



REVIEW ARTICLE

A systematic review of agricultural waste valorisation for circular bioeconomy: Technologies, sustainability trade-offs and resource recovery strategies

S Sheik Shalik*, M Meyyappan, D Senthilkumar, K Akshaya Dharshini, M Dhayanethi, C Raajkiran, J Sivanantha, P Raja Mohamed, C Madhan Raj & G Kayalvizhi

Department of Agronomy, Faculty of Agriculture, Annamalai University, Annamalai Nagar 608 002, Tamil Nadu, India

*Correspondence email - sheikshalikagri@gmail.com

Received: 22 April 2026; Accepted: 31 July 2026; Available online: Version 1.0: 31 August 2026

Cite this article: Sheik SS, Meyyappan M, Senthilkumar D, Akshaya DK, Dhayanethi M, Raajkiran C, Sivanantha J, Raja MP, Madhan RC, Kayalvizhi G. A systematic review of agricultural waste valorisation for circular bioeconomy: Technologies, sustainability trade-offs and resource recovery strategies. *Plant Science Today*. 2026; 13(sp5): 1-16. <https://doi.org/10.14719/pst.15158>

Abstract

Agricultural waste, traditionally regarded as a by-product of farming systems, is increasingly recognised as a valuable bioresource with significant potential to support sustainable agriculture and circular bioeconomy transitions. Globally, agricultural activities generate approximately 5–6 billion tonnes of biomass residues annually, yet a substantial proportion remains underutilised or is disposed of through environmentally harmful practices such as open-field burning, leading to nutrient losses, soil degradation and greenhouse gas emissions. This review provides a comprehensive and integrative synthesis of solid agricultural biomass valorisation pathways, focusing on the classification, physicochemical characteristics and resource potential of diverse waste streams, including crop residues, livestock wastes and agro-industrial by-products such as pressmud, bagasse and bone sludge. Major conversion technologies, including biological processes (composting and anaerobic digestion), thermochemical approaches (pyrolysis, gasification and combustion) and integrated biorefinery systems, are critically reviewed. A comparative assessment based on environmental performance, economic feasibility and operational complexity highlights key sustainability trade-offs, particularly regarding soil carbon dynamics, nutrient cycling and competing biomass uses. Biological approaches are suitable for decentralised and low-cost applications, whereas thermochemical and integrated systems offer enhanced energy recovery, scalability and carbon sequestration potential. The review integrates technological, environmental and economic perspectives within a unified analytical framework, with particular emphasis on underutilised agro-industrial residues such as bone sludge. Despite significant advancements, large-scale adoption remains constrained by techno-economic limitations, infrastructural gaps and limited long-term field validation. The study underscores the need for integrated, context-specific and policy-supported strategies to enable efficient biomass utilisation and sustainable resource recovery within circular bioeconomy systems.

Keywords: agricultural waste; anaerobic digestion; biomass valorisation; circular bioeconomy; nutrient recycling

Introduction

Agricultural waste, once regarded as an inevitable by-product of farming systems, is increasingly recognised as a strategic bioresource with significant implications for sustainable agriculture, climate resilience and circular bioeconomy development (1). Through biomass valorisation, agricultural residues contribute to climate resilience by reducing greenhouse gas emissions, enhancing soil organic carbon sequestration, improving soil moisture retention and promoting nutrient recycling, thereby strengthening the adaptive capacity of agricultural systems under changing climatic conditions. This paradigm shift reflects the growing need to transition from linear production systems toward resource-efficient and regenerative models, where agricultural residues are reintegrated into productive cycles. Biomass residues generated from crop production, livestock operations and agro-industrial processing represent substantial sources of organic carbon and essential plant nutrients, offering considerable potential for value creation and resource recovery (2).

Globally, agricultural systems generate approximately 5–6 billion tonnes of biomass residues annually, highlighting both the magnitude of the resource and the complexity of its management. In countries such as India, characterised by intensive cropping systems and expanding agro-industrial activities, agricultural waste generation exceeds several hundred million tonnes per year (3, 4). Despite this abundance, a significant proportion of residues remains underutilised or is disposed of through environmentally harmful practices such as open-field burning, leading to greenhouse gas emissions, nutrient losses and deterioration of soil health (5). These challenges are particularly evident in regions such as the Indo-Gangetic Plains, where residue mismanagement has severe environmental and public health consequences (6).

Beyond atmospheric impacts, improper handling of agricultural waste contributes to soil degradation, nutrient imbalance and water pollution through leaching and runoff, thereby adversely affecting ecosystem stability and agricultural productivity

(7, 8). At the same time, these residues represent a valuable opportunity for nutrient recycling, soil carbon sequestration and renewable energy production. The effective utilisation of agricultural waste is therefore central to achieving sustainable intensification and climate-smart agriculture (9).

Agricultural residues can be broadly categorised into crop residues, livestock wastes and agro-industrial by-products, each exhibiting distinct physicochemical characteristics and resource recovery potential (10). While crop residues constitute the largest share, agro-industrial by-products such as pressmud, bagasse and bone sludge are particularly significant due to their concentrated availability. Pressmud is rich in organic matter, phosphorus and calcium, bone sludge serves as a valuable source of phosphorus and calcium for nutrient recovery, whereas bagasse is primarily a lignocellulosic biomass suitable for bioenergy production and value-added bioproducts (11). However, the efficient utilisation of these diverse biomass streams requires appropriate technological alignment based on their composition, moisture content and functional properties. A wide range of biomass valorisation technologies has been developed, including biological processes (composting and anaerobic digestion), thermochemical conversion (pyrolysis, gasification and combustion) and integrated biorefinery approaches (12–14). These technologies enable the transformation of agricultural residues into value-added products such as organic fertilisers, bioenergy and bio-based materials, thereby supporting circular bioeconomy principles. However, their performance and suitability vary depending on feedstock characteristics, economic feasibility and local infrastructure (15). Despite the growing body of literature, existing studies remain largely fragmented, often focusing on individual technologies without integrating environmental, economic and operational perspectives within a unified analytical framework (16). Moreover, limited attention has been given to underutilised agro-industrial residues, long-term field validation under diverse agro-ecological conditions and integrated decision-

support frameworks capable of simultaneously evaluating technological, environmental and socio-economic trade-offs for practical implementation and policy-level decision-making (17). In addition, most studies are confined to laboratory-scale or short-term investigations, with insufficient long-term field validation under diverse agro-ecological conditions (18). Furthermore, existing studies also largely lack integrated decision-support frameworks that simultaneously evaluate technological, environmental and economic trade-offs under diverse agro-ecological conditions, thereby limiting their applicability for practical implementation and policy-level decision-making.

In this context, the present review aims to provide a comprehensive and integrative synthesis of agricultural waste valorisation pathways within a circular bioeconomy framework. Specifically, the objectives of this study are to: (i) examine the global status and environmental implications of agricultural waste generation; (ii) evaluate major biomass valorisation technologies and their resource recovery potential; (iii) assess sustainability trade-offs and techno-economic feasibility; and (iv) identify key research gaps, policy needs and future directions for advancing sustainable waste-to-wealth systems.

By integrating technological, environmental and economic dimensions, this review offers a systems-level perspective on agricultural waste valorisation. This review also highlights the role of underexplored agro-industrial residues and emphasises the need for context-specific and integrated strategies to enhance resource-use efficiency, support circular bioeconomy transitions and promote sustainable agricultural development. A conceptual framework illustrating agricultural waste valorisation within a circular bioeconomy system is presented in Fig. 1. Special emphasis is given to agro-industrial residues such as pressmud, bagasse and bone sludge, highlighting their potential for nutrient recovery and biochar-based applications in sustainable agricultural systems.

