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CIRCULAR BIOECONOMY APPROACHES FOR AGRICULTURAL AND FOOD PROCESSING WASTES: TECHNOLOGIES, BUSINESS MODELS AND SUSTAINABILITY ASSESSMENT

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ABSTRACT
One of the most abundant renewable feedstocks that can be used in a circular bioeconomy is agricultural and food processing wastes. These consist of crop residues, manure, fruit and vegetable by-products, dairy and brewery residues, slaughterhouse wastes, spent grains, oilseed cakes and mixed post-consumer food waste. These streams are often dumped, burned, landfilled or discharged into wastewater systems in a linear agri-food system, resulting in economic losses, public-health risks, odours, nutrient pollution and greenhouse-gas emissions. A circular bioeconomy redefines these materials as biological resources that can be prevented, recovered, cascaded, and converted to food, feed, organic fertilizers, soil amendments, bioenergy, biomaterials, platform chemicals and functional ingredients. This review aims to compile authoritative, peer-reviewed literature and institutional reports up to July 2026, focusing on technologies, business models and sustainability assessment approaches. Composting, anaerobic digestion, production of pyrolysis and biochar, gasification, hydrothermal processing, fermentation, enzymatic conversion, insect bioconversion, extraction of bioactive compounds and integrated biorefineries are key valorization technologies. The review also explores business models for resource recovery, cooperative ownership, industrial symbiosis, product-service systems, digital platforms, carbon and nutrient markets and cascading value chains. The concept of sustainability assessment is introduced via the concepts of life-cycle assessment, techno-economic analysis, life-cycle costing, social life-cycle assessment, material flow analysis, circularity metrics and multi-criteria decision analysis. The results indicate a reduction of about 1 t CO2e per tonne of food waste recycled, compared to landfill disposal, due to circular management of food waste, but this depends significantly on the quality of the feedstock, the design of the process, energy substitution, transport distances, digestate or compost application, market demand and policy incentives. Progress will need to be made using integrated biorefineries, harmonised assessment methods, safe use standards for recovered products, digital traceability, and inclusive financing and policies that focus on prevention rather than recycling. Circular bioeconomy strategies can help to decrease environmental impacts and generate new economic opportunities, but they need to be developed as a system that is balanced between ecological limits, social acceptance and economic viability.

KEYWORDS: Circular bioeconomy, food processing waste,circular business models, sustainability assessment.

1. INTRODUCTION

Agricultural and food processing systems are both food, livelihood, biomass and wastes and environmental pressures. Significant amounts of biological material are not part of the desired food chain during the production of crops, livestock, during post-harvest operations and industrial processing. There is some material that is unavoidable, like husks, peels, manure and extraction residues. Other parts are avoidable losses due to inadequate storage, harvesting inefficiencies, cosmetic requirements, lack of cold chains, market fluctuations, overproduction or waste by consumers. Many of these streams are considered as liabilities in conventional linear management. Residues are either burned in fields or buried in landfills, discharged into waterways, or disposed of with low-value disposal methods. This method results in loss of embedded nutrients, energy, water and labour, and methane emissions, eutrophication, air pollution and public-health issues (FAO, 2019; Gustavsson et al., 2011; UNEP, 2024).

The scale of the problem is such that it has an impact on climate, food security and economic development. The global estimate of food lost and wasted by FAO estimated that approximately 1.3 billion tonnes of food is lost or wasted annually, which is about one-third of the food produced for human consumption (Gustavsson et al., 2011). Food waste at the household, food service and retail levels was estimated to be 1.05 billion tonnes in 2022, which represents approximately 19% of all food available to consumers (UNEP, 2024). The State of Food and Agriculture 2019 highlighted that reducing food loss and waste is a key priority for food security, food production costs and environmental impacts, but also pointed out that policies need to be informed by the food loss and waste value chain and the benefits to be gained (FAO, 2019). Food systems are responsible for approximately one-third of global anthropogenic greenhouse-gas emissions and food loss and waste represent emissions from production, transport, processing and disposal (Crippa et al., 2021; Tubiello et al., 2022; Zhu et al., 2023).A circular bioeconomy can be a pathway to solve these interrelated issues. It is based on the principles of the circular economy (reduce, reuse, recover, recycle and regenerate) and the bioeconomy, which is based on the use of renewable biological resources. The circular bioeconomy does not see biomass as a one-time resource, but rather as a resource that can be kept in its highest value for as long as possible, safely returned to ecosystems, and replaced with bio-based products where suitable, and avoiding resource leakage (Khanna et al., 2024; Muscat et al., 2021). Muscat et al. (2021) put forward the ecological principles for biomass use: protect and restore agroecosystems' health; avoid unnecessary biomass products and waste of essential biomass products; focus on biomass products for basic human needs; recycle biomass by-products; and use renewable energy, while reducing the overall energy demand. The principles are relevant because circularity is not necessarily sustainable. A process can be circular but still use too much energy, pollute soils, shift food uses, or shift burden to workers and communities.

