

Valorization of Cereal and Millet Food Processing Waste: A Review of Value-Added Products and Technologies

R. Ravichandran* and Preeti Dixit*

Department of Humanities Science Education and Research,
PSS Central Institute of Vocational Education (NCERT), Shyamla Hills, Bhopal – 462 002, INDIA

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*Corresponding author:

E-mail: preetidixit07@yahoo.com;
ravincert@gmail.com

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Abstract:

Cereal and millet food processing generates substantial amounts of waste, which poses environmental and economic challenges. This review focuses on the valorisation of these waste streams into value-added products and technologies. It discusses the physical, chemical, and biological methods for transforming cereal and millet by-products into useful materials such as biofuels, biomaterials, dietary fibers, functional food ingredients, and fertilizers. The review explores the economic and environmental implications, emphasizing the cost-benefit analysis, waste reduction, and greenhouse gas emissions. Despite technical and commercialisation barriers, advances in biotechnology, green chemistry, and integrated biorefineries hold promise for future development. Policy and regulatory frameworks are crucial in driving innovation and promoting sustainable valorization practices. By addressing existing challenges, the valorization of cereal and millet waste has the potential to contribute significantly to resource efficiency, environmental sustainability, and the circular economy.

Keywords: Cereal and Millets; Food Processing Waste; Valorization; Value addition; Products and Technologies.

1. Introduction

Cereal and millet food processing generates vast quantities of waste, contributing to environmental and economic concerns (Dixit and Ravichandran, 2024). The effective valorization of these by-products is essential for promoting sustainable resource management and minimizing waste (Wang and Qi, 2024). Valorization technologies transform waste into valuable products such as biofuels, food ingredients, and biomaterials, helping reduce environmental impact while providing economic benefits (Rai *et al.*, 2023). This review aims to explore various physical, chemical, and biological methods of valorization, analyze the economic and environmental implications, and highlight key challenges and opportunities. By doing so, it underscores the potential of valorization in supporting the transition toward a circular economy.

Cereals and millets are staple crops in many parts of the world, particularly in developing regions where they serve as vital sources of nutrition. However, the processing of these crops generates significant amounts of waste, including husks, bran, germ, and other by-products. These by-products are often discarded or underutilized, contributing to environmental pollution and resource wastage (Ngwasiri *et al.*, 2022). For instance, rice milling can produce large quantities of rice husk, while wheat processing yields bran and germ. In millet processing, the outer husk and fibrous layers are often considered waste. Such food processing residues, if left untreated, can pose disposal challenges and lead to negative environmental impacts such as greenhouse gas emissions and land degradation. To provide a clearer picture, Table 1 summarizes major



cereals and millets, the key processing steps involved, and the by-products generated.

Table 1: Major Cereals/Millets, Processing Steps, and By-products

Crop	Processing Steps	Major By-products
Rice	Dehusking, Milling	Rice husk, rice bran
Wheat	Milling, Sieving	Wheat bran, wheat germ
Maize	Dry and wet milling	Maize bran, germ, husk
Barley	Pearling, Malting	Barley husk, spent grains
Oats	Dehulling, Rolling	Oat hulls, oat bran
Finger millet	Dehusking, Milling	Husk, outer fibrous layer
Pearl millet	Dehusking, Milling	Husk, bran
Sorghum	Decortication, Milling	Bran, husk
Foxtail millet	Dehusking, Sieving	Husk, fibrous outer layer

Recent reviews have emphasized that cereal and millet by-product valorization is gaining increased global attention, particularly within circular economy frameworks and sustainable food systems (Boruah *et al.*, 2024; Bamigbade and Oyelami, 2025).

In South Asia, food waste and agro-industrial residues also present unique environmental challenges that require region-specific valorization strategies (De and Das, 2023).

