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Agro-Industrial and Food Waste in the Circular Bioeconomy: Emerging Biorefineries, High-Value Bioproducts and System-Level Innovations

Nasruddin[1], Hasim[2], Mahludin Baruadi[3], Weny J. A Musa[4]

[1]Doctoral Program in Environmental Science, Universitas Negeri Gorontalo, Gorontalo, Indonesia
[2,3,4]Postgraduate Program, Universitas Negeri Gorontalo, Gorontalo, Indonesia

Corresponding Author: Nasruddin

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ABSTRACT

The rapid growth of agro-food and bioresource industries has intensified pressure on waste management infrastructures while simultaneously creating a vast, underutilised reservoir of organic, inorganic and mixed solid residues. Contemporary circular bioeconomy strategies increasingly reconceptualise these wastes as feedstocks for biorefineries that co-produce bioenergy, bio-based materials, high-value chemicals and environmental services. Building on earlier literature, this review integrates recent advances from 2023–2026 in microbial bioprocessing, thermochemical conversion, bioleaching, biopolymer and biosurfactant production, and circular supply chains for agro-industrial and food waste. Microbial routes now valorise residues into bio-enzymes, organic acids, hyaluronic acid, bioplastics, biosurfactants and biofertilisers, supported by process-intensified extractive technologies, novel solvents and non-sterile solid-state bioprocessing. Thermochemical pathways, including pyrolysis and gasification, are increasingly guided by computational fluid dynamics and feedstock-aware control strategies. Waste-derived functional materials, such as bioactive extracts for food, cosmetic and biomedical applications, and bio-based packaging from by-products, are progressing toward commercialisation. At the system level, digitalised reverse logistics, circular supply-chain optimisation, open innovation in SMEs, and supportive policy instruments (e.g., biofuel replanting schemes) are beginning to operationalise circularity at scale. Across these domains, we critically examine techno-economic feasibility, environmental performance, health and safety risks (including bioaerosols and pathogens), and social implications such as poverty reduction and regional economic development. Remaining challenges include feedstock heterogeneity, regulatory uncertainty, scale-up risks, and integrating bioproduct portfolios with market demand. We conclude with a research agenda for multi-product, digitally enabled, and regionally adapted biorefineries that treat agro-industrial and food waste as strategic resources rather than liabilities.

***Keywords*:** circular bioeconomy; agro-industrial waste; waste valorisation; biorefinery; bio-based products; sustainable bioprocessing; organic waste management

INTRODUCTION

Agro-industrial and food systems generate hundreds of millions of tonnes of solid and liquid residues each year. Traditionally, these materials have been treated as disposal problems, contributing to greenhouse gas emissions, local air and water pollution, odour, pathogen dissemination and land-use pressure. Recent policy and industrial agendas framed around the circular economy and bioeconomy have inverted this logic, positioning organic and even inorganic wastes as strategic feedstocks for high-value bioproducts, renewable energy and biomaterials.

Earlier generations of review articles have established the technical feasibility of converting agricultural residues, food processing by-products, municipal biowastes and selected industrial wastes into energy, compost, simple platform chemicals and low-value materials. More recent work, however, reveals a qualitative shift: integrated multi-product biorefineries, circular supply-chain design, digital logistics and new classes of bio-based materials and chemicals are pushing valorisation beyond incremental improvements in waste management toward systemic transformation.

Recent studies illustrate this shift across multiple scales and sectors. Solid-state bioprocessing with filamentous fungi such as *Lichtheimia ramosa* enhances enzyme production and nutrient recycling from complex agro-industrial residues under both sterile and non-sterile conditions (Farinon et al., 2026). Microbial fuel cells powered by olive-processing waste generate bioelectricity while addressing local waste burdens (Fayad et al., 2025). Circular supply-chain models for spent coffee grounds integrate Industry 4.0 technologies and data-driven logistics to optimise collection networks (Zohourfazeli et al., 2025). At the same time, reviews of bioplastics, biosurfactants and hyaluronic acid production increasingly emphasise the substitution of fossil-based feedstocks with agro-industrial residues and biomass (Adetunji & Erasmus, 2024; Mandal et al., 2024; Mioti et al., 2025; Parmar et al., 2025).