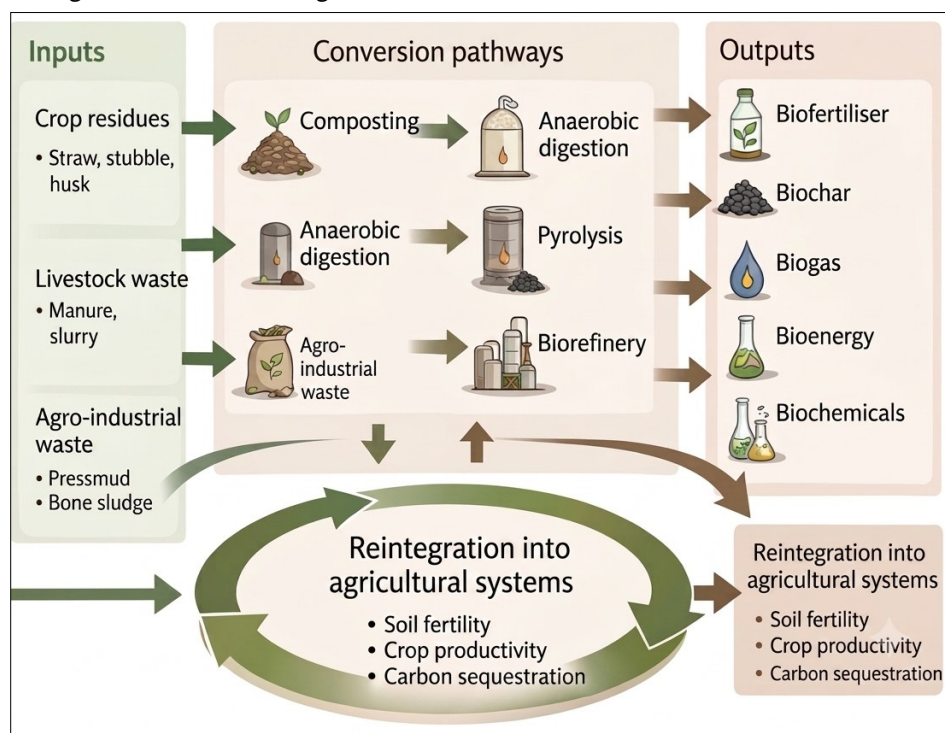


Fig. 1. Conceptual framework of agricultural waste valorisation within a circular bioeconomy system, illustrating the transformation of crop residues, livestock waste and agro-industrial by-products into value-added outputs and their reintegration into agricultural systems for enhanced sustainability.

Materials and Methods

This review was conducted using a systematic, transparent and reproducible approach to evaluate the current status, technological advancements and sustainability dimensions of agricultural waste valorisation within a circular bioeconomy framework. The methodological framework was designed to ensure comprehensive literature coverage, critical evaluation and structured synthesis of multidisciplinary research related to biomass-based waste-to-wealth systems.

Literature search strategy

A structured literature search was performed using major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, PubMed and Google Scholar. To capture emerging technologies and industrial applications, additional sources such as patent databases (Espacenet and the United States Patent and Trademark Office), government reports, policy documents and institutional publications (e.g., FAO, CPCB and Ministry of Agriculture of India) were also included. The search covered publications from 2005 to 2026 to ensure inclusion of both foundational studies and recent advancements. A combination of keywords and Boolean operators was used to refine the search, including: “agricultural waste”, “biomass valorisation”, “crop residue management”, “biochar”, “biogas”, “composting”, “circular bioeconomy”, “waste-to-wealth”, “bioenergy” and “agro-industrial waste recycling”. This

review was conducted following preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines, incorporating systematic identification, screening, eligibility assessment and inclusion stages. The detailed workflow is presented in Fig. 2. Duplicate records retrieved from multiple databases were identified through manual cross-checking of titles, authors, publication years and digital object identifiers (DOIs) and duplicate entries were removed before title and abstract screening.

Inclusion and exclusion criteria

The selection of literature followed predefined inclusion and exclusion criteria to ensure relevance and scientific rigour. Inclusion criteria comprised peer-reviewed journal articles, review papers, conference proceedings, book chapters, technical reports and patent documents focusing on agricultural waste generation, biomass valorisation technologies, sustainability assessment and circular bioeconomy frameworks. Studies were included if they provided experimental evidence, field-based validation, techno-economic analysis or practical applications relevant to agricultural waste utilisation. Exclusion criteria included non-English articles, opinion-based studies without scientific validation, duplicate records and studies not directly related to agricultural or biomass-based waste systems. Studies exclusively addressing municipal or industrial waste management without direct relevance to agricultural biomass or agro-industrial residues were excluded.

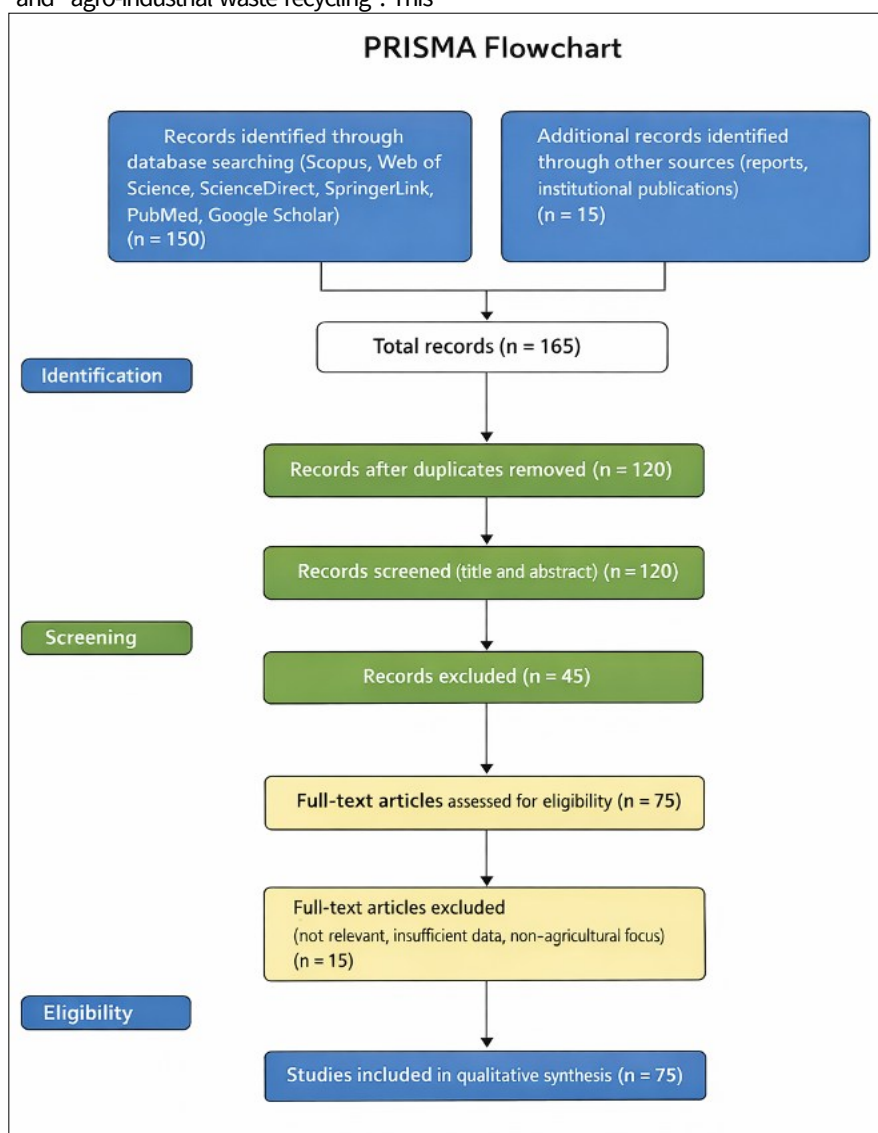


Fig. 2. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram illustrating the literature selection process.

Data extraction and synthesis

Relevant data from selected studies were systematically extracted using a structured framework capturing key parameters such as type and source of agricultural waste, conversion technologies, process efficiency, product outputs, environmental impacts, economic feasibility and scalability. Additional indicators, including nutrient recycling potential, carbon sequestration capacity and resource-use efficiency, were also recorded where available. The extracted data were synthesised to develop a comparative understanding of different biomass valorisation pathways, enabling identification of dominant trends, technological advancements and knowledge gaps across regions and production systems. A total of 165 studies were initially identified, of which 75 were selected for final synthesis based on relevance, quality and methodological rigour. A structured screening and selection approach was employed to ensure methodological consistency and transparency across all stages of the review. The complete study selection process, including records identified, screened, excluded (with reasons) and finally included, is presented in the PRISMA flow diagram (Fig. 2). Quality assessment of selected studies was performed to ensure scientific reliability and methodological rigour. Studies were evaluated according to criteria including experimental design, data completeness, relevance to agricultural waste valorisation and clarity of reported outcomes. Preference was given to peer-reviewed studies with well-defined methodologies and validated results. This step enhanced the robustness and credibility of the synthesised findings. The included studies were synthesised using a qualitative narrative synthesis approach to integrate evidence on agricultural waste classification, biomass valorisation technologies, sustainability trade-offs and resource recovery strategies across different study designs and geographical regions.

