maximum activity of 302 IU/mL within 24 hours, illustrating the efficiency of SmF for cellulolytic applications.[7] Sequential SSF-SmF hybrid systems have demonstrated synergistic improvements: cellulase and xylanase activities from Aspergillus tubingensis on palm empty fruit bunches reached 89.6 U/g and 196.8 U/g, respectively in sequential mode, compared to SSF or SmF alone.[15]

Physicochemical parameters governing enzyme production include substrate particle size, moisture content, carbon-to-nitrogen ratio, inoculum density, and incubation period. Pretreatment of substrates, using alkali, dilute acid, steam explosion, or oxidative (H2O2) methods, dramatically enhances enzyme yield by disrupting the lignin-hemicellulose matrix and improving cellulase accessibility. [9,21] Alkali-pretreated soybean hulls have yielded CMCase activities of 9.91 ± 0.04 U/g by A. niger in Nigerian studies.[9]

6. BIOTECHNOLOGICAL AND PHARMACEUTICAL APPLICATIONS

The enzymatic biodegradation of agricultural waste generates a cascade of value-added products with wide-ranging applications across energy, pharmaceutical, food, and environmental sectors. Table 3 summarises the principal enzymes, their waste substrates, and the corresponding value-added outputs relevant to Nigeria's development priorities.

Table 3. Enzymes from agricultural waste biodegradation and their value-added products in Nigeria

Enzyme/Product	Waste Substrate	Value-Added Output	Potential Application
Cellulase complex	Sugarcane bagasse, rice straw	Fermentable sugars (glucose)	Bioethanol, bioplastics, paper industry
Laccase	Corn stover, palm bunches	Delignified biomass	Bioremediation, textile dye decolorization
Manganese peroxidase (MnP)	Groundnut shell, sawdust	Lignin monomers (vanillin, syringol)	Pharmaceutical precursors, biofuel upgrades
Lignin peroxidase (LiP)	Sorghum stalks, cassava peels	Aromatic compounds	Specialty chemicals, biocomposites
Xylanase	Corn cob, rice husk	Xylose/xylooligosaccharides	Prebiotics, animal feed, paper bleaching
Amylase	Cassava peels, sorghum bran	Maltose, glucose syrups	Food industry, bioethanol, pharma excipients

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Enzyme/Product	Waste Substrate	Value-Added Output	Potential Application
Pectinase	Citrus peels, tomato pomace	Galacturonic acid, clarified juice	Fruit processing, wine, pharmacognosy
Protease	Soybean residue, fish waste	Bioactive peptides	Drug delivery, nutraceuticals, detergents

MnP = manganese peroxidase; LiP = lignin peroxidase.

Sources: Compiled from references [7,8,9,15,21]

6.1 Bioethanol and Bioenergy

Second-generation (2G) bioethanol production from lignocellulosic waste represents one of the most promising applications of enzymatic biodegradation in Nigeria. The sequential enzymatic hydrolysis of cellulose and hemicellulose releases hexose (glucose) and pentose (xylose) sugars, which are subsequently fermented by Saccharomyces cerevisiae or engineered xylose-fermenting organisms into bioethanol. [22,23] Nigeria's vast rice straw, corn stover, and sugarcane bagasse streams are estimated to have a theoretical bioethanol potential exceeding 10 billion litres per annum. Cellulase cocktails derived from T. reesei augmented with β-glucosidase from A. niger constitute the most effective enzymatic systems for saccharification of pre-treated bagasse.[11]

6.2 Pharmaceutical and Nutraceutical Applications

Laccases and peroxidases are increasingly recognised as biocatalysts in pharmaceutical synthesis. Lignin peroxidase-mediated oxidation of lignocellulosic substrates releases aromatic monomers, vanillin, syringol, catechol, and guaiacol, that serve as pharmaceutical precursors and fragrance compounds.[16] Manganese peroxidase-derived lignin depolymerisation products are under investigation as antioxidant, anticancer, and antimicrobial agents. Furthermore, bioactive peptides generated through protease-mediated hydrolysis of soybean and fish processing waste have demonstrated angiotensin-converting enzyme (ACE) inhibitory activity relevant to antihypertensive drug development.[24] Pectinases from citrus peel substrates facilitate the extraction of pectin, a pharmaceutical-grade excipient used in drug delivery matrices, wound dressings, and nutraceutical formulations.[25]