This article builds on an earlier literature review to incorporate this new wave of studies and to re-evaluate the field through a contemporary circular bioeconomy lens. We focus on four overarching questions:

How are feedstocks and product portfolios evolving as waste valorisation moves from single-product processes toward integrated biorefineries?

Which technological pathways are emerging as most promising for high-value bioproducts, including biopolymers, bio-active compounds, bioenergy and metals recovery?

How are system-level innovations in circular supply chains, digitalisation, policy and SME strategies reshaping the practical deployment of these technologies?

What cross cutting challenges and knowledge gaps remain for achieving environmentally and socio-economically robust circular bioeconomy models?

To answer these, we synthesise the recent literature, emphasising 2023–2026 contributions, and provide extensive summary tables that connect feedstocks, technologies, products and system conditions. Particular attention is paid to citation integrity and the traceability of key studies, aligning with the extracted bibliographic information provided.

METHOD

Waste as a multi-dimensional resource

Within the waste hierarchy, prevention and reduction remain primary goals, but once waste is generated, a sequence of preferred options—reuse, recycling, recovery and safe disposal guides policy and practice. In the bioeconomy context, agro-industrial and food waste transitions from being conceptualised as “end-of-pipe” material toward being viewed as multifunctional feedstock with biochemical, thermochemical and physical valorisation pathways.

Agro-industrial waste streams encompass lignocellulosic residues (straws, husks, shells, pruning residues), fruit and vegetable by-products (peels, pomaces, seeds), animal manures and slaughterhouse residues, industrial effluents rich in organic matter, insect frass, exuviae from insect production, and mixed organic fractions of municipal solid waste. Recent reviews categorise these streams not only by composition but by their compatibility with bioprocesses, such as microbial fermentation, solid-state cultivation, anaerobic digestion, biorefinery schemes and bioleaching (de Oliveira et al., 2025; Dhiman et al., 2025).

Biorefinery concepts and cascading use

Modern biorefinery concepts mirror petroleum refineries by co-producing multiple products from a single feedstock, maximising resource efficiency and economic resilience. Organic waste-based biorefineries have evolved from single-pathway facilities to cascading systems that:

- Extract high-value compounds (polyphenols, pigments, specialised polysaccharides, organic acids),
- Produce bulk biopolymers or materials (bioplastics, biosurfactants, bio-based films),
- Generate energy carriers (biogas, bioelectricity, syngas, liquid fuels),
- Recover nutrients and produce soil amendments (compost, vermicompost, biofertilisers),
- In some cases, recover metals and critical materials via bioleaching (Jaiswal et al., 2025).

Innovative frameworks such as GBAER-type biorefineries (biorefineries based on the organic fraction of municipal solid waste) integrate microbial production of hyaluronic acid with waste treatment, demonstrating how high-value products can be embedded within municipal waste management infrastructures (Pérez-Morales et al., 2024).

System-level circular bioeconomy

Recent contributions also broaden the lens from unit operations to system-level innovation. Circular supply-chain optimisation for spent coffee grounds couples waste collection, pre-drying and logistics decisions via mixed-integer linear programming, explicitly integrating cost, emissions and operational risk (Zohourfazeli et al., 2025). Circular economy practices in agricultural SMEs emphasize open innovation, eco-processes and eco-innovation to develop new products from waste streams while improving competitiveness (Worakittikul et al., 2025). Biofuel policies, such as Indonesia's replanting scheme, link agro-industrial productivity, poverty reduction and regional growth, illustrating the broader socio-economic dimensions of bio-based circularity (Halimatussadiah et al., 2025).

