

Biotechnological Valorization of Agri-Food Waste: A Pathway to Circular Bioeconomy

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ABSTRACT

Background: Food waste is a major global challenge, with nearly one-third of food produced lost annually, resulting in environmental, economic, and social consequences. In countries such as India, fragmented supply chains and limited infrastructure further intensify the problem. **Purpose:** This review highlights the role of biotechnology as a transformative driver in valorizing agri-food residues and integrating them into a circular bioeconomy framework. **Methods/Scope:** The article synthesizes findings on diverse feedstocks including soybean okara, potato residues, citrus peels, cruciferous vegetables, and other fruit-vegetable by-products. It further evaluates biotechnological pathways such as fermentation, enzymatic processing, single-cell protein production, biofertilizers, biodegradable biomaterials, and complementary bioenergy recovery. **Applications:** Valorization products demonstrate wide-ranging applications in food fortification, nutraceuticals, animal feed, sustainable packaging, pharmaceuticals, and functional ingredients. These conversions not only reduce waste accumulation but also generate economic value. **Policy Perspective:** The review connects food waste valorization to Sustainable Development Goals (SDGs), with emphasis on zero hunger, renewable energy, responsible consumption, and climate action. Global (EU, FAO) and national (India's bio-waste initiatives) frameworks are discussed alongside technological, economic, regulatory, and social challenges. **Findings:** Current evidence suggests that integrated biorefineries and digital technologies can enhance process efficiency and scale-up potential. Policy incentives and consumer trust will be crucial for successful implementation. **Conclusion:** Biotechnology provides a scalable pathway to transform food system residues into high-value products, positioning waste valorization as both an environmental necessity and an economic opportunity. The review emphasizes the critical importance of coordinated engagement among multiple stakeholders to promote sustainable food systems and expedite the shift toward a circular bioeconomy.

Keywords- biotechnological valorization, circular bioeconomy, food waste, nutraceuticals, sustainable packaging.

I. INTRODUCTION

Food waste has emerged as one of the most pressing challenges of the 21st century. Globally, it is estimated that nearly one-third of all food produced for human consumption is lost or wasted every year, representing not only a loss of resources but also a significant contributor to greenhouse gas emissions.[10]

In developing countries such as India, the problem is further intensified by fragmented supply chains, limited cold storage facilities, and inefficient postharvest management. The consequence is a dual burden: on the one hand, food insecurity and malnutrition persist; on the other, large volumes of valuable biomass end up discarded or underutilized. Traditionally, food systems have followed a linear model of “take–make–dispose,”

where agricultural residues and food by-products are treated as waste. This approach not only strains natural resources but also overlooks the hidden value locked within these materials. In contrast, the circular economy model seeks to transform waste into resources by closing material loops, promoting resource efficiency, and extending the life cycle of products. Within this framework, food industry by-products are no longer seen as liabilities but as renewable feedstocks for producing high-value compounds.[11] [19]

Biotechnology plays a central role in enabling this transformation. Through microbial fermentation, enzymatic processes, and bioconversion technologies, food residues can be upgraded into nutraceuticals, functional ingredients, animal feed, biofertilizers, biopolymers, and bioenergy.[21] Such valorization pathways align with global sustainability agendas by reducing environmental burdens, creating economic opportunities, and contributing to food security.[15]

The objective of this review is to synthesize current advances in the biotechnological valorization of agri-food waste, with a special emphasis on its role in advancing the circular bioeconomy.[6] [14] By examining a variety of raw materials (e.g., soybean okara, potato peels, citrus residues, cruciferous vegetables, and others), valorization technologies, and end-use applications, this article highlights the potential of biotechnology to convert food waste into value-added products.[19] Furthermore, it discusses the policy and economic dimensions that support the integration of biotechnology into sustainable food systems.[23] The transition from a traditional linear food system to a biotechnologically driven circular model is conceptually illustrated in **Figure 1**, emphasizing closed-loop resource utilization and waste-to-value conversion.[14] [21].