6.3 Bioremediation and Environmental Applications

Laccase-mediator systems are extensively applied in the decolourization and detoxification of synthetic textile dyes, phenolic effluents, and polycyclic aromatic hydrocarbons in industrial wastewaters. Trametes polyzona WRF03 laccase characterised from Nigerian isolates has demonstrated potential for dye decolourisation.[11] The lignin degradation products of MnP and LiP reactions also enhance soil quality by facilitating humus formation and improving nitrogen cycling in agricultural ecosystems.[26] Figure 3. Conceptual diagram of a circular bioeconomy framework for enzymatic biodegradation of agricultural waste in Nigeria, showing waste-to-enzyme-to-product cascades and feedback loops.

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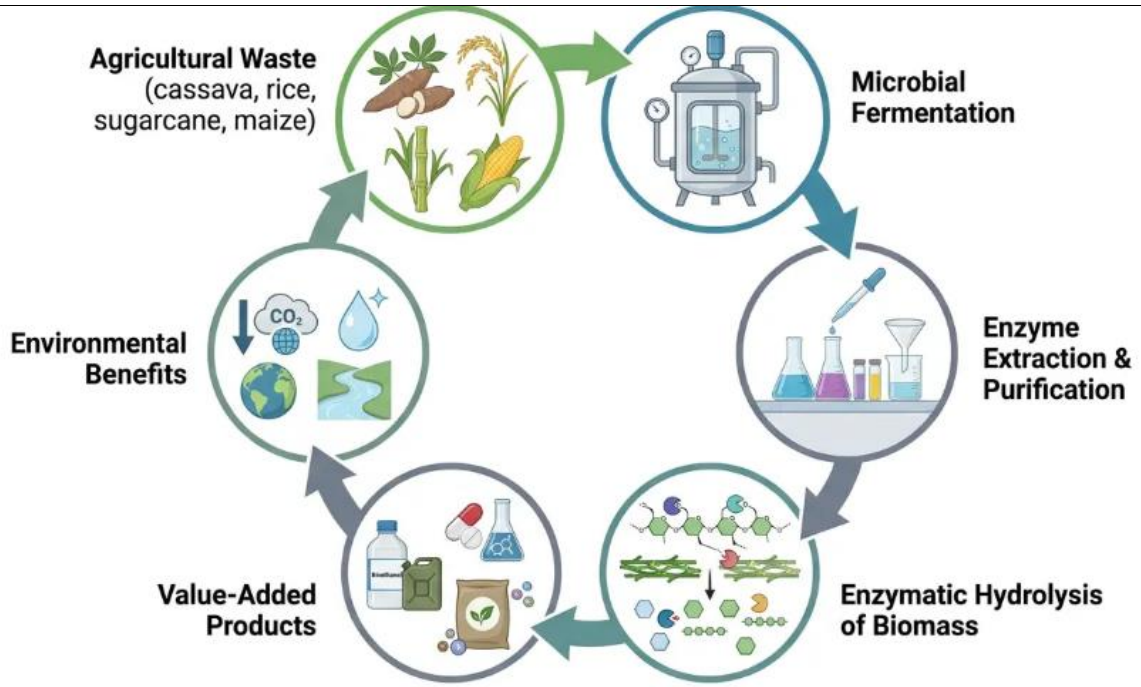


Figure 3. Conceptual diagram of a circular bioeconomy framework for enzymatic biodegradation of agricultural waste in Nigeria, showing waste-to-enzyme-to-product cascades and feedback loops.

Caption: A circular economy diagram showing the valorisation of Nigerian agricultural waste through enzymatic biodegradation. The diagram should be a circular flow chart with the following nodes arranged in a circle: (1) Agricultural Waste (cassava, rice, sugarcane, maize icons), (2) Microbial Fermentation (bioreactor icon), (3) Enzyme Extraction and Purification (flask icons), (4) Enzymatic Hydrolysis of Biomass (molecular breakdown icon), (5) Value-Added Products (bioethanol, pharmaceutical compounds, biofertilizer icons), (6) Environmental Benefits (CO2 reduction, clean water icons) feeding back to agriculture

Sources: Adapted from references [16] and [23].