Analytical framework

A thematic and comparative analytical approach was employed to evaluate agricultural waste valorisation strategies. Technologies were categorised into three major groups-biological, thermochemical and integrated systems-based on their primary conversion mechanisms and end products. Comparative evaluation was conducted using predefined criteria, including environmental performance (greenhouse gas emissions, resource recovery potential and pollution mitigation), economic feasibility (capital and operational requirements), operational complexity (technology maturity, infrastructure needs and technical expertise) and scalability for agricultural applications. Emphasis was placed on identifying sustainability trade-offs, including impacts on soil health, nutrient cycling, greenhouse gas emissions and competing biomass uses. The analysis was further aligned with circular bioeconomy principles by assessing resource-use efficiency, waste minimisation, nutrient recycling, renewable energy recovery, carbon sequestration potential and contribution to closed-loop resource systems. These indicators were used to evaluate the extent to which each technology supports sustainable agricultural intensification and circular resource management.

Replicability statement

To ensure transparency and reproducibility, all stages of the review process, including database selection, keyword strategy and inclusion-exclusion criteria, have been explicitly defined. The study adhered to PRISMA guidelines, ensuring transparency, reproducibility and methodological rigour throughout the review process. A formal risk-of-bias assessment was not performed

because this review synthesised evidence from diverse review articles, experimental studies and technical reports rather than conducting a quantitative meta-analysis. Consequently, the emphasis was placed on comprehensive evidence synthesis rather than statistical quality scoring of individual studies.

Results and Discussion

Global status of agricultural waste generation and management

Agricultural systems worldwide generate vast quantities of biomass residues because of intensified crop production, livestock operations and agro-industrial processing. These residues, traditionally considered wastes, are increasingly recognised as valuable bioresources within the framework of circular bioeconomy and sustainable agricultural systems (19). The magnitude, composition and distribution of agricultural waste vary significantly across regions, influenced by cropping intensity, livestock density, agro-climatic conditions and technological advancement in agricultural practices.

Worldwide biomass residue generation from agriculture remains substantial, reflecting the enormous resource recovery potential of agricultural systems (20). Crop residues constitute the largest share, particularly from cereals such as rice, wheat and maize, which dominate global food systems. In addition, livestock-derived wastes contribute substantially to organic nutrient pools, especially in mixed farming systems. Agro-industrial residues, including pressmud from sugar industries, bagasse and bone sludge, are generated in concentrated forms, offering significant potential for large-scale resource recovery (21, 22).

In emerging economies such as India, China and Brazil, the scale of residue generation is particularly high due to intensive cultivation and multiple cropping systems. India alone produces more than 500 million tonnes of crop residues annually, with rice and wheat accounting for a major proportion (23). The proportional distribution of major crop residues is illustrated in Fig. 3. China also generates enormous quantities of crop residues from rice, wheat and maize production, while countries in Southeast Asia face challenges associated with rice straw management and seasonal biomass burning. In Europe, agricultural residues are increasingly utilised for bioenergy, bio-based products and nutrient recycling under circular bioeconomy policies. Likewise, North and South America have expanded the use of crop residues for renewable energy production and soil conservation, although management practices vary depending on regional agricultural systems and policy support. However, regional disparities exist in residue utilisation, with northern regions often experiencing large-scale residue burning, while southern regions exhibit relatively better recycling practices.

Despite the enormous resource potential, efficient management of agricultural residues remains a global challenge. In South Asia, particularly the Indo-Gangetic Plains, open-field burning of rice and wheat residues remains a major environmental concern. Similar challenges are reported in China due to intensive cereal production, while several countries in Southeast Asia continue to experience seasonal biomass burning associated with agricultural residue management. In contrast, many European countries have promoted residue recycling and bioenergy utilisation through supportive policies and advanced biomass processing infrastructure.

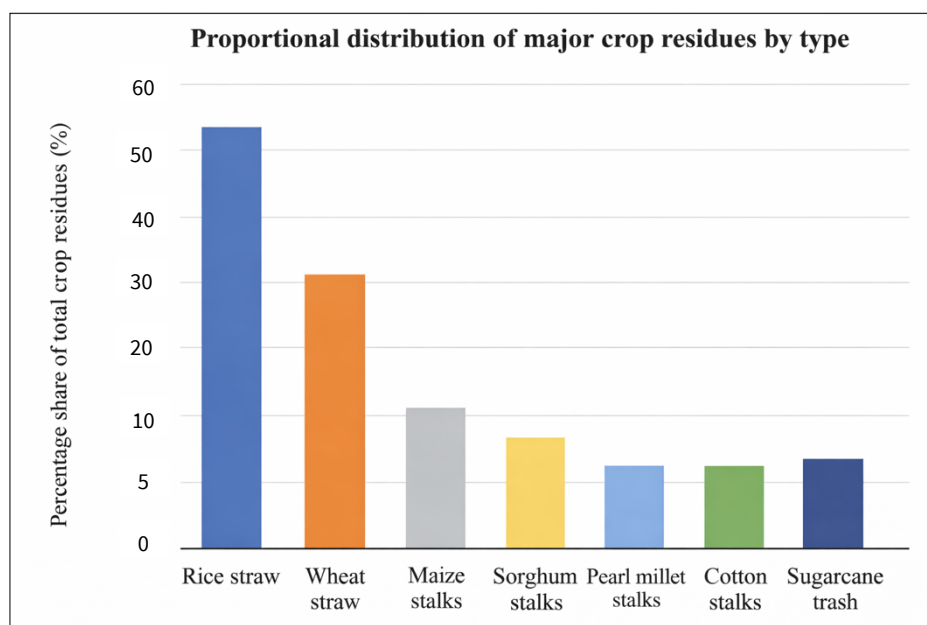


Fig. 3. Proportional distribution of major crop residues by type, highlighting the dominance of rice and wheat residues in total agricultural biomass generation (source: Central Pollution Control Board, India, 2022–23).

This practice results in significant environmental consequences, including emissions of greenhouse gases such as CO₂, CH₄ and N₂O, release of particulate matter and loss of essential plant nutrients (24, 25). These emissions contribute not only to climate change but also to severe air pollution and public health risks.

Improper handling of agricultural waste also leads to soil degradation and water contamination. Nutrient leaching, runoff and accumulation of organic pollutants in water bodies adversely affect soil fertility, groundwater quality and ecosystem stability (26). In contrast, efficient recycling and valorisation of these residues can enhance soil organic carbon, improve nutrient cycling and support renewable energy production through bio-based systems (27, 28).

Agricultural waste can be broadly classified into three categories: (i) crop residues such as straw, husk and stubble; (ii) livestock wastes including dung, slurry and urine; and (iii) agro-industrial by-products such as pressmud, bagasse and bone sludge (29). Among these, agro-industrial residues are particularly valuable due to their higher nutrient density, uniformity and ease of collection at centralised processing facilities (30). However, their utilisation remains constrained by limited technological adoption, inadequate infrastructure and lack of awareness among stakeholders.

The increasing pressure on land and water resources, coupled with climate variability and the need for sustainable

intensification, has necessitated a transition toward efficient agricultural waste management systems. Integrating these residues into productive use cycles is essential for improving resource-use efficiency, minimising environmental impacts and advancing circular bioeconomy principles (31).

Overall, the global scenario reflects a paradox of abundance and underutilisation, highlighting the urgent need for innovative, scalable and region-specific strategies to transform agricultural waste into valuable resources within sustainable farming systems.

Classification and characteristics of agricultural waste

Agricultural waste encompasses a diverse range of biomass materials generated from crop production, livestock systems and agro-industrial processing. These residues vary widely in their physicochemical composition, biodegradability, nutrient content and resource recovery potential. The systematic classification of agricultural waste is essential for selecting appropriate valorisation pathways and optimising their utilisation within circular bioeconomy frameworks (32). The classification presented in this review is based on residue origin, physicochemical composition, moisture content, biodegradability and resource recovery potential, as these characteristics largely determine the suitability of different biomass valorisation technologies. Classification, characteristics and resource potential of major agricultural waste streams are summarised in Table 1.

Table 1. Classification, characteristics and resource potential of major agricultural waste streams

Category	Sub-category	Examples	Key characteristics	Valorisation potential	Suitability for technology
Crop residues	Field residues	Rice straw, wheat straw and maize stover	High lignocellulose, high C : N ratio	Biochar, compost, mulching	Thermochemical dominant (pyrolysis, gasification)
Crop residues	Process residues	Husk, bagasse and molasses	Uniform structure, moderate nutrients	Bioenergy, industrial use	Thermochemical / integrated systems
Livestock waste	Solid	Dung and manure	Rich in NPK, organic matter	Compost, biogas	Biological dominant (composting, anaerobic digestion)
Livestock waste	Liquid	Slurry and urine	High moisture, easily degradable	Anaerobic digestion	Biological dominant
Agro-industrial waste	By-products	Pressmud, bone sludge and bagasse	Nutrient-rich, concentrated	Organic fertilisers, bio-products	Integrated / biological systems

NPK: nitrogen, phosphorus and potassium.