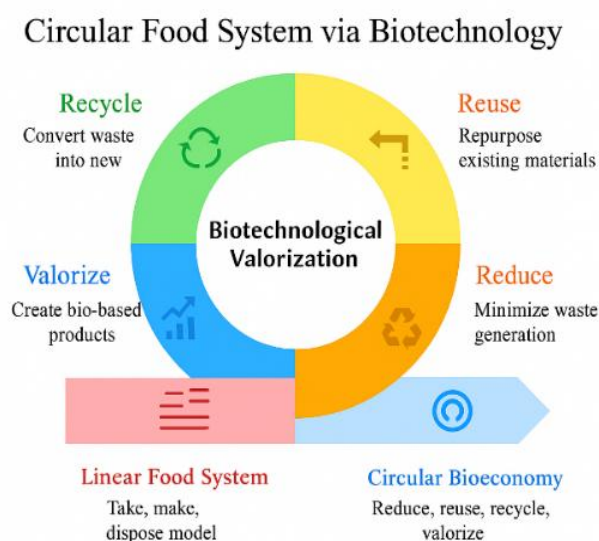


Figure 1: Conceptual transition from a linear “take–make–dispose” model to a circular bioeconomy through biotechnological valorization of agri-food waste.

II. RAW MATERIALS (FEEDSTOCKS)

Food processing industries generate diverse residues that hold significant potential as renewable resources for biotechnological valorization. These materials are often rich in carbohydrates, proteins, fibers, and bioactive compounds, making them attractive candidates for conversion into functional products.

2.1 Soybean okara Okara, the insoluble residue from soymilk and tofu production, is produced in millions of tons annually.[1] Although traditionally underutilized as animal feed or discarded, it contains high levels of dietary fiber, proteins, and isoflavones. These properties make okara an excellent substrate for fermentation processes aimed at producing nutraceuticals, probiotics, and functional food ingredients.

2.2 Potato residues The potato industry generates peels, pulp, and processing wastewater, which are typically treated as waste. These by-products are rich in starch, polyphenols, and antioxidants. Recent advances have demonstrated their potential in producing bioethanol, lactic acid, biodegradable films, and as fermentation substrates for microbial protein.[3].

2.3 Citrus/orange peels Citrus peels represent one of the largest fruit-processing wastes worldwide.[4] They are rich in pectin, essential oils, flavonoids, and limonene. Biotechnological conversion of citrus residues offers opportunities for producing functional fibers, natural flavoring agents, animal feed supplements, and biopolymers used in packaging. [5].

2.4 Cruciferous vegetable wastes Cabbage, broccoli, and cauliflower wastes are generated during harvesting and retail trimming. These residues contain glucosinolates, fibers, and phenolic compounds with antioxidant and antimicrobial properties. Valorization strategies target the extraction of bioactive phytochemicals and their application in functional foods and nutraceutical formulations.[7].

2.5 General fruit and vegetable by-products Beyond specific commodities, general residues such as apple pomace, grape marc, and tomato skins are abundant in sugars, polyphenols, carotenoids, and organic acids.[2] These compounds can be transformed into natural colorants, preservatives, dietary supplements, and biofertilizers.[16] [18].

2.6 Emerging biomass sources In addition to conventional food residues, novel feedstocks are gaining attention. Algal biomass offers lipids, proteins, and polysaccharides that can be upgraded into biofuels, pigments, and health-promoting metabolites.[24] Similarly, animal by-products such as whey from dairy processing or shellfish exoskeletons are being explored for chitosan, peptides, and other high-value molecules. Collectively, these diverse feedstocks highlight the breadth of opportunities for biotechnological interventions, positioning food waste as a valuable raw material base for the circular bioeconomy. The

compositional diversity and valorization potential of major agri-food residues are summarized in Table 1, highlighting the biochemical richness and corresponding technological applications of each feedstock.[18]

Table 1: Representative Agri-Food Residues and Their Biotechnological Valorization Potential

Feedstock / Residue	Principal Biochemical Components	Major Biotechnological Pathways	Key Value-Added Products
Soybean okara	Proteins, insoluble fiber, isoflavones	Fermentation, enzymatic hydrolysis	Probiotic formulations, dietary fiber supplements, nutraceutical ingredients
Potato processing residues	Starch, polyphenols, antioxidants	Fermentation, bioplastic synthesis, enzymatic processing	Bioethanol, lactic acid, biodegradable films
Citrus and orange peels	Pectin, flavonoids, limonene	Enzyme-assisted extraction, microbial fermentation	Pectin films, essential oils, flavoring agents
Cruciferous vegetable wastes (cabbage, broccoli, cauliflower)	Glucosinolates, phenolics, dietary fiber	Solvent-free extraction, fermentation	Antioxidants, functional food additives
Mixed fruit and vegetable residues (apple pomace, grape marc, tomato peels)	Sugars, carotenoids, polyphenols	Fermentation, bio-extraction	Natural colorants, biofertilizers, organic acids
Algal biomass	Lipids, proteins, carbohydrates	Biorefinery processing, microbial cultivation	Biofuels, pigments, omega-rich metabolites