RESULT

Conventional agro-industrial residues revisited

Traditional agro-industrial residues such as cereal straw, husks, mill by-products and fruit processing waste remain central to bioeconomy initiatives. Recent work updates their roles in light of circular economy targets:

- Fruit by-products serve as substrates for organic acids, bio-enzymes and bio-cleaners in multi-tech green processes that aim at zero-waste production (Agarwal et al., 2025).
- Chestnut shells are valorised via pressurised liquid extraction and advanced UHPLC-TIMS-QTOF-MS profiling to recover antioxidant polyphenols with potential food, cosmetic and animal feed applications (Pazara et al., 2025).
- Wine and grape by-products underpin bio-based films, coatings and packaging for small fruits, leveraging their polyphenolic content for antimicrobial and antioxidant functionality (Oliveira et al., 2025).

These studies collectively emphasise a shift from low-value composting or energy-only applications to the extraction of high-value bioactive compounds, often followed by secondary valorisation (e.g., using extracted residues as bioenergy substrates or soil amendments).

Novel and under-explored feedstocks

Recent literature highlights several emerging substrates that broaden the feedstock universe:

- Insect frass, the residual substrate from insect farming, shows biogas and methane yields comparable to traditional slurries when subjected to anaerobic digestion, though performance is sensitive to digestion conditions and co-substrate choice (Lovarelli et al., 2024).
- Hermetia illucens exuviae are processed via NADES-based chitin extraction and enzymatic deacetylation to produce high-purity chitin and structurally defined chitooligosaccharides, with coproducts such as eumelanin and biofertiliser integrated into a circular biorefinery (Sharma & Thangadurai, 2025).
- Spent coffee grounds are treated as an urban organic resource, with circular supply-chain designs demonstrating how pre-drying technologies and smart logistics can reduce costs and emissions (Zohourfazeli et al., 2025).
- Olive cake is utilised as a carbon-rich substrate in microbial fuel cells, coupling waste treatment with electricity generation (Fayad et al., 2025).
- Plant-derived saponin-bearing biomass (e.g., *Quillaja saponaria*, *Sapindus mukorossi*) provides the basis for green biosurfactant production with wide industrial applicability (Parmar et al., 2025).

These examples illustrate a broadening biological, compositional and functional diversity of feedstocks, which in turn requires more nuanced process design and control strategies.

Mixed and inorganic wastes

While organic wastes dominate biorefinery discussions, inorganic and mixed wastes are increasingly recognised as sources of valuable metals and even energy carriers. Bioleaching of e-waste, fly ash, spent catalysts and other inorganic residues using extremophilic microorganisms is framed as an "eco-friendly nano-factory" for sustainable inorganic waste management, with detailed mechanistic insights into redoxolysis, acidolysis and complexolysis pathways (Adetunji & Erasmus, 2024; Jaiswal et al., 2025). Circular bioeconomy strategies must therefore consider integrated management of both organic and inorganic fractions, particularly where they co-occur (e.g., municipal solid waste, industrial sludges).

Technological pathways for waste valorisation

Microbial bioprocessing remains a cornerstone of waste valorisation, but its scope has expanded substantially.

Comparative studies of sterile and non-sterile solid-state bioprocessing with *L. ramosa* on substrates such as sawdust, wheat bran, slaughterhouse sludge, dairy waste, apple pomace and manures demonstrate:

- Significant nitrogen enrichment and C: N reduction, indicating enhanced mineralisation,
- Substrate-specific induction of lignocellulolytic enzymes (cellulases, xylanases, amylases),
- Trade-offs between sterility (maximising targeted enzyme yields) and non-sterile conditions (facilitating cooperative microbial interactions and waste stabilisation) (Farinon et al., 2026).

Such work underscores that microbial consortia and process sterility are strategic design variables, not merely constraints.

Recent reviews of microbial bioprocessing of food and agro-industrial residues emphasise:

- The potential for biorefinery-style integration of bioproducts (enzymes, acids, biopolymers) with circular economy models,
- Challenges such as feedstock variability, process optimisation, strain robustness and regulatory hurdles,

- The promise of co-cultures, strain engineering and hybrid process configurations (Dhiman et al., 2025).