This review manuscript aims to bring together the state of the art of authoritative knowledge on circular bioeconomy solutions for agricultural and food processing wastes. The emphasis isn't just on naming technologies. Rather, the review connects technologies to business models and sustainability assessment as all three are necessary for successful transition. Technologies need to be appropriate to the characteristics of the feedstocks and local resource priorities. Business models need to be developed to ensure sustainable value propositions and cost and benefit sharing between farmers, processors, municipalities, consumers and investors. Sustainability assessment should not be a one-way street where recycling is seen as a good thing. The manuscript is structured in six sections: Waste streams and circular hierarchy, Technological pathways, Integrated biorefineries, Business models, Sustainability assessment and Future prospects.

2. Waste Streams and the Circular Bioeconomy Hierarchy

2.1 Agricultural residues and livestock wastes

The composition, moisture content, nutrient content, seasonality and contamination risk of the agricultural residues vary. The crop residues like rice straw, wheat straw, maize stover, sugarcane trash, cotton stalks and husks are generally lignocellulosic, containing high cellulose, hemicellulose and lignin. These materials can be composted, pyrolysed, combusted, gasified, hydrothermally processed, enzymatically hydrolysed and processed in second generation biorefineries. Their valorization is limited, however, by low bulk density, low production density, high collection costs, and seasonality of availability and competing uses for the straw such as bedding, mulch or in-field soil-carbon maintenance (Khanna et al., 2024; Muscat et al., 2021). Excessive residue removal can lead to decreased soil organic matter, erosion protection and nutrient cycling. Hence, the sustainable removal rates need to be identified in circular strategies instead of assuming that all residues can be used in industry.

Livestock wastes consist of manure, litter, bedding and wastewater from dairy, poultry, swine and cattle operations. The residues include nitrogen, phosphorus, potassium, organic matter and microbial communities. They produce methane and nitrous oxide in unmanaged systems, pollute surface and ground water and cause odour issues. Managed anaerobic digestion can be used to produce biogas and digestate from manure and composting can be used to stabilise organic matter for land application. However, pathogen reduction, nutrient balance, antibiotic residues, heavy metals and regional nutrient surpluses are challenges that need to be overcome in manure valorization. Digestate can not only be used as a nutrient carrier for safe reuse, but it is also a potential nutrient carrier that can help close nutrient loops (Alengebawy *et al*., 2024; Triviño-Pineda *et al*., 2024).

2.2 Food processing wastes and by-products

The food processing wastes include wastes generated in the industries involved in food processing like cleaning, peeling, pressing, milling, brewing, slaughtering, dairy processing, oil extraction etc. According to the U.S. Environmental Protection Agency's industrial food-processing waste analysis, fruit and vegetable wastes (including leaves, peels, pomace, skins, rinds, cores, pits, pulp, stems, seeds and spoiled materials), and brewery wastes, which are rich in organic material, are candidates for composting or anaerobic digestion (U.S. EPA, 2012). Dairy residues are high BOD whey and wastewater streams. The spent grains, yeast and wastewater are all considered brewery residues. Blood, fat, feathers, bones and offal are all examples of meat and slaughterhouse residues. Oilseed processing produces protein and residual oil rich cakes and meals.

They are generally more concentrated and predictable than the residues from farms, and are therefore interesting for industrial valorization. Fruit pomace can be used to produce fibre, pectin, polyphenols and fermented products. The essential oils, pectin and limonene can be extracted from citrus peels. Whey can be used for lactic acid fermentation, single cell protein or bioactive peptides production. The spent grain from the brewer can be utilized as feed, protein extraction, fibre ingredients, enzyme production or bioenergy. The variety of food-processing wastes also poses problems, however, such as spoilage, high moisture content, microbial contamination, varying composition, seasonal changes, and the need to preserve or pre-treat the wastes.

2.3 Prevention, cascading use and the waste hierarchy

Prevention and source reduction are the first steps in a rigorous circular bioeconomy. Avoiding waste should not be an excuse for high value recovery. The most preferred sequence is prevention, redistribution of edible surplus, use as animal feed (where safe and legal), extraction of high value compounds, conversion to food/feed ingredients, material recovery, anaerobic digestion/composting, energy recovery, and finally disposal. This hierarchy is based on the principle that biological resources should be used to satisfy basic needs before being used for lower valued products and/or energy (Muscat *et al*., 2021; Teigiserova *et al*., 2020).

The maximization of value is at the heart of cascading use. For instance, polyphenols or pectin can be extracted from fruit-processing wastes, followed by fermentation, composting or pyrolytic treatment of the remaining solid wastes. Before the residual fractions are used for biogas production, it is possible to extract proteins from Brewer's spent grain, which can then be used as animal feed. Biogas can be generated by anaerobic digestion and digestate nutrient recovery can be achieved as well as composting of the solid fraction. Cascading is a process that needs to be carefully balanced for mass and energy as each step can use water, solvents, heat or electricity. A complex cascade might not be as sustainable as a simpler one if the extra environmental load is not matched by the benefits recovered.

3. Technologies for Circular Valorization

3.1 Composting and aerobic stabilization

One of the most traditional and common methods to stabilize organic residues is composting. It is based on the aerobic microbial decomposition under controlled moisture, aeration, carbon-to-nitrogen ratio and temperature conditions. Thermophilic composting can be used to effectively lower levels of pathogens and weed seeds and transform unstable organic matter into soil amendment when managed properly. Compost helps to enhance soil structure, water holding capacity, microbial activity and nutrient availability. It is especially adapted for yard waste, crop residues, manure, food waste solids and digestate solids.