Classification of agricultural waste

Agricultural waste can be broadly categorised into three major groups based on origin and characteristics: (i) crop residues, (ii) livestock-derived wastes and (iii) agro-industrial by-products (33). This classification also reflects differences in availability, handling requirements and suitability for specific valorisation pathways, thereby influencing technology selection and resource recovery efficiency.

Crop residues represent the largest fraction of agricultural waste and include materials such as straw, stubble, husk, leaves and stems generated after harvest. These residues are typically lignocellulosic in nature, composed primarily of cellulose, hemicellulose and lignin, which influence their decomposition rate and suitability for biological or thermochemical conversion processes (34). While they are widely available, their low bulk density and dispersed distribution often limit efficient collection and utilisation. Representative examples of agricultural biomass residues are shown in Fig. 4.

Livestock-derived wastes include dung, slurry, urine and bedding materials generated from animal husbandry systems. These wastes are rich in organic matter and essential nutrients such as nitrogen, phosphorus and potassium, making them highly suitable for composting, anaerobic digestion and soil amendment applications (35). However, improper management can lead to methane emissions, nutrient losses and environmental pollution.

Agro-industrial by-products are generated during processing of agricultural commodities and include materials such as pressmud from sugar industries, bagasse, fruit and vegetable processing waste and bone sludge from meat and poultry processing units (36). These residues are often available in concentrated quantities and exhibit relatively higher nutrient content compared to field-based residues. For instance, bone sludge is particularly rich in phosphorus and calcium, making it a valuable resource for developing enriched composts and bio-based fertilisers (37).

Physicochemical characteristics

The physicochemical properties of agricultural waste play a crucial role in determining their suitability for different valorisation technologies. These characteristics directly influence technology selection because feedstocks with high moisture content and low carbon-to-nitrogen ratios are generally more suitable for biological processes such as composting and anaerobic digestion, whereas lignocellulosic residues with lower moisture content and higher carbon content are better suited for thermochemical processes including pyrolysis and gasification. Therefore, understanding feedstock properties is essential for optimising conversion efficiency and resource recovery.

Key parameters include moisture content, carbon-to-nitrogen (C : N) ratio, lignin content, pH, bulk density and nutrient composition (38). In addition, parameters such as biodegradability index, volatile solids content and structural composition significantly influence process efficiency, conversion pathways and selection of appropriate biomass valorisation technologies.

Crop residues generally exhibit high carbon content and wide C : N ratios, often exceeding 60 : 1, which can limit microbial decomposition unless supplemented with nitrogen-rich materials. Their high lignin content also contributes to slower degradation rates, making them more suitable for thermochemical processes such as pyrolysis and gasification (39).

In contrast, livestock wastes, including cattle manure, slurry and mixed animal wastes, typically exhibit C : N ratios ranging from 10 : 1 to 25 : 1, depending on livestock species and waste type, with generally higher moisture content, facilitating rapid microbial activity and making them ideal substrates for composting and anaerobic digestion (40). These wastes also contribute significantly to nutrient recycling when applied to agricultural soils.

Agro-industrial residues exhibit diverse characteristics depending on their source. Pressmud generally contains appreciable organic carbon together with nitrogen, phosphorus



Fig. 4. Representative examples of agricultural biomass residues, including crop residues, agro-industrial by-products, forest litter and woody biomass, illustrating the diversity of feedstocks available for waste-to-wealth valorisation pathways.

and potassium, whereas bone sludge is particularly rich in phosphorus and calcium, while bagasse is characterised by high cellulose content and relatively low nutrient concentrations (41). Bagasse, on the other hand, is rich in cellulose and is commonly used for bioenergy production. The variability in composition necessitates tailored processing approaches for efficient utilisation.

Resource recovery potential

The resource recovery potential of agricultural waste is determined by its biochemical composition and conversion efficiency. The resource recovery potential varies considerably among agricultural residues and conversion technologies. For example, anaerobic digestion of livestock manure can generate methane-rich biogas while simultaneously recovering nutrients through digestate application. Likewise, pyrolysis of lignocellulosic crop residues typically produces biochar together with bio-oil and syngas, whereas composting of nutrient-rich agro-industrial residues facilitates recovery of nitrogen, phosphorus and organic carbon for agricultural reuse (42).

Particularly, agro-industrial wastes such as bone sludge present significant opportunities for nutrient recovery and circular nutrient management. When processed through composting or enrichment techniques, these residues can improve soil fertility, enhance crop productivity and reduce dependency on synthetic fertilisers (43).

The efficiency of resource recovery is further influenced by feedstock heterogeneity, process integration and recovery efficiency of nutrients and energy, necessitating optimised and site-specific valorisation strategies. Overall, understanding the classification and characteristics of agricultural waste is fundamental for designing efficient and sustainable waste valorisation strategies. Integrating residue-specific properties with appropriate technological pathways is essential to maximise resource recovery while minimising environmental impacts within circular agricultural systems.

Biomass valorisation technologies

Agricultural waste valorisation involves the conversion of biomass residues into value-added products, including organic fertilisers, bioenergy, biochar and industrial raw materials. These technologies play a central role in transforming agricultural waste into economically viable and environmentally sustainable resources within circular bioeconomy systems (44). Based on processing pathways, biomass valorisation technologies can be broadly classified into biological, thermochemical and integrated systems, as summarised in Table 2.

Biological conversion technologies

Biological processes are widely adopted for the conversion of biodegradable agricultural residues into stabilised organic products. These processes are particularly suitable for decentralised and low-cost applications in rural and peri-urban agricultural systems. Biological processes are particularly suitable for biodegradable residues because microorganisms efficiently decompose readily degradable organic matter under controlled conditions, whereas thermochemical processes are better suited to dry, lignocellulosic biomass with high carbon content and low moisture levels. Composting is one of the most widely used biological methods, involving aerobic decomposition of organic matter by microorganisms to produce nutrient-rich organic manure (45). The stages of the composting process and associated temperature dynamics are illustrated in Fig. 5. It improves soil structure, enhances microbial activity and contributes to long-term soil fertility. Vermicomposting, an advanced form of composting, utilises earthworms to accelerate organic matter decomposition and produce high-quality vermicast with improved nutrient availability (46).

Anaerobic digestion is another important biological process that converts organic waste into biogas under oxygen-free conditions. This process generates renewable energy in the form of methane-rich gas while producing digestate, which can be used as a biofertiliser (47). Livestock wastes and agro-industrial residues are particularly suitable for anaerobic digestion due to their high moisture content and biodegradability.

Agro-industrial wastes such as bone sludge and pressmud can be effectively utilised in composting and enrichment processes to produce value-added organic fertilisers with enhanced nutrient profiles, particularly phosphorus and calcium. Bone sludge compost has also been shown to improve nutrient uptake and post-harvest soil nutrient status in rice (48). These approaches support circular nutrient management and reduce dependency on chemical fertilisers. Nutrient composition and agronomic potential of selected organic waste materials are summarised in Table 3.

Bone sludge and pressmud have gained increasing attention for their potential in producing nutrient-enriched biochar and fortified composts, contributing to improved phosphorus availability and sustainable nutrient management in cropping systems.

Thermochemical conversion technologies

Thermochemical processes involve the conversion of biomass into energy and carbon-rich materials through the application of heat

Table 2. Comparative assessment of major agricultural waste valorisation technologies

Technology	Category	Feedstock	Major outputs	Resource efficiency	Economic feasibility	Operational complexity	Environmental impact	Scalability
Composting	Biological	Crop residues and manure	Compost	High	High	Low	Low emissions, nutrient recycling	Small-scale / decentralised
Vermicomposting	Biological	Organic residues	Vermicast	High	High	Low-moderate	Environmentally safe, enhances soil biology	Small-scale
Anaerobic digestion	Biological	Slurry and wet biomass	Biogas and digestate	High	Moderate	Moderate	Reduces greenhouse gas (GHG) emissions, renewable energy	Medium-scale / rural systems
Pyrolysis	Thermochemical	Dry biomass	Biochar and bio-oil	Moderate	Moderate-high	High	High carbon sequestration potential	Medium to large-scale
Gasification	Thermochemical	Lignocellulosic biomass	Syngas	Moderate	Moderate-high	High	Moderate emissions, high energy efficiency	Large-scale / industrial
Biorefinery	Integrated	Mixed biomass	Biofuels, chemicals	Very high	Low-moderate	Very high	Optimised resource use, minimal waste	Large-scale / industrial