III. BIOTECHNOLOGICAL
VALORIZATION APPROACHES

Biotechnology provides diverse strategies to convert food system residues into value-added products, making it a central driver of the circular bioeconomy. Depending on the type of biomass, several routes can be applied:

3.1 Fermentation and Enzymatic Processing Microbial fermentation and enzyme-based treatments are widely used to release nutrients and generate bioactive compounds.[11] Solid-state fermentation of okara or vegetable pomace can yield organic acids (such as lactic or citric acid), flavor compounds, and functional proteins. Enzymatic hydrolysis helps liberate peptides and antioxidants, improving the nutritional and techno-functional properties of the recovered fractions.[5] [11] Probiotic fermentation also enhances safety and shelf-life, while simultaneously producing nutraceutical ingredients.[18] [20]

3.2 Biofertilizers and Bioconversion Biotechnological composting and microbial inoculants transform crop residues and peel wastes into soil-enriching biofertilizers.[8] These products improve soil structure, restore microbial biodiversity, and reduce dependence on synthetic fertilizers.[14] Specific microbial consortia can also be applied for bioconversion, turning vegetable waste into organic soil conditioners or growth-promoting agents.[17].

3.3 Single-Cell Protein (SCP) Production Food waste streams can serve as inexpensive substrates for microbial

protein production. Yeasts, fungi, and algae cultivated on starchy or fibrous residues generate single-cell protein, which is considered a sustainable alternative to conventional feed proteins. This approach supports both animal feed applications and potential future use in human nutrition, contributing to protein security.[20]

3.4 Packaging and Biomaterials Citrus peel, potato starch, and other polysaccharide-rich wastes are promising sources of biodegradable polymers. Through microbial or enzymatic modification, they can be converted into pectin films, starch-based packaging, and bioplastics. Such biomaterials reduce reliance on petroleum-based plastics, thereby closing the loop between food production and sustainable packaging. [9] [14].

3.5 Bioenergy Recovery (Complementary Pathway) Although not the primary focus of this review, energy valorization is another important dimension. Anaerobic digestion of mixed wastes generates biogas, while hydrolysis and fermentation yield bioethanol.[21] These routes are complementary to material valorization, ensuring that residual biomass is efficiently utilized within a cascading circular framework.[23]. The various biotechnological pathways available for converting food system residues into value-added products are depicted in **Figure 2**, reflecting the cascade utilization principle of a circular biorefinery. The principal biotechnological routes employed for food waste valorization, along with their respective feedstocks, conversion mechanisms, and resulting products, are summarized in **Table 2**.

Biotechnological Valorization Pathways for Agri-Food Waste

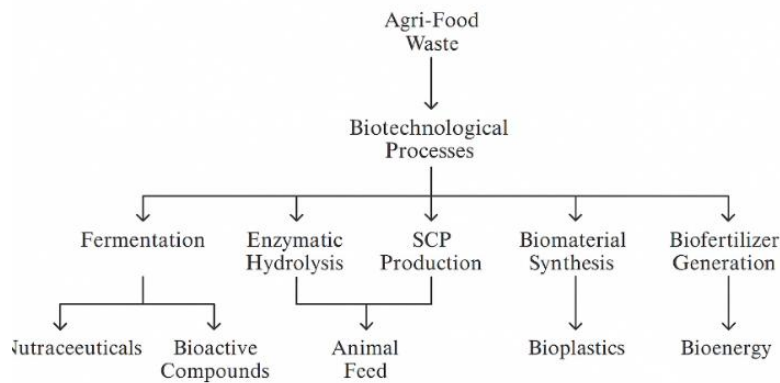


Figure 2. Overview of biotechnological valorization pathways converting agri-food residues into diverse bio-based products within a circular biorefinery framework.