The circular value of composting is to return carbon and nutrients to soil instead of letting them break down in landfills in an anaerobic environment. Based on field data, composting can significantly lower emissions compared to landfilling, especially if it prevents the production of methane (Wang *et al*., 2025). Composting can also increase soil organic matter, although the amount of carbon stored will vary depending on feedstock, process conditions, application rates and climate. It has a number of drawbacks such as the need for land, the need for odour control, the potential for contamination by plastics or heavy metals, relatively low nutrient levels, and the potential for nitrous oxide or ammonia emissions if aeration and moisture management are not optimized. Process control can be enhanced with advanced systems like aerated static piles, in-vessel composting and biofilter covered piles, but these systems are more expensive.

3.2 Anaerobic digestion and biogas systems

The process of anaerobic digestion is a hydrolysis, acidogenesis, acetogenesis and methanogenesis process, which produces biogas and digestate from organic matter. It can be used for wet, easily biodegradable feedstocks like manure, food waste, brewery residues, wastewater sludge and some crop residues, after pre-treatment. Co-digestion can be used to mix complementary feedstocks to enhance the carbon-to-nitrogen ratio, buffering capacity and methane production. For example, manure can be used to inoculate the system and buffer the pH, and food waste can be used to provide high biochemical methane potential (Alengebawy *et al*., 2024; Triviño-Pineda *et al*., 2024).

Biogas can be utilized for heat, CHP or upgraded to biomethane for grid injection or vehicle fuel. When applied safely, digestate can be used as an organic fertilizer and source of nutrients, instead of mineral fertilizers. The recovery of nutrients in digestate, such as the production of ammonium sulfate, struvite precipitation, membrane separation and drying, can enhance the transportability and minimize nutrient losses. The environmental benefits of anaerobic digestion are greatest when it recovers methane that would otherwise be released, replaces fossil energy and nourishes the soil. But methane emissions, sub-optimal energy utilization, digestate handling and storage issues, and long distances to digestate disposal sites can negate benefits. Economic challenges for digesters include high capital costs, technical skill needs, fluctuating feedstock supplies, interconnection restrictions, and reliance on policy support like renewable energy credits or feed-in tariffs.

3.3 Pyrolysis, gasification and biochar

The thermochemical processes produce energy carriers and carbon-rich materials from dry or dewatered biomass. Pyrolysis is a process that involves heating the biomass in a limited amount of oxygen to generate biochar, bio-oil and gases. Gasification is the process of converting biomass at high temperature and with controlled amount of oxygen or steam to syngas for heat, power or chemical synthesis. Hydrothermal carbonization and hydrothermal liquefaction are methods of processing wet biomass under pressure, which decreases the need for energy intensive drying.

Biochar has a special relevance for circular bioeconomy strategies as it has the potential to stabilize carbon, enhance soil properties and adsorb pollutants. Sudarsan *et al*. (2025) reviewed the applications of food-waste-derived biochar in carbon capture, wastewater treatment, catalysis, fuel, supercapacitors and soil enhancement in the RSC review in 2025, and noted that there is a lack of data from industrial scale. The benefits of biochar are dependent on the feedstock, pyrolysis temperature, residence time, ash content, pH, surface area and contaminant levels. Food waste biochars can be useful for providing nutrients, but can also contain salts or metals. Pyrolysis may be attractive for dry agricultural residues like husks and shells but for wet food waste, drying or mixing with other processes is required. The economic case strengthens when biochar is sold as a soil amendment, carbon removal credits or pollutant removal applications, but there is a lack of standards and long-term performance data.

3.4 Fermentation, enzymatic conversion and microbial products

Fermentation is a process which uses microbial metabolism to valorize food and agricultural wastes. Carbohydrate, protein and lipid rich substrates can be used for the production of organic acids, enzymes, ethanol, single cell protein, bioactive peptides, phenolics, biosurfactants, biopolymers and flavour compounds. In their recent review on agri-food waste fermentation, Tornuk and Akman highlighted the production of bioactive peptides, phenolics, single-cell proteins, polyunsaturated fatty acids, organic acids, and other compounds using selected bacteria, filamentous fungi and yeasts from agri-food waste and by-products, and the persistent barriers to scale-up and commercialization (Tornuk & Akman, 2026). Lactic acid is one of the most important platform chemicals as it can be polymerized to produce biodegradable polymer polylactic acid, and food and agricultural biowaste are identified as potential substrates for lactic acid production in recent reviews (Melikoglu, 2026; Song *et al*., 2024).

The value potential of fermentation is high as it can yield products of much higher market value than compost or energy. For example, whey can be fermented to lactic acid or microbial biomass, fruit pomace can be used to produce enzymes, ethanol or phenolic rich ingredients and lignocellulosic residues can be pretreated and enzymatically hydrolyzed to produce fermentable sugars. Fermentation routes, however, need to be closely monitored for sterility or microbial ecology, pH, temperature, and composition of the substrate and downstream purification. Heterogeneity of waste is one of the significant challenges as industrial fermentations require uniformity of feedstock. There may be an increase in costs due to pre-treatment, hydrolysis and detoxification. Hence, fermentation is most suited to integrated biorefineries which are able to accept variable streams and valorise residual fractions following high value extraction.