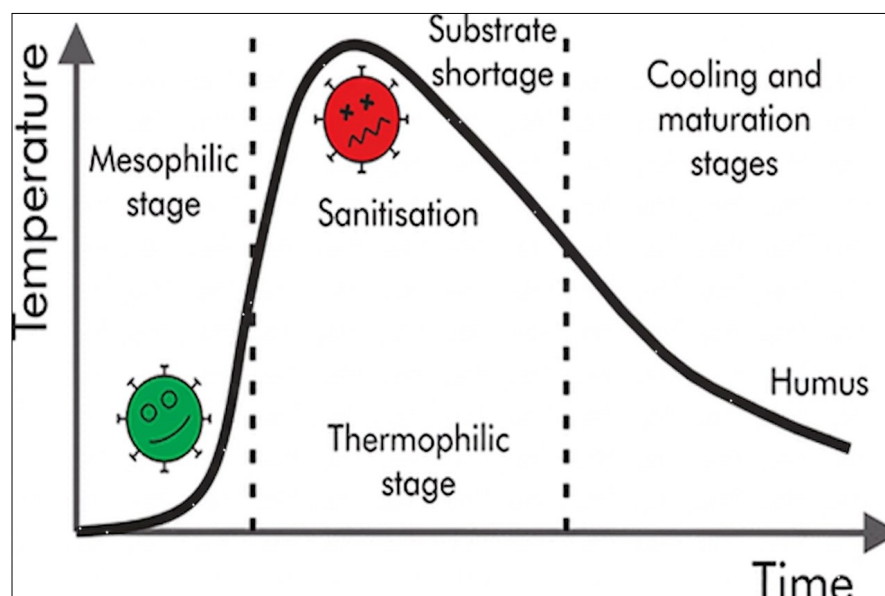


Fig. 5. Stages of the composting process showing temperature dynamics and microbial activity phases (mesophilic, thermophilic, cooling and maturation).

Table 3. Nutrient composition and agronomic potential of selected organic waste materials

Material	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Release pattern / availability	Agronomic significance
Cattle dung	0.35	0.12	0.17	Slow release	Improves soil organic matter and microbial activity
Sheep and goat manure	0.65	0.5	0.65	Moderate release	High nutrient density and suitable for enrichment
Blood meal	11	1.2	1	Rapid release (N)	Quick nitrogen supply for crop growth
Fish meal	7	6	2	Moderate release	Balanced nutrient source
Bone sludge / bone meal	1.5–3.5	9–11	1.1	Slow-release phosphorus	Long-term P source for soil fertility

under controlled conditions. These technologies are particularly suitable for lignocellulosic residues with low moisture content. Recent advancements in process optimisation, including reactor design improvements, temperature control strategies and catalyst-assisted conversion, have significantly enhanced the efficiency and product yield of thermochemical technologies. Optimisation of parameters such as heating rate, residence time and feedstock particle size plays a critical role in determining the quality of biochar, bio-oil and syngas. Furthermore, the use of catalytic pyrolysis and advanced gasification systems has improved energy conversion efficiency and reduced emission intensity, thereby strengthening the sustainability profile of these technologies.

Pyrolysis is a widely used thermochemical process in which biomass is heated in the absence of oxygen to produce biochar, bio-oil and syngas (49). Biochar has gained significant attention due to its potential for carbon sequestration, soil amendment and improvement of soil physicochemical properties. Recent meta-analyses have demonstrated that biochar application can improve soil organic carbon, water-holding capacity and nutrient retention, although the magnitude of these benefits depends on feedstock type, pyrolysis conditions and soil characteristics.

Despite the well-documented benefits of biochar, considerable scientific debate remains regarding its long-term carbon sequestration potential. Several studies report that biochar stability varies substantially depending on feedstock type, pyrolysis temperature, soil properties and climatic conditions. In some cases, biochar application may induce positive or negative priming effects, altering the decomposition of native soil organic carbon and influencing the overall carbon balance. Consequently, the environmental benefits of biochar cannot be generalised across all production systems and long-term field experiments under diverse

agro-ecological conditions are required to validate its net carbon sequestration potential.

Gasification involves partial oxidation of biomass at high temperatures to produce syngas, which can be used for electricity generation or as a feedstock for chemical synthesis (50). Although combustion is a conventional method, is used for direct energy generation but is often associated with lower efficiency and higher emissions compared with advanced thermochemical processes.

These technologies offer advantages in terms of energy recovery and waste volume reduction; however, their adoption is often limited by high capital costs, technical complexity and the need for centralised infrastructure (51). Comparatively, biological processes such as composting and anaerobic digestion are more suitable for decentralised and low-cost applications, whereas thermochemical technologies such as pyrolysis and gasification offer higher energy recovery efficiency and carbon sequestration potential but require higher capital investment and technical expertise. Biological and thermochemical technologies differ considerably in their operational characteristics and application potential. Biological processes such as composting and anaerobic digestion are generally more suitable for decentralised applications because of their lower capital requirements and efficient nutrient recycling. Digestate generated during anaerobic digestion can be further utilised as a biofertiliser following appropriate stabilisation. In contrast, thermochemical technologies are more suitable for dry lignocellulosic biomass and provide higher energy recovery. Slow pyrolysis primarily maximises biochar production, whereas fast pyrolysis favours bio-oil production because of rapid heating rates and shorter vapour residence times. Their comparative technical, environmental and economic characteristics are summarised in Table 2.

Evidence supporting different biomass valorisation technologies vary considerably in methodological quality. Composting and anaerobic digestion are supported by numerous field-scale investigations demonstrating consistent improvements in nutrient recycling and waste stabilisation. In contrast, many studies evaluating advanced thermochemical technologies remain confined to laboratory or pilot-scale conditions, limiting the generalisability of their findings. Therefore, technology selection should be guided not only by reported conversion efficiency but also by the strength of available evidence and site-specific implementation requirements.

Integrated and emerging systems

Integrated biomass valorisation systems combine multiple technologies to maximise resource recovery and improve overall system efficiency. These systems are designed to utilise agricultural waste streams in a cascading manner, ensuring minimal waste generation and optimal utilisation of resources (52).

Biorefinery approaches represent advanced integrated systems where biomass is processed into multiple products, including biofuels, bio-based chemicals and organic fertilisers. Practical examples of integrated biorefinery systems include sugarcane biorefineries, where bagasse is utilised for bioethanol and electricity generation, while pressmud is converted into organic fertilisers or compost, thereby maximising resource recovery. Similarly, rice biomass-based biorefineries have demonstrated cascade utilisation by converting rice straw into biochar, bioenergy and value-added biochemicals, with the residual materials subsequently applied as soil amendments. These integrated approaches improve resource-use efficiency, reduce waste generation and enhance the economic viability of agricultural biomass valorisation systems. These systems align closely with circular bioeconomy principles by promoting zero-waste strategies and value chain optimisation (53). The concept of cascade utilisation further enhances the efficiency of integrated systems by enabling sequential extraction of multiple value-added products from a single biomass stream. In such systems, primary processing generates high-value compounds, while residual biomass is subsequently utilised for energy recovery or soil amendment, thereby minimising waste and maximising resource efficiency. This cascading approach aligns with circular bioeconomy principles and contributes to improved economic viability and sustainability of biomass valorisation pathways.

In addition, emerging technologies incorporating digital tools such as artificial intelligence, remote sensing and precision agriculture are increasingly being integrated into biomass management systems to improve efficiency, monitoring and scalability (54).

Overall, biomass valorisation technologies provide multiple pathways for converting agricultural residues into valuable resources. The selection of appropriate technology depends on feedstock characteristics, economic feasibility, infrastructure availability and environmental considerations. Integrating biological, thermochemical and advanced systems offers a promising approach for achieving sustainable and circular agricultural waste management.

Future advancements in biomass valorisation are expected to focus on hybrid systems integrating biological and thermochemical processes, supported by artificial intelligence,

digital twins, internet of things (IoT)-based monitoring and real-time process optimisation to enhance efficiency, resource recovery and scalability.

Sustainability trade-offs and environmental impacts

Agricultural waste valorisation offers substantial opportunities for resource recovery, environmental protection and sustainable agricultural development. However, the adoption of these technologies is often associated with complex sustainability trade-offs involving environmental, economic and operational dimensions. A critical evaluation of these trade-offs is essential to ensure that waste-to-wealth strategies do not inadvertently create new environmental or resource-related challenges (55). Life cycle assessment (LCA) studies are commonly conducted in accordance with ISO 14040 and ISO 14044 standards, considering system boundaries from feedstock collection to end-product utilisation and evaluating impact categories such as global warming potential, energy demand, eutrophication, acidification and resource depletion.