These findings reinforce the need for flexible, robust bioprocess platforms capable of handling multiple waste types and product targets.

Integrated green approaches for converting fruit waste into organic acids, bio-enzymes and bio-cleaners combine fermentation, green extraction and process intensification. Key innovations include:

- Multi-stage extraction–fermentation–purification pipelines that maximise product recovery,
- Use of alternative solvents and energy-efficient technologies,
- Techno-economic evaluations oriented toward zero-waste and circular economy objectives (Agarwal et al., 2025).

Biopolymers, bioplastics and bio-based materials

Agri-waste components support microbial or mechanical production of bioplastics that substitute fossil-derived polymers. Reviews highlight:

- Diverse carbohydrate-rich and lignocellulosic residues as feedstocks for polyhydroxyalkanoates and other biopolymers (Mandal et al., 2024),
- Life-cycle analyses indicating environmental benefits but also the importance of scaling and process optimisation,
- The role of microalgae as a versatile feedstock whose biomass can be transformed into bioplastics, integrated with carbon capture and wastewater treatment (Adetunji & Erasmus, 2024).

Bioplastic additives such as plasticisers, stabilisers and performance enhancers are also being developed with environmental footprints in mind, balancing functionality with degradability and toxicity concerns (Menon et al., 2025).

Bio-based packaging and edible films

The development of bio-based films and coatings for food packaging increasingly leverages by-products from the wine and fruit industries, which are rich in polyphenols and other bioactives. Sustainability-oriented reviews report:

- Edible coatings that extend shelf life, improve safety and reduce plastic waste,
- Exploitation of grapevine by-products and small-fruit residues as functional fillers and active agents,
- Challenges related to mechanical and barrier properties, scalability and cost (Oliveira et al., 2025).

Waste-derived antioxidants and polyphenols from chestnut shells and grape pomace are similarly used to design value-added food and cosmetic ingredients, illustrating the convergence of nutraceutical, cosmetic and packaging applications (Pazara et al., 2025; Sampaio et al., 2023).

High-value polysaccharides: hyaluronic acid and chitin derivatives

Hyaluronic acid (HA) has emerged as a flagship high-value biomolecule for biomedical, cosmetic and food applications. Recent reviews and case studies show a transition from animal-derived HA to microbial fermentation using biomass and waste-derived carbon sources (Mioti et al., 2025; Pérez-Morales et al., 2024). These works highlight:

- The trade-off between high yields using conventional refined substrates and lower costs but more complex process optimisation with agro-industrial residues,
- The scarcity of validated large-scale case studies using organic waste as primary C and N sources, indicating substantial research gaps,
- The potential integration of HA production into municipal solid waste-based biorefineries (GBAER-type).

In parallel, chitin and chitosan valorisation from insect biomass via NADES extraction, enzymatic deacetylation and depolymerisation yields well-defined chitooligosaccharides with high purity and low environmental impact, demonstrating how advanced solvent systems can transform established biopolymers into circular bioeconomy exemplars (Sharma & Thangadurai, 2025).

Thermochemical conversion and hybrid energy systems

Thermochemical routes, including pyrolysis and gasification, complement bioprocessing by handling heterogeneous, contaminated or hard-to-digest wastes.

- Pyrolysis of segregated plastic waste (e.g., HDPE) at educational institutions has been modelled techno-economically, showing potential for liquid fuel production from campus waste streams and contributing to climate mitigation and resource recovery (Paneru et al., 2024).
- Gasification of organic solid wastes (OSWs) is analysed via CFD simulations to quantify the impact of feedstock heterogeneity on temperature profiles, reaction zones and syngas quality. Introducing an equivalent ratio on a dry ash-free basis improves control over oxidation and tar formation, suggesting new control strategies for mixed OSW gasifiers (Wang et al., 2025).