The valorization of cereal and millet food processing waste is an emerging strategy aimed at transforming these by-products into valuable resources. By developing technologies to convert such waste into value-added products—such as dietary fibers, protein concentrates, or fermentation substrates—we can promote sustainable resource management and reduce environmental impact (Danciu *et al.*, 2023). Importantly, valorization supports food security by enabling the development of low-cost, nutrient-rich food ingredients that can be reintroduced into the food chain, especially in resource-constrained settings. This approach also helps reduce food system losses and enhances the overall efficiency of food production, contributing to better utilization of natural resources. Furthermore, integrating waste valorization into agri-food systems aligns with circular economy principles, ensuring that more of the edible biomass is used beneficially rather

than discarded. Cereal processing generates significant by-products and wastes, which can be valorized into value-added products through various methods. These by-products, primarily consisting of bran, germ, and spent grains, are rich sources of proteins, dietary fibers, antioxidants, and other bioactive compounds (Skendi *et al.*, 2020; Tomar *et al.*, 2023). Valorization techniques include physico-chemical and biological treatments, with biological methods being more efficient and cost-effective for pollutant removal and waste conversion (Hassan *et al.*, 2021). Extraction of valuable components, such as proteins and arabinoxylans, can be achieved through conventional methods like enzyme-assisted extraction and membrane filtration, as well as non-thermal technologies (Galanakis, 2022). The recovered compounds have diverse applications in biotechnology, food industry, and bakery products (Galanakis, 2022). Valorization of cereal processing waste not only reduces environmental impact but also creates economic opportunities in various industries, including nutraceuticals, cosmetics, and pharmaceuticals (Skendi *et al.*, 2020).

2. Characterization of Cereal and Millet Food Processing Waste

2.1. Physical and chemical properties

Cereal and millet food processing waste exhibit diverse physical and chemical properties depending on the crop type, processing method, and region of cultivation. These wastes generally consist of husks, bran, germ, and other fibrous materials. For instance, rice husk is a common by-product with high lignocellulosic content, while wheat bran is rich in dietary fiber and essential nutrients like vitamins, minerals, and proteins (Hassan *et al.*, 2021). Millets, including sorghum and pearl millet, produce outer hulls and bran that are similarly rich in fiber, cellulose, and hemicellulose.

Key physical properties include bulk density, particle size, and moisture content. Cereal wastes tend to have relatively low bulk density, making their transport and storage challenging. Moisture content also varies significantly, with freshly processed waste containing higher levels, increasing the risk of microbial contamination if not properly managed. Chemically, these by-products contain complex polysaccharides, lignin, proteins, lipids, and phenolic compounds, which can be extracted for value-added applications (Yadav *et al.*, 2020).



2.2. Proximate and ultimate analysis

Proximate analysis provides insights into the general composition of food processing waste, focusing on moisture, ash, crude fiber, protein, lipid, and carbohydrate content. Cereal and millet processing wastes are typically high in fiber and carbohydrates, which makes them suitable for conversion into biofuels or biodegradable materials (Kamusoko *et al.*, 2021). For example, rice husk contains around 70–85% carbohydrates, while wheat bran is rich in non-starch polysaccharides like arabinoxylans.

Ultimate analysis, on the other hand, focuses on determining the elemental composition, including carbon, hydrogen, oxygen, nitrogen, and sulfur content. This information is crucial for evaluating the energy potential of these wastes, especially for biofuel production (Liu *et al.*, 2023). Rice husk, for instance, has a relatively high carbon content (around 35–40%), making it suitable for pyrolysis and biochar production. The nitrogen content, though low in most cereal and millet wastes, is significant for applications like composting and soil amendment.

Table 2: Proximate and Ultimate Composition of Selected Cereal and Millet Processing Wastes

By-product	Moisture (%)	Ash (%)	Crude Fiber (%)	Protein (%)	Lipid (%)	Carbohydrate (%)
Rice husk	9–12	15–20	30–35	3–4	0.5–1	70–85
Wheat bran	10–14	5–7	10–15	14–17	3–5	55–65
Maize husk	8–11	6–8	20–25	5–7	1–2	60–70
Finger millet bran	9–11	4–6	12–16	7–9	2–3	60–68
Pearl millet husk	10–13	5–6	18–22	6–8	1–2	65–70

Data compiled from various sources including Kamusoko *et al.* (2021), Liu *et al.* (2023), and other compositional studies. Values are approximate ranges and may vary with processing conditions and geographical origin.

Recent studies have demonstrated that wheat bran arabinoxylans possess significant functional potential as dietary fibers and health-promoting compounds (Bilal *et al.*, 2025; Kulathunga *et al.*, 2025; Liu *et al.*, 2025).

Rice husk residues, beyond their carbohydrate content, have also been extensively studied for applications in biochar, pyrolysis, and composite materials (Chen *et al.*, 2025; Kang *et al.*, 2024; Premchand *et al.*, 2024).