The LCA-based studies enable comparison of different technologies in terms of greenhouse gas emissions, energy efficiency and resource-use intensity, thereby supporting evidence-based decision-making. For instance, biological processes generally exhibit lower energy inputs but may have higher emissions under inefficient management, whereas thermochemical systems offer improved carbon sequestration potential through biochar production. Integrating LCA approaches is therefore essential for optimising technology selection and ensuring environmentally sustainable waste management strategies (56). A critical dimension of sustainability trade-offs in agricultural waste valorisation lies in the competition among alternative biomass utilisation pathways, particularly between soil amendment, bioenergy production and industrial applications. The diversion of crop residues for bioenergy or industrial uses may reduce their availability for soil incorporation, thereby affecting soil organic carbon dynamics, nutrient cycling and long-term soil fertility. Conversely, exclusive retention of residues in the field may limit opportunities for renewable energy generation and economic value addition. Therefore, balancing these competing demands requires context-specific allocation strategies based on agro-ecological conditions, resource availability and sustainability priorities. Sustainability trade-offs in agricultural waste valorisation are highly context-dependent and vary across spatial scales, ranging from farm-level to regional and national systems. Technologies that are environmentally beneficial at the local scale may exhibit different impacts when assessed across broader supply chains, particularly in terms of transportation emissions, energy inputs and resource distribution. A systems-level approach is therefore essential to evaluate cumulative environmental impacts, optimise resource allocation and avoid burden shifting between different stages of the value chain.

The sustainability performance of agricultural waste valorisation technologies is highly context-dependent. While numerous studies report positive environmental outcomes, differences in feedstock characteristics, climatic conditions, management practices and assessment methodologies often lead to contrasting conclusions. For example, technologies that demonstrate high environmental performance under controlled experimental conditions may not achieve comparable outcomes under commercial farming systems. These methodological differences should be considered when interpreting reported environmental benefits and comparing alternative valorisation pathways.

In addition, uncertainty and variability in feedstock quality, climatic conditions and management practices necessitate adaptive and flexible strategies for sustainable agricultural waste valorisation.

A comprehensive evaluation of sustainability trade-offs requires integration of multiple analytical frameworks that capture environmental, economic and operational dimensions of biomass utilisation systems. From a systems-level perspective, the sustainability of agricultural waste valorisation pathways should be evaluated using integrated LCA and multi-criteria decision analysis (MCDA) frameworks. These approaches enable simultaneous assessment of environmental impacts, economic feasibility and operational performance, facilitating identification of optimal trade-offs among resource efficiency, energy use and long-term soil health. Such integrated decision-support tools are essential for developing context-specific and policy-relevant strategies for sustainable biomass utilisation.

Environmental benefits

Efficient utilisation of agricultural waste contributes to multiple environmental benefits, including reduction in greenhouse gas emissions, improvement in soil health and conservation of natural resources. Biological processes such as composting and anaerobic digestion facilitate nutrient recycling, enhance soil organic carbon and reduce reliance on synthetic fertilisers (57). Recent studies have reported that composting and anaerobic digestion can substantially reduce greenhouse gas emissions, improve soil organic carbon content, enhance nutrient-use efficiency and increase nutrient recovery compared with conventional waste disposal practices, although the magnitude of these benefits varies with feedstock characteristics and management conditions.

Thermochemical technologies, particularly pyrolysis, play a key role in carbon sequestration through biochar production. Biochar application has been shown to improve soil structure, water retention and microbial activity, while also contributing to long-term carbon storage (58).

Additionally, diversion of crop residues from open-field burning significantly reduces emissions of particulate matter, carbon monoxide and greenhouse gases, thereby improving air quality and reducing associated public health risks.

Environmental risks and limitations

Despite their benefits, agricultural waste valorisation systems can also pose environmental risks if not properly managed. For instance, excessive or unregulated application of compost and organic amendments may lead to nutrient imbalances, particularly nitrogen and phosphorus accumulation, resulting in soil degradation and water eutrophication (59). These risks are particularly evident under repeated or excessive compost application without nutrient-based management, where phosphorus accumulation and nitrate leaching may increase the potential for eutrophication of adjacent water bodies.

Similarly, the use of untreated or inadequately treated agro-industrial residues and wastewater can introduce heavy metals, pathogens and organic contaminants into the soil-plant system, affecting crop quality and environmental safety (60). In thermochemical processes, improper operational conditions may lead to emissions of toxic gases and particulate matter, thereby offsetting environmental gains (61).

Another critical concern is salinity build-up and alteration of soil physicochemical properties, particularly in systems involving

wastewater reuse and repeated application of organic residues. These changes can negatively affect crop productivity and long-term soil sustainability if not monitored and managed effectively (62). For example, long-term application of saline wastewater or excessive organic residues may increase soil electrical conductivity (EC) and sodium adsorption ratio (SAR), adversely affecting soil structure, water infiltration and crop productivity under poorly managed conditions.

Economic and operational trade-offs

The economic feasibility of agricultural waste valorisation technologies varies significantly across scales and regions. Biological processes are generally cost-effective and suitable for small-scale, decentralised applications; however, they may have limitations in terms of processing time and consistency of output quality (63). Recent techno-economic assessments indicate that composting and anaerobic digestion generally require lower capital investment but provide comparatively lower revenue generation than thermochemical technologies such as pyrolysis and gasification, which involve higher initial costs but produce higher-value energy and carbon products.

In contrast, thermochemical and integrated systems offer higher efficiency and scalability but require substantial capital investment, technical expertise and infrastructure. These factors often limit their adoption in developing regions and among smallholder farmers (64).

Logistical challenges, including collection, transportation and storage of biomass residues, further influence the economic viability of these systems. The dispersed nature and seasonal availability of crop residues increase operational complexity and cost (65). Emerging economic instruments such as carbon credit mechanisms and circular bioeconomy-based market incentives further influence the financial viability of agricultural waste valorisation systems. Technologies such as biochar production and anaerobic digestion can generate additional revenue streams through carbon sequestration and renewable energy credits, thereby improving overall cost-effectiveness and investment attractiveness. However, the realisation of these benefits depends on robust policy frameworks, market accessibility and standardised carbon accounting methodologies. In this context, the application of techno-economic feasibility models and cost-benefit analyses is crucial for assessing the long-term viability and scalability of agricultural waste valorisation systems under diverse agro-economic conditions.

In addition, the integration of MCDA frameworks can significantly enhance the evaluation and selection of appropriate biomass valorisation pathways. The MCDA enables simultaneous consideration of multiple indicators, including economic cost, environmental impact, energy efficiency and social acceptability, thereby supporting context-specific and stakeholder-driven decision-making. For example, MCDA has been successfully applied to compare composting, anaerobic digestion, pyrolysis and gasification by integrating environmental, economic and technical criteria, thereby supporting the selection of the most appropriate biomass valorisation pathway for specific regional conditions. The combined application of MCDA with techno-economic and environmental assessment tools facilitates identification of optimal waste management strategies under varying agro-ecological and socio-economic conditions.

Balancing trade-offs for sustainable systems

Achieving sustainable agricultural waste management requires a balanced approach that integrates environmental benefits with economic feasibility and operational practicality. Site-specific strategies, supported by policy interventions and technological innovation, are essential for optimising resource recovery while minimising adverse impacts (66). Examples include government-supported crop residue management programmes, carbon credit incentives, precision biomass collection systems, sensor-based monitoring and integrated biorefinery technologies, which have improved agricultural waste utilisation and resource recovery in several regions.

Furthermore, uncertainty analysis and sensitivity assessment are essential to evaluate the robustness of different valorisation pathways under fluctuating economic and environmental conditions. Overall, while agricultural waste valorisation presents a promising pathway toward circular bioeconomy, its long-term sustainability depends on careful assessment and management of associated trade-offs. Integrating scientific, technological and policy-driven approaches is critical to ensure environmentally sound and economically viable implementation.

A decision-support framework for selecting appropriate agricultural waste valorisation technologies under varying agro-ecological and resource conditions is presented in Table 4.

Challenges, policy gaps and future perspectives

Despite significant advancements in agricultural waste valorisation technologies, large-scale adoption remains constrained by several interconnected barriers. Technical barriers include feedstock heterogeneity and limited processing technologies; economic barriers include high capital investment and uncertain market returns; institutional barriers involve inadequate infrastructure and limited technical capacity; and policy-related barriers include insufficient regulatory support, weak incentive mechanisms and inconsistent waste management policies. Addressing these barriers is essential for achieving sustainable circular bioeconomy systems in agriculture (67).

Although substantial progress has been achieved in agricultural waste valorisation research, much of the current evidence is derived from laboratory-scale experiments, short-term trials and region-specific case studies. Relatively few investigations have evaluated long-term field performance, economic viability and large-scale operational feasibility under diverse agro-ecological conditions. Future research should therefore emphasise multi-location validation, standardised assessment methodologies and interdisciplinary approaches to strengthen the evidence base for commercial implementation.