7. CHALLENGES FACING ENZYMATIC BIODEGRADATION IN NIGERIA

Despite the evident potential, the translation of enzymatic biodegradation research into industrial or commercial practice in Nigeria faces multiple interrelated challenges. The high cost of commercial enzyme preparations remains the most critical bottleneck, with cellulase enzyme costs currently accounting for 20–40% of total bioethanol production costs globally. [13] In Nigeria, this challenge is compounded by limited local enzyme manufacturing capacity and heavy reliance on imported commercial cellulases.

Substrate recalcitrance, arising from the complex crystalline structure of cellulose and the tight lignin-hemicellulose matrix, requires energy-intensive or chemically demanding pretreatment steps that increase production costs and may generate fermentation inhibitors such as furfural, hydroxymethylfurfural (HMF), and acetic acid.[27] The optimisation of pretreatment conditions

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for locally sourced Nigerian biomass has not been sufficiently characterised for scale-up applications.

Institutional and infrastructural gaps, including unreliable electricity supply, limited access to advanced bioreactor systems, a shortage of trained biochemical engineers, and weak technology transfer policies, constrain the scaling of enzyme production processes beyond laboratory demonstrations. Furthermore, the regulatory framework for biotechnological products in Nigeria is underdeveloped, posing challenges for product approval and commercialisation. Inadequate funding for applied biotechnology research and fragmented academia-industry linkages further impede progress.[28]

8. FUTURE PROSPECTS

Several emerging technologies and strategic opportunities are poised to transform the enzymatic biodegradation of agricultural waste in Nigeria. Protein engineering approaches, including directed evolution, rational mutagenesis, and computational de novo design, are enabling the development of thermostable, pH-tolerant, and inhibitor-resistant cellulase and laccase variants tailored to specific local substrates.[12] Enzyme immobilisation on magnetic nanoparticles, zeolites, and biochar supports derived from agricultural char residues offers improved enzyme reuse, stability, and reduced production costs.[22]

Consolidated bioprocessing (CBP), in which a single microorganism or synthetic co-culture simultaneously produces enzymes, saccharifies biomass, and ferments sugars to biofuels or chemicals, represents a paradigm-shifting approach that could drastically reduce process complexity and cost.[27] Advances in metagenomics and functional genomics are accelerating the discovery of novel extremophilic enzymes from Nigerian agricultural environments with superior catalytic properties.

The circular bioeconomy framework provides a compelling policy rationale for national investment in enzymatic bioconversion. By converting waste to wealth, Nigeria can simultaneously address waste pollution, reduce import bills for industrial enzymes and petroleum-based chemicals, and create green employment in rural processing communities. The National Biotechnology Development Agency (NABDA) and the Tertiary Education Trust Fund (TETFund) represent existing mechanisms for channelling research investment toward this agenda. International collaborations with enzyme technology leaders in Europe and North America also present prospects for capacity building and technology transfer.

9. CONCLUSION

Enzymatic biodegradation of agricultural waste constitutes a scientifically robust and commercially promising strategy for Nigeria's transition toward a sustainable, bio-based economy. This review has documented the diversity of agricultural waste streams available nationally, characterised the principal enzyme systems involved in their deconstruction, and highlighted the microorganisms, particularly Aspergillus, Trichoderma, Trametes, and Bacillus species, already identified in Nigerian contexts. The applications of enzymatic bioconversion span bioenergy, pharmaceuticals, nutraceuticals, bioremediation, and the circular bioeconomy. Key challenges, including high enzyme costs, pretreatment barriers, and infrastructural gaps, are significant but tractable with targeted policy, sustained funding, and strategic academic-industry collaboration. Future priorities should include the screening and engineering of locally sourced microbial strains,

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pilot-scale biorefinery demonstrations, and the development of a national enzyme biotechnology framework. Nigeria's vast agricultural biomass, if enzymatically valorised, represents not merely a waste management solution but a foundational resource for a diversified, knowledge-driven green economy.

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Conflict of Interest

The authors declare no conflict of interest.

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