2.3. Challenges associated with handling and storage

Handling and storage of cereal and millet food processing waste pose several challenges, mainly due to their bulkiness, moisture content, and susceptibility to microbial growth. The low bulk density of materials like rice husk and wheat bran makes them difficult to transport economically over long distances. Storage can also be problematic, as high-moisture residues are prone to spoilage, mold growth, and degradation, leading to loss of material quality (Paini, *et al.*, 2022).

Another challenge is the heterogeneity of the waste, with different crops and processing methods yielding by-products of varying compositions. This complicates the standardization of valorization techniques. Additionally,

cereal and millet wastes can generate dust during handling, posing health hazards for workers and increasing fire risks (Gari *et al.*, 2024). Proper storage conditions, such as low humidity and temperature control, are essential to mitigate these issues and ensure that the waste remains viable for further processing or valorization.

3. Valorization Technologies for Cereal and Millet Food Processing Waste

3.1. Physical Methods

Drying: Drying is a fundamental method used to reduce the moisture content of cereal and millet processing waste. This helps prevent microbial growth and spoilage, ensuring the waste can be stored for longer periods. In valorization processes, drying is a preparatory step for other methods like milling, fermentation, or pyrolysis (Akin *et al.*, 2025). It is often employed using techniques like sun-drying, hot air drying, or vacuum drying.

Milling: Milling involves the mechanical reduction of waste materials into smaller particles, which can then be used for further processing or as additives in food, feed, or biomaterial production. For example, rice husk can be milled into fine powder and used as a filler in composite materials, while wheat bran is milled to improve its texture and functionality as a dietary fiber additive.

Extrusion: Extrusion technology uses high temperature and pressure to transform cereal and millet wastes into



new forms. This method is applied in producing value-added products such as feed pellets or bio-based packaging materials. The process enhances the digestibility of waste materials and improves their mechanical properties, making them suitable for various applications.

Fermentation: Fermentation is used to convert the sugars and starches present in cereal and millet wastes into useful products such as bioethanol, organic acids, and enzymes. In valorization, microbial fermentation can enhance the nutritional profile of these wastes, producing food ingredients or animal feed that are rich in proteins, amino acids, and probiotics.

3.2. Chemical Methods

Hydrolysis: Hydrolysis is a chemical process where water is used to break down complex molecules, such as cellulose and starch, present in cereal and millet processing waste. This technique can be employed to produce simple sugars, which are later fermented into biofuels like bioethanol, or to extract bioactive compounds used in food and pharmaceutical applications (Nayak and Bhushan, 2019).

Solvolysis: In solvolysis, solvents are used to break down lignocellulosic materials in waste, allowing for the recovery of valuable components such as lignin, cellulose, and hemicellulose. This method is crucial for converting cereal and millet wastes into bio-based chemicals and materials.

Pyrolysis: Pyrolysis involves heating the waste in the absence of oxygen to produce bio-oil, biochar, and syngas. This thermochemical process is suitable for the valorization of high-lignin content residues like rice husk, converting them into energy-dense fuels or soil-enhancing biochar.

Gasification: Gasification is another thermochemical process where waste materials are partially oxidized at high temperatures to produce syngas (a mixture of hydrogen and carbon monoxide). This syngas can be used as a clean energy source or as a feedstock for producing chemicals and fuels.

3.3. Biological Methods

Composting: Composting is the biological breakdown of organic waste materials into nutrient-rich compost through aerobic microbial activity. Cereal and millet processing waste, particularly high-fiber residues like bran and husks,

can be composted to produce natural fertilizers (Tagade and Sawarkar, 2023).

Anaerobic Digestion: In anaerobic digestion, microorganisms break down organic material in the absence of oxygen, producing biogas (methane) and digestate, which can be used as fertilizer. Cereal and millet waste rich in carbohydrates and fibers are ideal substrates for this process, contributing to renewable energy production.

Biorefining: Biorefining involves the integrated processing of cereal and millet wastes to produce a spectrum of products, including biofuels, food ingredients, and chemicals. This holistic approach maximizes resource recovery and minimizes waste generation by employing multiple valorization pathways in a single facility. Pyrolysis and thermochemical conversion of residues such as rice husk have also been identified as promising routes for renewable energy and bio-oil generation (El-Sayed *et al.*, 2025).