Table 2. Biotechnological Valorization Routes and Targeted End Products

Valorization Approach	Mechanism / Conversion Strategy	Representative Feedstocks	End Products / Applications	Illustrative Microbes or Enzymes
Fermentation	Microbial metabolism converting substrates into bioactive metabolites	Okara, fruit pomace, peels	Organic acids, flavor compounds, probiotics	<i>Lactobacillus</i> , <i>Aspergillus</i> , <i>Saccharomyces</i>
Enzymatic Hydrolysis	Catalytic breakdown of macromolecules to functional biomolecules	Potato, citrus, fruit residues	Peptides, antioxidants, oligosaccharides	Amylase, protease, pectinase
Single-Cell Protein Production	Microbial growth on nutrient-rich wastes	Starch-rich residues, fruit pulp	Microbial protein biomass for feed or food	<i>Candida utilis</i> , <i>Chlorella sp.</i> , <i>Spirulina sp.</i>
Bioconversion to Biofertilizers	Microbial composting and nutrient recovery	Vegetable peels, crop residues	Compost, biofertilizer, soil conditioners	<i>Azotobacter</i> , <i>Bacillus</i> , <i>Rhizobium</i>
Biomaterial Generation	Biopolymer extraction and modification	Citrus peel, potato starch	Pectin and starch-based packaging, bioplastics	—

IV. APPLICATIONS OF BIOTECHNOLOGICAL VALORIZATION

The products derived from food and agricultural residues through biotechnology have wide-ranging applications. These applications not only prevent waste accumulation but also generate economic value, thereby strengthening the circular bioeconomy.

4.1 Food Fortification and Nutraceuticals Nutrient-rich by-products such as soybean okara, citrus peel, and cruciferous residues contain proteins, fibers, antioxidants, and phytochemicals. After biotechnological processing, these compounds can be used to fortify bakery items, beverages, or dairy analogues.[1] [4] Bioactive peptides, polyphenols, and carotenoids isolated from wastes also serve as nutraceutical ingredients, supporting gut health, immunity, and chronic disease prevention.[15] [16].

4.2 Animal Feed Bioconversion of residues into feed ingredients reduces dependence on conventional soy and

fishmeal. Fermented potato pulp, citrus by-products, and single-cell proteins provide a balanced source of amino acids, vitamins, and fibers.[14] Incorporation of probiotics through fermentation further enhances feed digestibility and animal health. This application not only adds value but also contributes to sustainable livestock systems.[20].

4.3 Sustainable Packaging Biotechnology enables the transformation of polysaccharide- and pectin-rich wastes into biodegradable films, edible coatings, and bioplastics. For example, starch from potato peels or pectin from orange residues can be processed into packaging materials with good barrier properties. Such innovations directly address plastic pollution while ensuring that food supply chains become more circular and environmentally responsible.[9].

4.4 Pharmaceuticals and Functional Ingredients Fruit and vegetable wastes are rich in phytochemicals with therapeutic potential. Fermentation and enzymatic hydrolysis can release compounds such as flavonoids, glucosinolates, and dietary fibers, which find applications

in functional foods, dietary supplements, and pharmaceutical formulations. These ingredients have demonstrated benefits in antioxidant defense, metabolic regulation, and inflammation control, making them valuable in the health sector.[24].

V. CIRCULAR BIOECONOMY & POLICY PERSPECTIVE

5.1 Concept of Circular Economy The circular economy framework focuses on maintaining resources within the production–consumption cycle for extended periods, maximizing their utility, and facilitating the regeneration of natural ecosystems. In relation to food waste management, it advocates a transition from the conventional “take–make–dispose” linear model to a sustainable system where agri-food residues are regarded as renewable raw materials. Biotechnology serves as a pivotal enabler of this shift by harnessing the nutritional,

biochemical, and energetic potential embedded within biomass.[17] [23].

5.2 Connection to Sustainable Development Goals (SDGs)

Biotechnological valorization of food and agricultural residues directly supports several United Nations SDGs:

SDG 2 (Zero Hunger): Residue-based feed and nutrient recovery enhance food security.

SDG 7 (Affordable and Clean Energy): Bioenergy pathways from wastes contribute to renewable energy targets.

SDG 12 (Responsible Consumption and Production): Waste minimization and resource efficiency align with sustainable production models.

SDG 13 (Climate Action): Reduced landfill disposal lowers methane emissions and carbon footprint. The relationship between food waste valorization pathways and selected United Nations Sustainable Development Goals (SDGs) is illustrated in Table 3, demonstrating the broader sustainability impact of circular bioeconomy strategies.[6] [17] [23].