These studies underscore the importance of feedstock-aware thermochemical system design, especially when integrating multiple waste streams.

Bioenergy, bioelectricity and nutrient recovery

Beyond thermochemical routes, bioenergy and nutrient recovery are being expanded:

- Anaerobic digestion of insect frass achieves methane yields in the range of traditional slurries, positioning insect farming residues as promising bioenergy feedstocks (Lovarelli et al., 2024).
- Microbial fuel cells powered by olive cake generate electricity while valorising a problematic residue and enabling localised renewable energy production (Fayad et al., 2025).
- Vermicomposting in educational institutions is optimised via multi-criteria decision-making and mathematical programming to minimise costs and production times while maximising environmental benefits (Bhakuni et al., 2025).

Such examples illustrate an increasingly multi-functional role for waste-based systems, where energy, nutrient recovery and educational or social benefits intersect.

Metal recovery and nano-materials via bioleaching and biosynthesis

Bioleaching and bio-synthesis approaches extend circularity to inorganic and hybrid wastes:

- Extremophiles have been identified as powerful agents for metal solubilisation from industrial solid wastes under harsh conditions, with optimisation of pH, temperature and redox potential enabling high extraction yields (Adetunji & Erasmus, 2024).
- Detailed reviews of bioleaching for metal and nanoparticle recovery from e-waste, fly ash and spent catalysts examine mechanistic pathways, kinetic models, response-surface optimisation and economic constraints, positioning bioleaching as a core technology in sustainable inorganic waste management (Jaiswal et al., 2025).
- Waste-derived carbon quantum dots with antibacterial and sensing properties demonstrate how waste valorisation can intersect with advanced material science, enabling high-performance nanomaterials for environmental monitoring and health applications (Dutta et al., 2025).

System-level innovations: digitalisation, policy and SMEs

Digitalisation and smart waste systems

Digital technologies are increasingly embedded in circular waste systems:

- Intelligent waste sorting using deep learning achieves high classification accuracy for multiple waste categories, providing a backbone for automated, high-resolution segregation in smart cities (Ahmad et al., 2025).

- Circular supply-chain models for spent coffee grounds introduce smart bins, real-time analytics, and data-driven routing to reduce costs and environmental impacts; strategic placement of pre-drying equipment emerges as a key lever (Zohourfazeli et al., 2025).

These developments support data-intensive, adaptive waste management, but also raise questions about digital infrastructure, cybersecurity, and equity in access to smart technologies.

Policy instruments and regional development

Biofuel policies provide a vivid example of how circular bioeconomy initiatives can reshape regional economies. Indonesia's palm oil-based biodiesel policy, with blending targets such as B35, has stimulated debates about land use, deforestation and smallholder livelihoods. Ex-ante analyses of replanting schemes for existing plantations show potential for reducing poverty, increasing provincial growth and meeting biodiesel demand without extensive land expansion (Halimatussadiah et al., 2025). Such analyses illustrate that policy design must balance energy targets, environmental safeguards and socio-economic outcomes.

SMEs, open innovation and circular practices

Agricultural SMEs face resource constraints but are critical actors for scaling circular bioeconomy practices. Empirical work in Thailand shows that:

- Eco-processes (e.g., waste reduction, resource efficiency, clean technologies) are the strongest drivers of SME sustainability initiatives,
- Open innovation collaborating with external partners, universities and customers—supports the development of new products from waste,
- Eco-products and eco-managerial practices, while conceptually important, may have weaker direct impacts unless integrated into coherent strategies (Worakittikul et al., 2025).

Taken together, these findings emphasise capability building, partnerships and organisational innovation as essential complements to technological development.

Demonstration infrastructures and scale-up facilities

Pilot and demonstration plants, such as the BioCampus MultiPilot in Straubing, provide shared infrastructure for scaling up fermentation and bioprocesses using 20-L to 25-m^3 reactors and associated downstream equipment (Lukin, 2025). These facilities lower entry barriers for SMEs and research groups, enabling:

- Scale-up of waste-derived bioprocesses,
- Regulatory and food-grade compliance testing,
- Real-world techno-economic and environmental assessments.