4. Value-Added Products from Cereal and Millet Food Processing Waste

4.1. Food Ingredients

Dietary Fiber: Many cereal and millet processing wastes, such as wheat bran, rice bran, and millet husks, are rich in dietary fiber. These fibers can be extracted and incorporated into functional foods, offering health benefits like improved digestion and cholesterol reduction (Rai *et al.*, 2023).

Functional Ingredients (Antioxidants, Phytochemicals): Cereal and millet by-products often contain bioactive compounds, including antioxidants and phytochemicals like polyphenols, flavonoids, and carotenoids. These compounds can be extracted and used as natural additives in food and nutraceuticals, promoting health benefits such as anti-inflammatory and anti-carcinogenic properties. Emerging technologies are enabling the extraction of phenolic compounds and bioactives from cereal and millet bran, offering opportunities for functional foods and nutraceuticals (de Oliveira *et al.*, 2025; Rosales *et al.*, 2023). Millets in particular have attracted interest for their bioactive potential, with new evidence linking millet bran phenolics to antioxidant capacity and health benefits (Jacob *et al.*, 2024; Liang *et al.*, 2024; Nani and Krishnaswamy, 2023).



Animal Feed: Processed cereal and millet waste can be a valuable source of animal feed. The high fiber, protein, and carbohydrate content make these by-products suitable for livestock, poultry, and aquaculture feeds, often enhancing the nutritional profile of the feed.

4.2. Biofuels

Bioethanol: Lignocellulosic wastes from cereal and millet processing, particularly husks and bran, can be fermented to produce bioethanol, a renewable biofuel. Bioethanol production from these wastes provides an environmentally friendly alternative to fossil fuels (Gari *et al.*, 2024).

Biodiesel: Oil-rich by-products, such as rice bran oil, can be processed into biodiesel through transesterification. This not only provides a sustainable energy source but also helps reduce reliance on conventional fossil fuels.

4.3. Biomaterials

Bioplastics: Cereal and millet processing residues can be used as raw materials for the production of biodegradable plastics. Starches, lignin, and cellulose extracted from these wastes serve as precursors for creating bioplastics, which are gaining popularity as eco-friendly alternatives to petroleum-based plastics (Taneja *et al.*, 2023).

Biocomposites: By incorporating cereal and millet processing wastes, such as rice husk or wheat bran, into polymer matrices, biocomposites can be developed for use in construction, packaging, and automotive industries. These composites offer sustainability benefits due to their biodegradability and lower environmental impact.

Other Products

Fertilizers: Composting and anaerobic digestion of cereal and millet waste can produce organic fertilizers. These fertilizers enhance soil fertility and structure, offering a sustainable alternative to chemical fertilizers while contributing to soil health and agricultural productivity (Enawgaw *et al.*, 2023).

Activated Carbon: Waste materials like rice husk, due to their high carbon content, can be thermochemically treated to produce activated carbon. This material is highly porous and used in applications such as water purification, gas adsorption, and air filtration.

5. Economic and Environmental Implications

5.1. Cost-benefit analysis of valorization technologies

The economic viability of valorization technologies is a critical factor in determining their scalability and adoption. While some methods, such as composting and drying, are relatively low-cost and straightforward, advanced processes like pyrolysis, gasification, and biorefining require significant capital investment in infrastructure and technology (Rai *et al.*, 2023).

The initial costs for installing advanced technologies, such as reactors for pyrolysis or gasification, can be high. Operational costs, including energy, maintenance, and labor, add to the financial burden. For instance, fermentation processes may involve high costs for microbial cultures, enzymes, and feedstock preparation. However, physical methods like milling or extrusion tend to have lower operational costs but may yield less value-added products compared to biochemical or thermochemical methods.

The economic benefits come from the marketable products derived from these wastes, such as biofuels, bioplastics, animal feed, and functional food ingredients. These products can generate revenue and offset initial investment costs. For instance, bioethanol production from cereal waste can be profitable if economies of scale are achieved, and the same holds for the commercialization of dietary fibers or bioplastics from waste streams. Additionally, reducing waste disposal costs and earning revenue from by-products further improves the cost-benefit ratio (De and Das, 2023).

Ultimately, the success of valorization technologies hinges on the balance between production costs and the market demand for the derived products. Optimizing production processes and enhancing the quality of value-added products can significantly improve the economic outlook of these technologies.