Technological and operational challenges

One of the major limitations in agricultural waste management is the lack of appropriate and scalable technologies tailored to diverse agro-ecological conditions. Many existing technologies are either too resource-intensive or not adaptable to smallholder farming systems, particularly in developing countries (68). Examples include decentralised anaerobic digesters, modular pyrolysis units, mobile biomass briquetting systems and small-scale composting facilities. Their adoption in smallholder farming is often constrained by high initial investment, limited technical expertise, inadequate maintenance services and irregular biomass supply.

Biological processes such as composting and anaerobic digestion, although widely applicable, often face challenges related to process optimisation, inconsistent output quality and longer processing durations. Thermochemical technologies, on the other hand, require high capital investment, technical expertise and reliable feedstock supply chains, which restrict their widespread adoption (69). Feedstock variability can be minimised through preprocessing methods such as drying, size reduction, pelletisation, blending of complementary biomass feedstocks and standardised storage practices, thereby improving conversion efficiency and process stability.

In addition, the heterogeneous nature of agricultural waste, variations in moisture content and seasonal availability of residues further complicate efficient processing and utilisation (70).

Scalability should be distinguished from adoption potential when evaluating agricultural waste valorisation technologies. Scalability refers to the technical and operational capacity of a technology to maintain its performance when expanded from laboratory or pilot scale to commercial or regional implementation, whereas adoption potential reflects the willingness and ability of end users to implement the technology under prevailing socio-economic and institutional conditions. Pilot studies and demonstration projects play a crucial role in bridging the gap between laboratory-scale research and field-scale implementation by validating technical performance, economic feasibility and operational reliability under real farming conditions. However, many promising technologies have been evaluated only under controlled experimental conditions, limiting confidence in their long-term field performance across diverse agro-ecological environments. Therefore, greater emphasis should be placed on large-scale demonstration projects, multi-location field validation and stakeholder participation to facilitate successful technology scaling and wider adoption. In addition, standardised performance indicators, including resource recovery efficiency, economic viability, environmental impact and operational reliability, should be used to evaluate scalability across different agro-ecological conditions.

Table 4. Decision-support framework for selection of agricultural waste valorisation technologies under different agro-ecological conditions

Agro-ecological condition	Biomass type	Recommended technology	Key rationale	Sustainability outcome
Dry regions with low moisture	Crop residues (straw and stubble)	Pyrolysis / gasification	Low moisture suitability, high lignin content	Carbon sequestration, energy recovery
Irrigated regions with mixed farming	Crop + livestock waste	Composting / anaerobic digestion	Availability of moisture and nutrients	Nutrient recycling, soil fertility improvement
Livestock-dominated systems	Dung and slurry	Anaerobic digestion	High biodegradability, methane potential	Renewable energy + biofertiliser
Agro-industrial clusters	Pressmud, bagasse and bone sludge	Composting / biorefinery	High nutrient density, centralised availability	Value-added products, nutrient recovery
Resource-constrained small farms	Mixed residues	Composting / vermicomposting	Low-cost, easy implementation	Improved soil health and sustainability
Industrial-scale biomass utilisation	Lignocellulosic biomass	Gasification / biorefinery	High volume processing, energy demand	Large-scale energy production

Infrastructure and logistical constraints

Efficient collection, transportation and storage of agricultural residues remain significant challenges due to their dispersed and bulky nature. In many regions, the absence of organised biomass supply chains and decentralised processing units limits effective waste utilisation (71). Potential solutions include decentralised biomass processing centres, farmer cooperatives, biomass aggregation hubs, improved rural transportation networks and digital supply-chain platforms for biomass collection and distribution.

Storage of biomass residues also poses risks of degradation, nutrient loss and fire hazards, particularly under improper handling conditions. These logistical constraints increase operational costs and reduce the overall efficiency of valorisation systems.

Policy and institutional gaps

Policy support plays a pivotal role in promoting sustainable agricultural waste management; however, existing policies are often fragmented and lack effective implementation mechanisms. In many countries, there is limited coordination between agricultural, environmental and energy sectors, leading to inefficiencies in policy design and execution (72). Cross-sectoral coordination can be strengthened through integrated policy frameworks involving agriculture, environment, energy and rural development agencies, supported by interdepartmental committees, digital information-sharing platforms and coordinated biomass management strategies.

Financial incentives, subsidies and regulatory frameworks supporting biomass utilisation are either inadequate or inconsistently applied. Moreover, lack of awareness among farmers and stakeholders regarding the benefits of waste valorisation further hinders adoption (73). Key challenges and corresponding strategic interventions are summarised in Table 5. Financial incentives such as capital subsidies, carbon credit schemes, feed-in tariffs for bioenergy and farmer awareness programmes have significantly improved the adoption of biomass valorisation technologies in several countries by reducing investment risks and enhancing stakeholder participation.

Future perspectives and research directions

Future research should focus on developing cost-effective, scalable and region-specific technologies for agricultural waste valorisation. Emphasis should be placed on integrated and hybrid systems that combine biological and thermochemical processes to maximise resource recovery and minimise waste (74). Priority research areas include hybrid composting-anaerobic digestion systems, pyrolysis-biochar integrated nutrient management, AI-assisted process optimisation, digital twins for biomass conversion systems and integrated biorefineries capable of producing multiple bio-based products.

The integration of digital technologies such as artificial intelligence (AI), machine learning (ML), the IoT, remote sensing and data analytics offers significant potential to improve process monitoring, efficiency and decision-making in biomass

management systems (75). The AI- and ML-based models are increasingly being used to optimise composting conditions, predict biogas yield from anaerobic digestion, classify biomass feedstocks and optimise process parameters in thermochemical conversion systems. The IoT-enabled sensors facilitate real-time monitoring of critical variables such as temperature, moisture content and gas composition, enabling improved process control and operational efficiency. Remote sensing and geospatial technologies support biomass resource mapping, feedstock availability assessment and supply chain planning for large-scale biomass utilisation. Emerging pilot studies have demonstrated the application of AI-assisted compost process optimisation, IoT-enabled smart biogas plants and remote sensing-based biomass inventory systems, indicating promising opportunities for improving the efficiency and scalability of agricultural waste valorisation. Despite these advances, most digital technologies remain at pilot or demonstration stages in many agricultural regions and their widespread adoption is constrained by limited digital infrastructure, high initial investment costs, inadequate technical expertise, data interoperability challenges and concerns regarding data security. Strengthening technology readiness through interdisciplinary research, capacity building and supportive policy frameworks will be essential for facilitating the large-scale adoption of Industry 4.0 technologies in agricultural waste valorisation systems. Recent applications include AI-based feedstock characterisation, IoT-enabled biogas monitoring, drone-assisted biomass estimation and machine-learning models for optimising composting and anaerobic digestion performance.

Furthermore, long-term field studies are required to evaluate the impacts of waste-derived products on soil health, crop productivity and environmental sustainability under diverse agro-ecological conditions. These evaluations should include soil organic carbon, nutrient availability, crop productivity, greenhouse gas emissions, microbial activity, heavy metal accumulation, economic returns and overall environmental sustainability indicators. Strengthening policy frameworks, promoting public-private partnerships and enhancing stakeholder awareness are also critical for scaling up adoption (76).

Overall, overcoming existing challenges and bridging policy gaps requires a holistic and interdisciplinary approach that integrates technological innovation, institutional support and stakeholder participation. Advancing these strategies will be crucial for realising the full potential of agricultural waste within circular bioeconomy systems. This review has certain limitations that should be acknowledged.

Limitations of the study

Although a systematic approach based on PRISMA guidelines was followed, the study was limited to English-language publications and selected databases, which may have excluded some relevant regional or non-indexed studies. In addition, variability in experimental conditions, feedstock characteristics and methodological approaches across studies may affect the comparability of results. Despite these limitations, this review

Table 5. Key challenges, implications and strategic interventions for agricultural waste valorisation systems

Challenge	Implication	Strategic intervention	Stakeholder level
High capital cost	Low adoption	Subsidies and financial support	Government / industry
Poor infrastructure	Inefficient biomass utilisation	Decentralised processing systems	Government
Limited awareness	Low adoption	Training and extension programs	Farmers / institutions
Policy gaps	Weak implementation	Integrated policy frameworks	Government
Market limitations	Low profitability	Market development and incentives	Industry / policymakers

provides a structured synthesis of agricultural waste classification, biomass valorisation technologies, sustainability trade-offs and circular bioeconomy strategies. It also identifies important knowledge gaps related to long-term field validation, techno-economic assessment, integrated biomass utilisation and policy support, thereby providing priorities for future research and sustainable agricultural waste management.