They also act as innovation hubs where multi-stakeholder collaborations can test circular concepts under industrially relevant conditions.

Health, safety and environmental performance

Life-cycle perspectives on waste valorisation reveal both benefits and trade-offs:

- NADES-based chitin extraction from insect exuviae shows gate-to-gate GHG emissions substantially lower than conventional acid–alkali routes, with high solvent recovery and water reuse, exemplifying process-level decarbonisation (Sharma & Thangadurai, 2025).
- Gasification and pyrolysis systems can reduce landfill dependence and recover energy but may generate tar, particulates and other emissions if poorly designed (Paneru et al., 2024; Wang et al., 2025).
- Bioplastic production from agri-waste and microalgae appears environmentally favourable relative to fossil plastics, but the benefits are sensitive to feedstock logistics, energy sources and end-of-life management (Adetunji & Erasmus, 2024; Mandal et al., 2024).

Consequently, robust LCA and techno-economic assessments are required for each pathway and regional context.

Bioaerosols, pathogens and occupational health

Valorisation facilities are not risk-free. Studies of microbial communities in garbage rooms and waste handling facilities show diverse bacterial populations, including potential pathogens, in bioaerosols and surface contaminants (Hui et al., 2024). This underscores:

- The need for ventilation, personal protective equipment and monitoring in biowaste facilities,
- Occupational health protocols as core components of circular bioeconomy projects,
- The importance of integrating biosafety considerations into process design (e.g., closed systems, appropriate filtration).

Food safety, antimicrobial resistance and product quality

Waste-derived products for food, cosmetic or biomedical applications must meet stringent safety standards:

- Virucidal extracts from grape pomace show broad antiviral activity but require thorough characterisation of active components and toxicology (Sampaio et al., 2023).
- Nano-materials such as carbon quantum dots with antibacterial activity and heavy-metal sensing functions must be carefully evaluated for environmental and human health impacts (Dutta et al., 2025).
- The use of antibiotics in animal production and subsequent valorisation of manures or slaughterhouse waste raises concerns about antibiotic residues and antimicrobial resistance pathways; while not always directly addressed, these issues are implicit in discussions of sustainable waste management.

Future work should thus reinforce toxicological testing, regulatory alignment and risk-benefit analysis for all high-value bioproducts emerging from waste streams.

Table 1. Recent bioprocessing routes for agro-industrial and food waste

Feedstock / residue	Core technology / pathway	Main products / services	Process context / scale	Key circularity feature	Ref.
Mixed agro-industrial residues	Sterile & non-sterile solid-state bioprocessing	Lignocellulolytic enzymes, enriched compost	Lab–pilot SSB, 28-day runs	Sterility as design lever for enzyme vs. mineralisation	Farinon et al., 2026
Fruit processing waste	Multi-tech green extraction & fermentation	Organic acids, bio-enzymes, bio-cleaners	Process-intensified, commercial scale oriented	Zero-waste strategy, process intensification	Agarwal et al., 2025
Insect frass	Anaerobic digestion	Biogas, biomethane	Lab–pilot digesters	New biomass class for bioenergy, circular insect farming	Lovarelli et al., 2024
Spent coffee grounds	Circular reverse-logistics optimisation, pre-drying	Feedstock for bioenergy / bioproduct facilities	City-scale modelling (MILP)	Digitalised, data-driven circular supply chain	Zohourfazeli et al., 2025
Olive cake	Microbial fuel cells	Electricity, partial COD removal	Bench-scale MFCs	Coupled waste treatment and bioelectricity	Fayad et al., 2025