5.2. Environmental benefits

Waste Reduction: One of the most significant environmental benefits of valorizing cereal and millet food processing waste is the reduction in waste sent to landfills. By converting waste into useful products, valorization helps alleviate the pressure on waste disposal systems, especially in regions where waste management infrastructure is limited. For example, valorizing rice husks into biochar



or bioplastics minimizes the environmental burden of disposal while creating useful materials (Gari *et al.*, 2024).

Greenhouse Gas Emissions: Valorization technologies, particularly those that convert waste into biofuels like bioethanol and biodiesel, contribute to reducing greenhouse gas emissions. Replacing fossil fuels with biofuels derived from cereal and millet waste can significantly lower the carbon footprint of energy production (Nani and Krishnaswamy, 2023). Additionally, converting agricultural waste into biochar through pyrolysis can sequester carbon in the soil, helping mitigate climate change. Moreover, anaerobic digestion of organic wastes produces biogas, a renewable energy source, which can offset reliance on non-renewable energy sources and reduce methane emissions from conventional waste decomposition in landfills.

Circular Economy: Valorization promotes a circular economy by transforming waste into raw materials for new products, thus extending the lifecycle of resources. This minimizes resource extraction, reduces environmental degradation, and fosters a more sustainable production and consumption model.

5.3. Policy and regulatory frameworks for promoting valorization

Incentives and Subsidies: Governments can play a crucial role in promoting the adoption of valorization technologies by providing financial incentives, such as subsidies, tax breaks, or low-interest loans, for companies investing in waste valorization infrastructure. These policies can help reduce the initial capital expenditure associated with advanced technologies like pyrolysis or biorefining, making them more accessible to industries and encouraging widespread adoption (Saba *et al.*, 2023).

Waste Management Policies: Many countries are enacting stricter regulations on waste disposal, imposing landfill taxes or banning the landfilling of organic waste altogether. Such regulations push industries to explore valorization options as a sustainable waste management alternative. The enforcement of extended producer responsibility (EPR) laws can also encourage food processing companies to take ownership of their waste streams and invest in valorization technologies.

Sustainability Certifications: Regulatory frameworks may also involve sustainability certifications and labeling

schemes that promote valorization. For example, products derived from valorized waste, such as bio-based plastics or organic fertilizers, can be certified as eco-friendly, making them more attractive to environmentally conscious consumers and creating additional market demand (Sharma *et al.*, 2023).

International Cooperation: Global policy initiatives, such as the Paris Agreement on climate change, emphasize the reduction of carbon emissions and sustainable development goals (SDGs). These frameworks promote valorization technologies as part of a broader strategy to reduce waste, enhance resource efficiency, and create green jobs.

The economic and environmental implications of valorization are intertwined. The adoption of these technologies depends not only on their cost-effectiveness but also on supportive policy frameworks and the growing demand for sustainable, eco-friendly products. Governments, industries, and consumers all have roles to play in realizing the full potential of cereal and millet food processing waste valorization.

6. Challenges and Future Perspectives

6.1. Technical challenges in valorization processes

Heterogeneity of Waste: One of the major technical challenges in valorizing cereal and millet food processing waste is the variability in composition. Different types of cereals and millets, as well as variations in processing methods, produce waste streams with diverse physical, chemical, and nutritional properties. This heterogeneity complicates the standardization of valorization processes, as technologies must be adapted to specific waste types to ensure optimal conversion efficiency and product quality (Yoha and Moses, 2023).

Pretreatment Requirements: Many valorization processes, such as fermentation or pyrolysis, require significant pretreatment of waste materials. For instance, lignocellulosic materials like rice husk or wheat bran need to be broken down to release fermentable sugars or to improve their thermal properties. These pretreatment steps can be energy-intensive, costly, and time-consuming, thus reducing the overall efficiency of the valorization process (Ortiz-Sanchez *et al.*, 2023).

Low Yields and Product Quality: The extraction of valuable compounds such as antioxidants, dietary fibers,



or biofuels from cereal and millet wastes often results in low yields. Improving the extraction efficiency and enhancing the quality of the end products are ongoing challenges. For instance, the high lignin content in some cereal wastes can impede bioethanol production, while the extraction of bioactive compounds may require toxic solvents, raising concerns over product safety.