Table 3. Contribution of Food Waste Valorization to United Nations Sustainable Development Goals (SDGs)

SDG	Core Objective	Linkage with Food Waste Valorization	Illustrative Impact
SDG 2: Zero Hunger	End hunger and ensure food security	Recovery of nutrients and protein for feed and fortification	Enhanced nutrition availability
SDG 7: Affordable and Clean Energy	Promote renewable energy access	Bioenergy and biogas generation from agro-wastes	Reduced dependency on fossil fuels
SDG 12: Responsible Consumption and Production	Foster sustainable production patterns	Resource circularity and waste reduction	Efficient material recovery
SDG 13: Climate Action	Mitigate climate change impacts	Reduced landfill emissions through valorization	Lower greenhouse gas footprint

5.3 Global and National Initiatives At the global level, organizations such as the European Union (EU) and FAO are promoting food waste valorization through biorefineries, sustainable packaging, and circular economy strategies. The EU Green Deal highlights bio-based solutions as part of climate neutrality goals. In India, initiatives under Swachh Bharat Mission, Food Waste to Wealth Mission, and policies supporting biofuels and composting highlight the growing recognition of biomass valorization. Academic institutions and start-ups are increasingly partnering to translate lab-scale research into commercial-scale operations. [10] [17].

5.4 Challenges Despite strong potential, several barriers hinder large-scale implementation:

Technological: Efficient, low-cost bioprocesses are still under development.

Economic: Collection, segregation, and processing of heterogeneous wastes raise costs.

Regulatory: Lack of standardized safety and quality guidelines limits adoption.

Social Acceptance: Consumers and industries may hesitate to embrace products derived from “waste” streams.

5.5 Opportunities Ahead The future of circular bioeconomy lies in integrated biorefineries, where diverse residues are fractionated and converted into multiple products simultaneously. Advances in digital tools, AI, and IoT can improve waste tracking, supply chain efficiency, and process optimization. Policy incentives such as carbon credits, subsidies for bio-based products, and strong waste management regulations will further accelerate adoption. Together, these measures can transform food waste valorization into a cornerstone of sustainable development.[17] [19] A conceptual model of an integrated biorefinery that converts heterogeneous food residues into multiple high-value bio-based products within a closed-loop system is shown in **Figure 3**.

Integrated Biorefinery Cycle

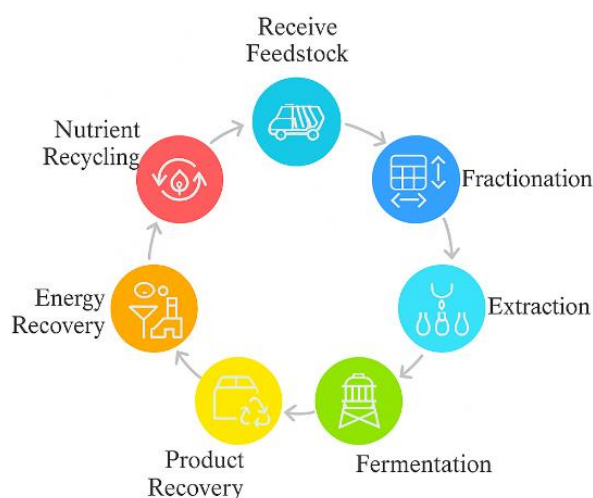


Figure 3: Integrated biorefinery framework demonstrating multi-product conversion of agri-food residues and feedback loops for energy and nutrient recovery within the circular bioeconomy.

VI. CONCLUSION & FUTURE OUTLOOK

Biotechnology has emerged as a central driver in transforming food and agricultural residues into valuable resources, thereby bridging the gap between waste management and sustainable development.[6] By enabling the production of biofertilizers, functional ingredients, proteins, packaging materials, and clean energy, biotechnology offers a pathway to convert waste into wealth.[10] This transition reflects a shift from a linear economy to a value-added circular economy.[19] [23]

The realization of this transition can only be achieved through the unified and coordinated involvement of all relevant stakeholders. Academia, industries, policymakers, and consumers must work together to scale up innovations, reduce costs, and ensure safe and efficient utilization of bio-based products. Social acceptance and regulatory clarity will also play crucial roles in determining the pace of adoption.[25] Looking ahead, the focus should be on developing scalable, cost-effective, and environmentally friendly bioprocesses that can handle diverse waste streams. Incorporating digital technologies and fostering global collaborations will further accelerate progress. Most importantly, building consumer trust in waste-derived products will help close the loop of a truly circular bioeconomy.[20] [24] In conclusion, the biotechnological valorization of food waste represents not merely an environmental imperative but also a promising economic and social prospect capable of reshaping the concept of sustainability in the forthcoming decades.[10] [23].

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