Table 2. Waste-derived biopolymers, bioplastics and bio-based materials

Feedstock / resource	Biopolymer / material focus	Process / route	Application domain	Key challenge / research gap	Ref.
Agri-waste carbohydrates, lignocellulose	Bioplastics (e.g., PHAs, starch blends)	Microbial fermentation, mechanical processing	Packaging, agriculture, consumer goods	Scale-up economics, property optimisation	Mandal et al., 2024
Microalgal biomass	Bioplastics, biopolymers	Cultivation + polymer extraction / synthesis	Packaging, construction, healthcare	High production costs, LCA uncertainties	Adetunji & Erasmus, 2024
Wine and grape by-products	Bio-based edible films, coatings, packaging	Film casting, incorporation of polyphenolic extracts	Small fruits, fresh produce packaging	Mechanical/barrier performance, cost	Oliveira et al., 2025
Chestnut shells	Polyphenol-rich extracts	Pressurised liquid extraction + UHPLC-TIMS-QTOF-MS	Functional food, cosmetic ingredients	Scaling PLE, valorising spent solids	Pazara et al., 2025
Insect exuviae (*H. illucens*)	Chitin, chitosan, chitooligosaccharides	NADES extraction, enzymatic deacetylation & depolymerisation	Biomedical, cosmetic, agriculture	Industrial deployment of NADES, market development	Sharma & Thangadurai, 2025

Table 3. Hyaluronic acid production and integration into waste-based biorefineries

Production route / system	Feedstock / carbon source	Process scale / configuration	Key performance aspects	Integration context	Ref.
Conventional microbial fermentation	Refined sugars, complex media	Industrial fermenters	High HA titers, high substrate cost	Stand-alone HA plants	Mioti et al., 2025
Biomass-assisted fermentation	Agro-industrial waste-derived sugars	Lab–pilot studies	Lower costs but variable yields	Emerging circular HA concepts	Mioti et al., 2025
GBAER-type MSW biorefinery	Organic fraction of MSW	Integrated biorefinery, conceptual	Limited demonstrated HA yields, high potential	Coupled waste treatment–HA production	Pérez-Morales et al., 2024
HA in broader bioprocessing portfolios	Organic wastes, municipal streams	Multi-product biorefineries	Co-production with bioenergy/chemicals	Strategic high-value product in waste biorefineries	Mioti et al., 2025; Pérez-Morales et al., 2024

Table 4. System-level circular innovations and enabling conditions

Domain	Instrument / innovation	Targeted system outcome	Illustrative context	Limitation / open question	Ref.
Digital waste management	Deep learning-based waste classification	High-accuracy automatic sorting	Smart city waste systems	Data requirements, robustness, deployment cost	Ahmad et al., 2025
Circular supply chains	MILP-optimised reverse logistics, smart bins	Cost- and emission-efficient collection & pre-treatment	Spent coffee grounds in Montreal	Transferability, behavioural aspects	Zohourfazeli et al., 2025
Policy & regional	Biofuel replanting	Poverty reduction,	Indonesian palm oil	Land-use safeguards,	Halimatussadiah et al., 2025

development	scheme	regional growth, biodiesel supply	sector	finance, smallholder inclusion	
SME eco-innovation	Open innovation, eco-process focus	Eco-innovation, new products from waste	Agricultural SMEs in Thailand	Weak eco-product/managerial leverage	Worakittikul et al., 2025
Demonstration infrastructure	Shared bioprocess scale-up facilities	Lowered scale-up risk, industrial validation	BioCampus MultiPilot, Straubing	Access models, long-term financing	Lukin, 2025

Managing feedstock heterogeneity and uncertainty

Heterogeneity in composition, moisture content, contaminants and physical form remains one of the foremost barriers to robust waste-based biorefineries. Gasification studies explicitly show how feedstock variability drives temperature fluctuations and syngas quality, necessitating new control parameters such as equivalent ratio on a dry ash-free basis (Wang et al., 2025). Similar issues arise in fermentation (variable C:N ratios, inhibitors), extraction (matrix effects) and logistics (variable waste generation patterns).