Energy and Resource Intensity: Some valorization methods, especially those involving thermochemical conversion (e.g., pyrolysis, gasification), are highly energy-intensive. The environmental benefits of valorization are diminished if the energy consumed in the process outweighs the benefits of the products generated. Developing more energy-efficient technologies is essential to ensure the overall sustainability of valorization (Priyadarshini and Abhilash, 2023).

Scale-up and commercialization barriers

Economic Viability: While laboratory-scale valorization processes often show promise, scaling up to industrial levels remains a major hurdle. The costs associated with building infrastructure, optimizing processes, and meeting regulatory standards can be prohibitive (Nayak and Bhushan, 2019). Additionally, market demand for some valorized products, such as bioplastics or biofuels, may not yet be strong enough to justify the investment needed for large-scale production.

Supply Chain Management: Efficient collection, transportation, and storage of cereal and millet processing waste pose logistical challenges, especially in rural and decentralized areas where processing facilities are often located. The low bulk density of materials like rice husk and wheat bran adds to transportation costs, which can erode profit margins. Establishing localized valorization hubs close to production sites may mitigate this issue but requires significant capital investment.

Market Competition: Products derived from cereal and millet waste must compete with conventionally produced alternatives in the market. For example, bio-based plastics face stiff competition from cheaper, petroleum-based plastics, while biofuels compete with traditional fossil fuels. Until consumer preferences shift strongly toward sustainable products, or government regulations mandate their use, valorized products may struggle to gain a foothold in the market (Bobier *et al.*, 2024).

Regulatory and Certification Barriers: Complying with regulatory requirements for food ingredients, animal feed, and bio-based products can be a lengthy and costly process. Stringent safety standards must be met, especially for products used in food and feed applications. Moreover, obtaining certifications such as organic or eco-friendly labels can further complicate commercialization efforts (Di Fraia *et al.*, 2023).

6.2. Future research directions and emerging trends

Biotechnological Advancements: Future research in biotechnology holds great promise for improving the efficiency of valorization processes. Advances in genetic engineering and synthetic biology could lead to the development of more robust microorganisms and enzymes capable of breaking down complex lignocellulosic materials more efficiently, thus improving yields in biofuel and bioproduct production (Đorđević and Pintač-Šarac, 2024). Additionally, innovations in bioconversion pathways could enable the extraction of high-value nutraceuticals and bioactive compounds, contributing to both health and sustainability agendas.

Green Chemistry and Sustainable Solvents: To address environmental concerns related to the use of toxic solvents in extraction processes, future research may focus on developing green chemistry approaches, including the use of supercritical fluids, ionic liquids, or water-based extractions (Danciu *et al.*, 2023). This is especially important for producing food-grade ingredients or pharmaceutical precursors from processing residues. Sustainable bioprocesses will increasingly depend on the development of advanced solvents such as natural deep eutectic solvents (NaDESs), which show potential for food-grade extraction (Bezerra *et al.*, 2025).

Integrated Biorefineries: The adoption of integrated biorefineries is a key trend supporting the zero-waste approach. These systems aim to utilize every fraction of food processing waste through cascading valorization steps—converting one waste stream into multiple products like biofuels, bioplastics, biochemicals, and biofertilizers (Kaur *et al.*, 2023). Future work should focus on scalable, cost-effective biorefinery models tailored for cereal and millet-based agri-industrial clusters, especially in developing countries.

Recent work also highlights industrial symbiosis as a driver of circular economy models in food waste valorization,



where by-products from one sector serve as inputs for another (Saba *et al.*, 2023).

In addition, novel approaches such as sustainable protein recovery from cereal wastewater are expected to define future research priorities (Sharma *et al.*, 2025; Wang and Qi, 2024).

7. Research Gaps and Priorities

Despite promising advancements, several research gaps persist. These include:

- Limited studies on the valorization potential of underutilized millets.
- Lack of techno-economic feasibility analyses for small-scale valorization units.
- Inadequate data on the long-term environmental impacts of certain valorization processes.
- Standardization challenges for bio-based products derived from food waste.
- Bridging these gaps requires interdisciplinary research involving food science, biotechnology, materials science, and environmental engineering.