3.5 Extraction of functional compounds and biomaterials

By-products of food processing can be valuable compounds that can be recovered prior to the residual biomass being processed for energy or soil. The polyphenols, pigments, dietary fibre, essential oils and pectin are found in fruit peels and pomace. Proteins and bioactive peptides are found in oilseed cakes. Collagen, gelatin, chitosan, enzymes and lipids can be obtained from fish and slaughterhouse by-products. The recovered compounds can be used in food, nutraceutical, cosmetic, pharmaceutical and packaging and agriculture industries.

Functional-compound recovery is consistent with cascading principles, and involves the recovery of higher value molecular functions before lower value energy and nutrient recovery. Green extraction technologies such as supercritical CO2, pressurized liquid extraction, ultrasound-assisted extraction, microwave-assisted extraction, enzymatic extraction and membrane separations can help to decrease the solvent and energy loads compared to conventional extraction. But the sustainability of extraction relies on the type of solvent used, the yield of the product, the need for purification, the source of electricity and the acceptance of the product in the market. The use of simple feeds or composts may be more desirable than a low yield extraction with toxic solvents. Recovered compounds re-entering food or feed chains are also subject to food safety and regulatory approval.

3.6 Insect-based bioconversion

Insect bioconversion is one of the new biological processes that converts food and agricultural residues into protein, oil and frass. The black soldier fly (*Hermetia illucens*) is the most important species due to its ability to rapidly develop on a wide variety of organic materials and be able to convert residues into high-protein biomass that can be used in aquaculture, poultry, pet food and even other feeds. Recent reviews indicate that black soldier fly larvae are able to significantly decrease the amount of organic waste, convert food waste, manure and agricultural by-products into protein and fat rich biomass, and generate frass which can be used as an organic fertilizer (Caisin, 2025; Wilson *et al*., 2025).

The advantage of insect systems is that they are able to reduce waste and produce alternative proteins. Additionally, they can help to alleviate the pressure on fishmeal and soy, depending on the use of the larvae and the feedstocks allowed. However, there are technical and regulatory issues regarding insect bioconversion: substrate safety, pathogen risk, heavy metals, pesticide residues, antibiotic residues, allergens, processing standards and consumer acceptance. There are a number of jurisdictions that limit the types of waste that can be used for insects for animal feed. Environmental control, automation, regular supply of feedstock, odour control and markets for larvae and frass are required to scale up the production. Insects are not a panacea, but are a viable option in the presence of safe substrates, clear regulations and feed markets.

3.7. Integrated biorefineries and cascading platforms

It is not possible to optimally valorise all agri-food waste streams with a single technology. Integrated biorefineries are a collection of unit operations that are integrated to produce fuels, chemicals, materials and soil amendments.

A fruit-waste biorefinery could be used to recover essential oils and pectin, to ferment sugars to organic acids, and to digest the remaining residues to produce biogas and compost digestate solids. Whey lactose could be used for lactic acid, single cell protein or ethanol production, and the remaining effluent would be fed into anaerobic digestion. Mechanical fractionation, pretreatment, enzymatic hydrolysis, fermentation, lignin valorization and biochar production may be part of a lignocellulosic residue platform.

Integrated approaches can enhance the economics, by diversifying products and lowering the disposal costs. They can also help to enhance sustainability by pairing each biomass fraction with a suitable application. But integration adds complexity as well. The cost of capital increases, supply chains need to be coordinated, product markets need to be reliable and process residues need to be managed. Life-cycle and techno-economic evaluations are thus crucial prior to scaling. The optimal circular configuration depends on the context: in one area, composting can be the most beneficial as soil organic matter is needed; in another, anaerobic digestion can be the best option as the focus is on renewable energy and manure methane capture; in another, fermentation can be the best option as concentrated by-products and specialty chemical markets exist.