Future research priorities include:

- Standardised characterisation protocols for emerging feedstocks (e.g., insect frass, exuviae, novel agro-industrial residues),
- Adaptive process control systems that adjust operating conditions in response to real-time feedstock properties,
- Blending and pre-processing strategies (pre-drying, torrefaction, fractionation) optimised via multi-objective models.

From unit operations to integrated biorefineries

Many recent studies still focus on single processes or products. Moving toward fully integrated biorefineries requires:

- Rigorous process integration and pinch analysis across biochemical and thermochemical operations,
- Multi-product optimisation that accounts for market volatility, product quality specifications and regulatory constraints,
- Cascading use designs in which high-value product extraction precedes energy recovery and nutrient recycling.

Pilot-scale facilities and shared infrastructure are key to generating the data necessary to design and validate such systems (Lukin, 2025).

Socio-economic embedding and just transitions

Circular bioeconomy projects do not automatically yield positive social outcomes. Work on biofuel policy, SME innovation and educational-institution composting highlights that:

- Design choices can enhance or undermine poverty reduction, smallholder inclusion and regional equity (Halimatussadiah et al., 2025),
- Capacity building and participatory governance are essential, especially where SMEs and municipalities are central actors (Worakittikul et al., 2025; Bhakuni et al., 2025),
- Financial mechanisms (green bonds, blended finance, replanting subsidies) and policy coherence (land-use, waste, energy, agriculture) strongly condition outcomes.

Research should therefore integrate political economy, social science and behavioural insights into technical evaluations.

Health, safety and regulatory alignment

Ensuring that waste-derived bioproducts meet safety and quality standards is a non-negotiable requirement for top-tier applications. Priorities include:

- Comprehensive toxicological and microbiological assessments for food, feed and biomedical products derived from wastes (e.g., polyphenol extracts, nano-materials, bio-active coatings),
- Frameworks for occupational and environmental health in facilities handling high-microbial-load wastes and bioaerosol-rich environments (Hui et al., 2024),
- Harmonised regulatory pathways that recognise the specificities of waste-derived bioproducts while maintaining stringent safety thresholds.

Digital, AI and data governance

Digital and AI-enabled waste systems must grapple with:

- Data quality, interoperability and standardisation across sensors, logistics platforms and process control systems,
- Governance of AI decision-making, including transparency, accountability and potential biases in waste classification or supply-chain decisions,
- Cybersecurity and resilience, especially where critical infrastructure (energy, water, health) is coupled to digital waste systems (Ahmad et al., 2025; Zohourfazeli et al., 2025).

CONCLUSIONS

The last few years have witnessed a rapid maturation of agro-industrial and food waste valorisation from a niche environmental management option into a central pillar of the circular bioeconomy. The literature now documents sophisticated bioprocesses (solid-state cultivation, NADES-enabled extraction, biomass-assisted fermentation), advanced thermochemical systems (heterogeneity-aware gasification, plastic pyrolysis), and a growing array of high-value products (bioplastics, biosurfactants, hyaluronic acid, virucidal extracts, nano-materials) derived from diverse waste streams. Simultaneously, work on circular supply chains, digitalised waste logistics, SME eco-innovation, biofuel policy and demonstration infrastructure shows that system-level conditions are beginning to align with technological potential. Rather than treating waste valorisation as an add-on to linear production systems, these developments point toward integrated, multi-product biorefineries and circular value chains embedded within regional economies. Yet substantial gaps remain. Feedstock heterogeneity, scale-up risks, regulatory complexity, health and safety concerns, and socio-economic justice all pose non-trivial challenges. The research agenda ahead is therefore inherently interdisciplinary, demanding that engineers, biotechnologists, economists, social scientists and policymakers co-design solutions. If these challenges can be addressed, agro-industrial and food waste will cease to be a symbol of inefficiency and environmental harm and will instead anchor resilient, low-carbon and inclusive bio-based economies, delivering not only waste reduction and climate benefits but also new materials, medicines, energy and livelihoods.

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