8. Public-Private Collaborations (PPPs)

The development and commercialization of valorization technologies can benefit significantly from public-private partnerships (PPPs). Collaborations between academic institutions, government agencies, and industry players can accelerate the translation of lab-scale technologies to market-ready solutions. PPPs can also facilitate knowledge exchange, co-funding of pilot projects, and infrastructure development, particularly in rural or semi-urban regions where millet and cereal processing is concentrated.

Circular Economy and Industrial Symbiosis: The push toward a circular economy is likely to drive future innovations in valorization. Industries are increasingly looking for ways to close the loop by repurposing waste streams and reintegrating by-products into the production cycle (Saba *et al.*, 2023). Examples include using bran as a fermentation substrate in the biotech industry or husks in packaging material production.

Advanced Materials from Waste: Emerging trends in materials science suggest that cereal and millet processing waste could be used to produce high-performance materials such as nanocellulose, bio-based adhesives, or

Table: Emerging Trends, Research Gaps, and Future Directions in Cereal and Millet Waste Valorization

Theme / Trend	Emerging Focus Areas	Key Research Gaps	Future Directions / Strategies
Biotechnological Advancements	Engineered microbes, novel enzymes for lignocellulose breakdown	Limited strain diversity for millets; scale-up issues	Develop robust microbial consortia; pilot-scale validation
Green Chemistry	Use of supercritical fluids, ionic liquids, eco-friendly solvents	Lack of cost-effective, food-safe solvents for large-scale use	Design scalable green extraction methods
Integrated Biorefineries	Zero-waste cascading valorization models	High capital costs; limited rural adoption	Low-cost modular biorefineries; community-level units
Circular Economy & Industrial Symbiosis	Waste-to-resource pathways across industries	Poor inter-industry linkages; lack of policy incentives	Promote industrial symbiosis hubs; policy alignment
Advanced Materials	Nanocellulose, bioplastics, composites	Processing challenges; commercial viability issues	Optimize production for packaging & automotive use
Policy-Driven Innovation	Regulations on landfill reduction & renewable adoption	Slow regulatory enforcement in developing countries	Stronger PPP models to align research, policy & industry
Public-Private Partnerships	Academia-industry-government collaborations	Lack of funding models & infrastructure in rural regions	PPPs for pilot projects & rural entrepreneurship



advanced composites (Tufail *et al.*, 2022). These materials have applications in food packaging, construction, and automotive industries, and offer higher economic value compared to traditional uses like compost or animal feed.

Policy-Driven Innovation: As governments around the world tighten regulations on waste management and emissions, future research and development in valorization technologies will likely be driven by policy changes (Akin *et al.*, 2025). Regulations mandating the reduction of landfill use, the use of renewable energy, and the promotion of sustainable materials will create new opportunities for innovation and investment in waste valorization technologies.

While significant challenges remain in the technical, economic, and regulatory aspects of valorizing cereal and millet food processing waste, future research and innovation hold the potential to overcome these barriers. Emerging trends in biotechnology, green chemistry, and integrated resource management are likely to drive the next wave of advancements in this field, making valorization a key component of sustainable resource management.

Conclusion

The valorization of cereal and millet food processing waste offers significant opportunities for sustainable resource management, economic benefits, and environmental protection. By converting agricultural by-products into valuable products such as biofuels, biomaterials, food ingredients, and fertilizers, these processes reduce waste generation, lower greenhouse gas emissions, and contribute to the circular economy. The review of various valorization technologies, including physical, chemical, and biological methods, highlights the potential of transforming this waste into high-value products. However, several technical, economic, and regulatory challenges must be addressed to fully realize the potential of these technologies. The heterogeneity of waste, high costs of advanced processes, and market barriers pose hurdles to the commercialization and large-scale adoption of valorization strategies. Despite these challenges, future advancements in biotechnology, green chemistry, and integrated biorefineries hold promise for improving the efficiency and viability of valorization processes. Continued research and innovation, coupled with supportive policy frameworks, will be key to overcoming these challenges and fostering the development of sustainable valorization

pathways. By optimizing technologies and aligning them with global sustainability goals, the valorization of cereal and millet food processing waste can play a crucial role in resource efficiency, economic growth, and environmental conservation in the years to come.

Author contributions

The review was written and enriched by RR and PD. All authors read, edited, and approved the final manuscript.

Conflict of interest

The authors declare no conflict of interest.

Ethical Approval

The article doesn't contain any study involving ethical approval.

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