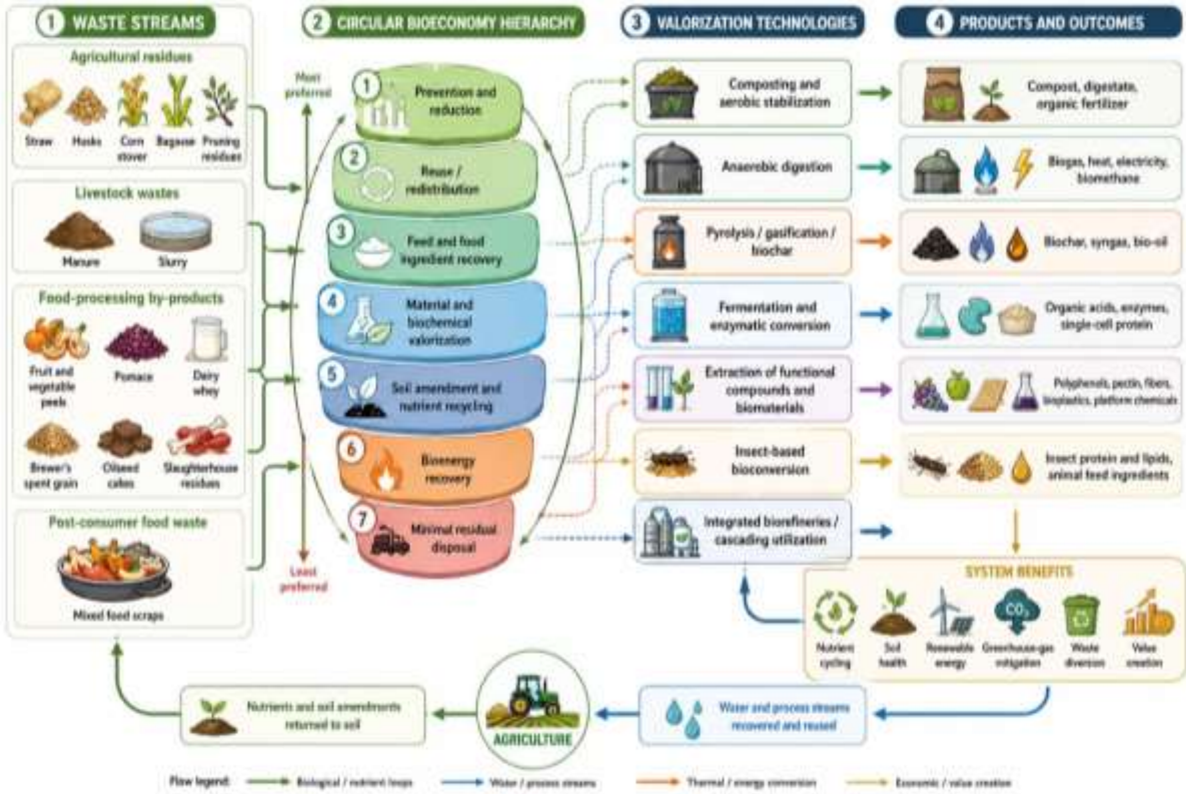

Fig. 1. Circular bioeconomy framework for agricultural and food-processing wastes

4. The business models for the implementation of circular bioeconomy.

4.1 To understand the need for technologies to have business models.

Technological feasibility is not a prerequisite for adoption. The lack of reliable feedstocks, markets for recovered products, unclear regulations, high capital costs, and benefits going to different actors than costs are some of the reasons why many waste valorization technologies are not successful. Circular business models are the rules that guide the creation, delivery and capture of value and minimize resource leakage. Business models need to deal with the biological variability, rural logistics, seasonal production, quality requirements and stakeholder trust in agri-food systems.

Khanna *et al*. (2024) stated that the circular bioeconomy needs to transcend the techno-centric approach and take an economic perspective, considering the costs, benefits and distributional impacts. This is crucial since the socially optimal level of circularity might not be the privately profitable level. If energy costs are low, a farmer might not be interested in investing in a digester even if society would benefit from the reduction of methane. If buyers are not confident in the recovered ingredients, a processor might not be willing to process them. If gate fees are lower than separate organic collection, a municipality may choose to dispose of the organic waste in a landfill. Policy, finance and market design is therefore a determinant of circular outcomes.

4.2 Resource recovery and reuse models

Resource recovery and reuse models are revenue-generating waste management services and recovered products. Otoo and Drechsel (2018) reported a wide variety of business models for recovering energy, nutrients and water from municipal, agro-industrial and food waste in LMICs. These include compost enterprises, briquette production, biogas enterprises, wastewater reuse, nutrient recovery and integrated sanitation-resource recovery models. Their work is especially useful as it not only considers waste recovery as a technology but also as a business ecosystem that needs to be analyzed in the market, managed in terms of safety, financed, and coordinated institutionally.

Resource recovery models in agricultural areas can be farmer-owned, cooperative, municipal or private. A manure digester is a system that is owned by the farmer, which recovers methane from manure and provides on-farm energy. A cooperative digester combines the manure and food waste from several farms and processors to benefit from economies of scale. Separated organics are sent to a municipal composting facility for sale of compost in the area. A private biorefinery enters into long-term contracts with the processing residues, and generates ingredients or bio-based chemicals. There are unique dangers with each model. Financing and technical maintenance challenges can be encountered at the farm level; transport costs and community resistance can be issues for centralized systems; and product price fluctuations and feedstock competition can be problems for private biorefineries.

4.3 Circular business model archetypes

Useful archetypes from the literature of the sustainable circular business model. De Keyser and Mathijs (2023) created a typology to differentiate purposeful and scaled-up versions of sufficiency, functionality and stewardship models. In the context of waste valorization, a purposeful stewardship model can be based on local soil health and community benefits, achieved by composting, and a scaled up functionality model can provide nutrient management services instead of selling fertilizer products directly. A sufficiency model can focus on waste prevention and waste reduction of unnecessary consumption before valorization.

Donner *et al*. (2021) analyzed 39 business cases of valorization of agricultural waste and by-products and found critical success and risk factors. Stable feedstock availability, product quality, collaboration between value chain actors, regulatory support, consumer acceptance, diversified revenue streams and leadership are key success factors. The risk factors are high investment costs, reliance on subsidies, volatile markets, logistics, seasonal feedstocks, product quality fluctuations and the competition of existing products. These are very relevant for projects in the field of circular bioeconomy, as often the recovered product is competing with cheap fossil based, mineral or virgin alternatives.

4.4 Industrial symbiosis, platforms and cooperative models

Industrial symbiosis is when the waste or by-product of one actor is the input of another. This can connect farms, mills, breweries, dairies, processors, biogas plants, composters and feed producers in agri-food areas. Spent grain can be fed to livestock farms, yeast to feed producers and wastewater to anaerobic digestion in a brewery. The peels can be used for pectin extraction and the residual pulp for fermentation in a fruit-processing plant. Whey processing, anaerobic digestion and nutrient recovery are possible in a dairy cluster.

Digital platforms can facilitate waste generators and users to match. Can give information about quantity, timing, composition, contamination and location. Traceability and quality assurance can be enhanced with the use of sensors, blockchain and digital product passports. But platforms are not enough to achieve circularity when there is a lack of infrastructure, rules and markets. Cooperative models can be particularly appropriate for farmers as they share risk, enhance their bargaining power and share benefits at the local level. For municipal organic waste, public-private partnerships can be helpful as the government may have control over the collection system, and the private sector may offer technology and market development.

4.5 Financing and policy-enabled value capture

Blended finance is needed for many projects in the circular bioeconomy. Revenue can be generated from product sales, tipping fees, energy tariffs, nutrient credits, carbon credits, avoided disposal costs and public subsidies. Biochar and methane reduction are becoming more and more relevant to carbon markets, which need credible monitoring, reporting and verification. In watersheds that are polluted with nutrients, nutrient trading schemes could incentivize nutrient recovery. Biogas and biomethane can be supported with renewable energy policies. The EPR can incentivize packaging and food manufacturers to invest in organic waste recovery or reduction.

Policy design should not include perverse incentives. Subsidies for energy production from edible food waste can have a negative impact on prevention or food donation. Recycling is less competitive if the tipping fee at landfills is too low. Digestate and compost markets are weak if there are too many regulations or unclear regulations on organic fertilizer. In order to achieve a coherent policy, the following targets for prevention, source separation, food donation systems, safe feed rules, compost and digestate standards, renewable energy incentives, carbon accounting and public procurement of recovered products are required for a circular bioeconomy.

5. Sustainability Assessment of Circular Bioeconomy Pathways

5.1 Life-cycle assessment

Life-cycle assessment (LCA) is the most mature approach to assess environmental impacts from the extraction of raw materials to their production, use and end-of-life. It is defined by ISO 14040 and ISO 14044 standards, and consists of goal and scope definition, inventory analysis, impact assessment and interpretation (ISO, 2006a, 2006b). Datola and Oppio (2026) identified LCA as the most used methodology for environmental assessment of circular technologies in agriculture, followed by multi-criteria analysis and performance-based models that are able to incorporate environmental, economic and social aspects.

Multi-functionality is a challenge for LCA for agri-food waste. A composting system is a system that is used to manage waste and create soil amendment. Waste is used for anaerobic digestion, energy is produced and digestate is generated. Waste is used as feed for insects and frass is produced as waste. Allocation of environmental burdens and credits to these functions can have a significant impact on the results. The boundaries of the system also are important: Avoided landfill methane, Avoided synthetic fertilizer, Soil carbon changes, Energy substitution and transport can change conclusions. The functional unit should be based on the decision that is being made, e.g. one tonne of waste treated, one megajoule of energy produced, one kg of nutrient recovered or one ha of soil amended. There is growing evidence that food waste recycling has less impact on climate than disposal. Wang *et al*. (2025) combined field data to determine that composting, anaerobic digestion and re-feed reduces emissions by approximately 1 t CO2e per tonne of food waste recycled, compared to landfill disposal. They calculated that if food waste were not disposed of in landfills, it would be able to offset 10% of the emissions from the U.S. agricultural system, 5% of the EU's and 17% of China's. This does not imply that all projects will have the same benefit, as this will be dependent on the methane capture rate of the landfill, the energy mix, the efficiency of the processing and the use of recovered products. However, the overall trend is confirmed: Landfill avoidance and resource recovery are high priority strategies.

5.2 Techno-economic analysis and life-cycle costing

Techno-economic analysis (TEA) is a study of capital expenditure, operating cost, product yields, revenue, payback period, net present value and sensitivity to market variables. It is crucial since many potential technologies are still in the lab because of poor economics. Fermentation and extraction pathways can be valuable products, but are very costly to pre-treat, sterilize and purify. Only if there are carbon credits or high-value applications, can biochar systems be profitable. The energy price, tipping fees and policy incentives are important factors in anaerobic digestion.

Life-cycle costing is used in conjunction with TEA to consider costs throughout the life cycle of the system, such as collection, transport, processing, maintenance, compliance, disposal and product use. The issue for municipalities might not be if compost can be sold at a high price, but if a separate organic collection and composting system can lower overall waste-management expenses, landfill use and emissions. The question for farmers might involve the cost of not buying fertilizer, benefits to soil health and manure management. The boundaries of TEA and LCA need to be harmonised, otherwise one assessment may indicate an environmental benefit, while the other does not consider the cost of achieving it (Datola & Oppio, 2026; Khanna *et al*., 2024).

5.3 Social and institutional assessment.

Social sustainability is often not sufficiently developed in the assessment of circular bioeconomy. However, circular projects can generate employment, cut down on odours, boost sanitation, boost the rural economy and improve food security. They can also pose risks, such as the loss of livelihoods for informal waste workers, opposition from communities to odour or traffic, and smallholders' exclusion from high-tech value chains. Social life-cycle assessment focuses on worker health, wages, community impacts, equity, governance and human rights. Particularly in the case of recovered products that are returned to land or food/feed chains, participative assessment is of major importance.

Regulations, standards, property rights and incentives and stakeholder coordination are included in institutional assessment. For instance, the use of digestate needs to be regulated by the fertilizer law, set limits for contaminants and be trusted by farmers. Clear permissions for the use of insect feed and rules for the safety of animal feed. There is a need for liability protection and logistics in food donation. Plastics and pathogens need to be controlled in compost markets through quality standards. Technically viable circular pathways can get stuck without institutional support.

5.4 Circularity metrics and multi-criteria decision analysis

Circularity metrics measure the recirculation of materials, the recycled content, nutrient recovery, waste diversion, substitution of renewable energy or resource productivity. But, high circularity does not necessarily equal low impact. High energy or contamination of outputs may be needed for a process that recycles a significant percentage of the material. Hence, the use of circularity indicators should be done in conjunction with LCA, TEA and social indicators.

Multi-criteria decision analysis (MCDA) is helpful because agri-food waste decisions are made to address a number of objectives: emissions, cost, nutrient recovery, soil health, odour, jobs, food safety, acceptance and scalability. MCDA can take into account the preferences of the stakeholders and can compare alternatives even if some of the criteria are qualitative. Datola and Oppio (2026) pointed out the need for more integrated assessment frameworks and stakeholder sensitive approaches. The following elements should be part of a practical assessment framework for circular bioeconomy projects: feedstock characterization, mass and energy balances, LCA, TEA, life-cycle costing, risk assessment, social assessment, market analysis and policy analysis.

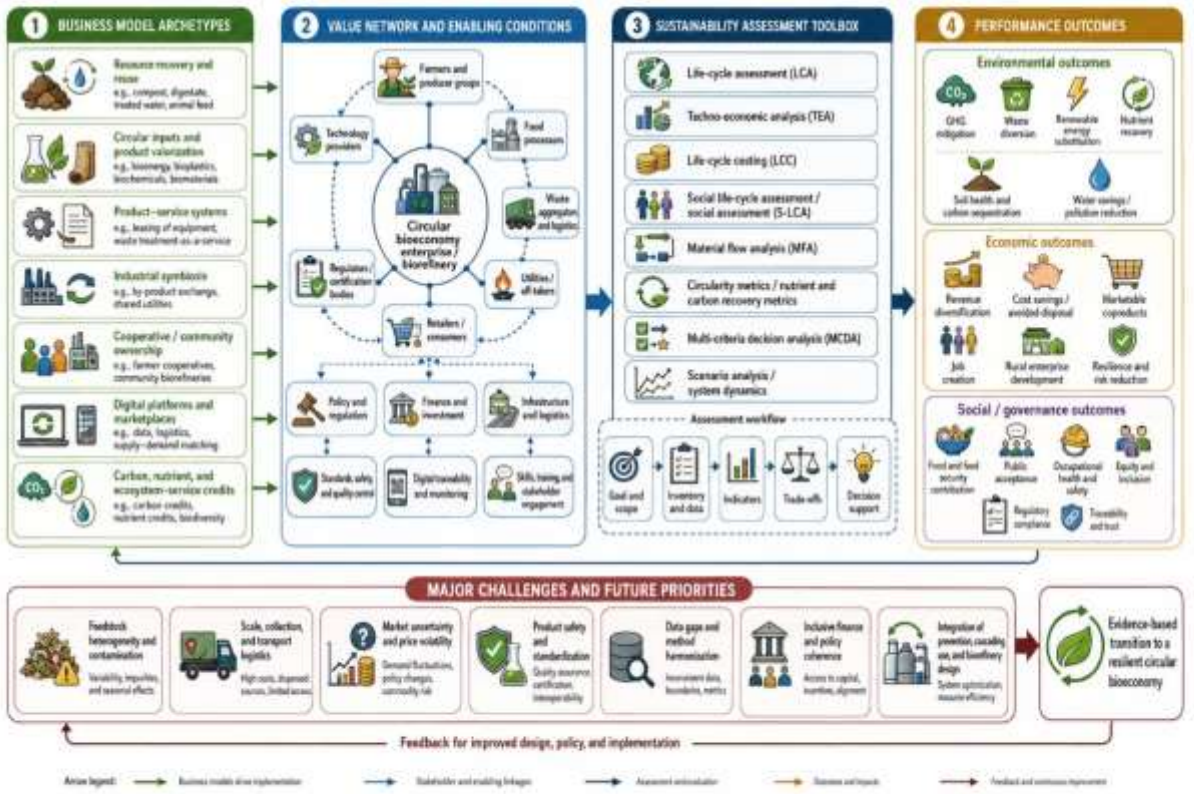

Fig.2. Implementation pathways, Business models and Sustainability assessment for bioeconomy systems

6. Challenges, Knowledge Gaps and Future Prospects

6.1 Feedstock heterogeneity and contamination

The biggest technical challenge is feedstock variability. Agricultural residues are seasonal, variety, harvesting and weather and storage dependent. The amount of food waste is dependent on the household behaviour, food menu, packaging and food collection system. The higher the moisture content the more expensive the transport and drying. Compost, digestate, biochar or insect substrates may be contaminated with plastics, glass, pesticide residues, salts and pathogens. Source separation is thus a key element. Poor upstream management is no justification for relying on technology. Quality control can be enhanced by digital monitoring, fast spectroscopy, AI sorting and standardisation of the feedstock specifications.

6.2 Logistics and scale

Biomass is bulky, seasonal and dispersed. Long-distance transport of low value wet waste can jeopardize environmental and economic benefits. Decentralized systems are less transport intensive, but may not be technically proficient or have economies of scale. Centralized systems provide better process control, but create greater logistics and social acceptance issues. Hybrid hub-and-spoke models can work – local preprocessing, densification or storage connected to regional biorefineries. Risk can be shared and infrastructure can be shared between farmer cooperatives and municipal partnerships.

6.3 Safety, regulation and market confidence

Recovered products are required to be safe and trusted. Soil amendments such as compost, digestate, frass and biochar should be pathogen-free, contain no heavy metals, plastics, organic pollutants or nutrient imbalance. The recovered compounds for use in food, feed or cosmetics must be approved and traceable. Strong safety evidence and consumer acceptance is needed for insect based feeds and single cell protein. If markets think that recovered products are not of good quality or are risky, then the circular systems can fail. It is crucial to have standards, certification, clear labelling and long-term field trials.

6.4 Research and innovation priorities

Future research should focus on whole system, context-specific conversions instead of laboratory conversions. Some potential avenues are: low-energy pre-treatment of lignocellulosic residues, robust mixed-culture fermentation, microbial and enzymatic platforms that are resistant to the use of heterogeneous feedstocks, safe digestate nutrient recovery, biochar standardization and carbon permanence verification, insect-rearing automation, and digital traceability. Integrated biorefineries should be developed in a cascading value, with high value compounds recovered first and the remaining fractions should go to energy or soil.

There is a need to further the development of assessment research. Soil carbon, biodiversity, nutrient cycling, methane leakage, microplastics and regional water impacts should be better included in LCA. Uncertainty and policy incentives and market volatility should be included in TEA. Social assessments should consider the inclusion of smallholders, gender impacts, labour conditions and community acceptance. Decision-support tools for policymakers that compare various prevention, donation, feed, composting, anaerobic digestion, biochar and biorefinery options for local conditions.

6.5 Policy prospects

The best policies will be those that will incentivize waste reduction in line with the waste hierarchy. The focus should be on prevention, which can be achieved by measurement, reporting, procurement planning, and changing consumer behaviour, as well as improving storage. Surplus food should be diverted to people, if safe. Use of feeds should be encouraged (if permitted by regulation) to ensure safety. Availability of feedstocks for recycling can be enhanced by implementing organic waste disposal bans, landfill taxes and source separation requirements. Recovery technologies can be supported by renewable energy incentives, nutrient credits, carbon markets and green procurement. But policy should not create a disincentive to prevent higher value treatment pathways (such as prevention or reuse) from becoming established.

7. CONCLUSION

Agricultural and food processing wastes are a significant opportunity for transformation in the circular bioeconomy. They are rich in carbon, nutrients, proteins, fibres, lipids and bioactive compounds which can be utilized for energy, fertilizers, soil amendments, feed, biomaterials and platform chemicals. Organic recycling and methane mitigation are proven technologies – composting and anaerobic digestion. Production of pyrolysis and biochar can provide potential carbon storage and soil improvement. Advanced processing and viable markets, in addition to consistent feedstocks, are needed for fermentation, extraction and integrated biorefineries to produce higher value products. While insect bioconversion is a viable solution between waste management and alternative protein production, safety and regulations need to be developed.

The main message is that circularity can't be judged as a slogan, it needs to be considered as a system. A technology will be sustainable if the overall life-cycle effects, costs, risks and social consequences are positive in the context. The incentive alignment of business models needs to be done between waste generators, processors, farmers, municipalities, consumers and investors. LCA, TEA, social impacts, circularity metrics and stakeholder priorities need to be incorporated into the assessment frameworks. The future circular bioeconomy will probably be pluralistic, with different sectors playing a role depending on the local feedstocks, soils, energy systems and markets: prevention, redistribution, feed use, composting, anaerobic digestion, biochar, fermentation and biorefineries. Agri-food wastes can be valuable strategic resources for climate mitigation, soil regeneration, rural development and sustainable industrial innovation with coherent policy, robust science and inclusive business models.

Declaration on generative AI and AI-assisted technologies

During manuscript revision, the authors used ChatGPT solely to assist with language editing, structural organization, image clarity enhancement and consistency checking. No experimental data were generated or analyzed by the tool. All scientific statements, interpretations, citations, and final wording were critically reviewed and verified by the authors, who take full responsibility for the content of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

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