Conclusion

This review systematically synthesised the global status, classification, technological advancements and sustainability dimensions of agricultural waste management, highlighting its potential to transform biomass residues into valuable resources. The analysis indicates that agricultural waste, including crop residues, livestock wastes and agro-industrial by-products, constitutes a substantial yet underutilised resource base. Valorisation technologies, particularly biological and thermochemical processes, offer diverse opportunities for converting these residues into organic fertilisers, bioenergy and bio-based materials. Among these, agro-industrial residues such as pressmud, bagasse and bone sludge exhibit considerable potential for nutrient recovery, biochar production and soil fertility enhancement, emphasising their role in circular nutrient management strategies.

This review also highlights that the successful implementation of agricultural waste valorisation depends on balancing technological efficiency with environmental sustainability, economic feasibility and practical field applicability. Although these technologies provide significant opportunities for resource recovery, renewable energy production and waste minimisation, challenges related to technological limitations, feedstock variability, logistical constraints, high investment costs, policy gaps and limited long-term field validation continue to restrict their widespread adoption. Furthermore, sustainability trade-offs, including nutrient imbalances, contaminant accumulation in specific waste streams and operational constraints, require careful management to ensure environmentally sound and economically viable implementation. An important contribution of this review is the integration of technological, environmental, economic and policy perspectives within a single analytical framework. By comparatively evaluating biological, thermochemical and integrated biomass valorisation technologies, the review identifies important knowledge gaps, including the need for standardised sustainability assessment methods, region-specific technology optimisation, long-term agronomic validation, comprehensive life cycle assessment (LCA), techno-economic evaluation and improved decision-support frameworks for technology selection.

Future research should prioritise integrated biomass utilisation systems that combine biological and thermochemical conversion pathways, supported by digital technologies such as artificial intelligence, internet of things (IoT), remote sensing and precision agriculture for improving process efficiency and resource-use optimisation. Greater emphasis should also be placed on strengthening policy support, developing decentralised biomass supply chains, improving stakeholder awareness and promoting interdisciplinary collaboration to facilitate large-scale adoption of agricultural waste valorisation technologies.

Overall, the findings of this review emphasise that agricultural waste should be regarded as a valuable bioresource

rather than a disposal challenge. Sustainable biomass valorisation requires alignment between appropriate technologies, agro-ecological conditions, resource availability, environmental safeguards and socio-economic considerations. Strengthening policy support, infrastructure development, scientific validation and stakeholder engagement will be essential for realising the full potential benefits of agricultural waste valorisation within circular bioeconomy systems while ensuring long-term agricultural sustainability.

Acknowledgements

The authors sincerely acknowledge the Department of Agronomy, Faculty of Agriculture, Annamalai University, Chidambaram, for providing the necessary facilities and support to carry out this study. The authors also express their gratitude to faculty members and colleagues for their valuable guidance and support.

Authors' contributions

SSS conceptualised the study, designed the methodological framework, conducted the literature review and prepared the original manuscript draft. MM provided academic supervision, refined the conceptual structure and critically reviewed the manuscript. DS, KAD, MD and CR contributed to literature collection, data extraction, organisation, comparative analysis and preparation of tables and figures. JS, PRM, CMR and GK contributed to validation of literature sources, data cross-checking, technical revision, language refinement and final quality improvement of the manuscript. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: All authors do not have any conflicts of interest to declare.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this article, the authors used Grammarly to improve language readability. After using this tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References

1. Lackner M, Besharati M. Agricultural waste: challenges and solutions, a review. *Waste*. 2025;3(2):18. <https://doi.org/10.3390/waste3020018>
2. Shu H, Zhang P, Chang C, Wang R, Zhang S. Agricultural waste. *Water Environ Res*. 2015;87(10):1256–85. <https://doi.org/10.2175/106143015X14338845155660>
3. Damian CS, Devarajan Y, Jayabal R. A comprehensive review of resource efficiency and sustainability in biofuel production from industrial and agricultural waste. *J Mater Cycles Waste Manag*. 2024;26(3):1264–76. <https://doi.org/10.1007/s10163-024-01918-6>
4. Ufitikirezi JDDM, Filip M, Ghorbani M, Zoubek T, Olšan P, Bumbálek R. Agricultural waste valorization: exploring environmentally friendly approaches to bioenergy conversion. *Sustainability*. 2024;16(9):3617. <https://doi.org/10.3390/su16093617>

5. Manna MC, Rahman M, Naidu R, Sahu A, Bhattacharjya S, Wanjar RH, et al. Bio-waste management in subtropical soils of India: future challenges and opportunities in agriculture. *Adv Agron.* 2018. <https://doi.org/10.1016/bs.agron.2018.07.002>
6. Elbasiouny H, Elbanna BA, Al-Najoli E, Alsherief A, Negm S, Abou El-Nour E. Agricultural waste management for climate change mitigation: some implications to Egypt. In: Negm AM, Shareef N, editors. *Waste management in MENA regions.* Cham: Springer; 2020. p. 149–69. https://doi.org/10.1007/978-3-030-18350-9_8
7. Sheik Shalik S, Sivakumar G. Investigating the impact of bone sludge compost on nutrient uptake and post-harvest soil nutrient levels. *Crop Res.* 2024;59(3–4). <https://doi.org/10.31830/2454-1761.2024.CR-974>
8. Noor RS, Shah AN, Tahir MB, Umair M, Nawaz M, Ali A. Recent trends and advances in additive-mediated composting technology for agricultural waste resources: A comprehensive review. *ACS Omega.* 2024;9(8):8632–53. <https://doi.org/10.1021/acsomega.3c06516>
9. Shahzad HMA, Asim Z, Khan SJ, Almomani F, Mahmoud KA, Mustafa MRU. Thermochemical and biochemical conversion of agricultural waste for bioenergy production: An updated review. *Discov Environ.* 2024;2(1):134. <https://doi.org/10.1007/s44274-024-00171-w>
10. Mujtaba M, Fernandes Fraceto L, Fazeli M, Mukherjee S, Savassa SM, Araujo De Medeiros G. Lignocellulosic biomass from agricultural waste to the circular economy: A review with focus on biofuels, biocomposites and bioplastics. *J Clean Prod.* 2023;402:136815. <https://doi.org/10.1016/j.jclepro.2023.136815>
11. Rao P, Rathod V. Valorization of food and agricultural waste: A step towards greener future. *Chem Rec.* 2019;19(9):1858–71. <https://doi.org/10.1002/tcr.201800094>
12. Trninić M, Jovović A, Stojiljković D. A steady state model of agricultural waste pyrolysis: A mini review. *Waste Manag Res.* 2016;34(9):851–65. <https://doi.org/10.1177/0734242X16649685>
13. Sivakumar G, Sheik Shalik S. Effect of enriched bio-digested bone sludge compost on the yield and economics of rice cultivation var. ADT 43. *Int J Res Agron.* 2024;7(3):227–30. <https://doi.org/10.33545/2618060X.2024.v7.i3d.424>
14. Riseh RS, Vazvani MG, Hassanisaadi M, Thakur VK. Agricultural wastes: A practical and potential source for the isolation and preparation of cellulose and application in agriculture and different industries. *Ind Crops Prod.* 2024;208:117904. <https://doi.org/10.1016/j.indcrop.2023.117904>
15. Yu B, Liu X, Ji C, Sun H. Greenhouse gas mitigation strategies and decision support for the utilization of agricultural waste systems: A case study of Jiangxi Province, China. *Energy.* 2023;265:126380. <https://doi.org/10.1016/j.energy.2022.126380>
16. HMT, Unnikrishnan S. Utilization of industrial and agricultural waste materials for the development of geopolymer concrete: A review. *Mater Today Proc.* 2022;65:1290–97. <https://doi.org/10.1016/j.matpr.2022.04.192>
17. Wang B, Dong F, Chen M, Zhu J, Tan J, Fu X. Advances in recycling and utilization of agricultural wastes in China: based on environmental risk, crucial pathways, influencing factors and policy mechanism. *Procedia Environ Sci.* 2016;31:12–17. <https://doi.org/10.1016/j.proenv.2016.02.002>
18. Koul B, Yakoob M, Shah MP. Agricultural waste management strategies for environmental sustainability. *Environ Res.* 2022;206:112285. <https://doi.org/10.1016/j.envres.2021.112285>
19. Duque-Acevedo M, Belmonte-Ureña LJ, Cortés-García FJ, Camacho-Ferre F. Agricultural waste: review of the evolution, approaches and perspectives on alternative uses. *Glob Ecol Conserv.* 2020;22:e00902. <https://doi.org/10.1016/j.gecco.2020.e00902>
20. Yusuf M. Agro-industrial waste materials and their recycled value-added applications. *Handb Ecomater.* 2017;1:1–11. https://doi.org/10.1007/978-3-319-48281-1_48-1
21. Phiri R, Rangappa SM, Siengchin S. Agro-waste for renewable and sustainable green production: A review. *J Clean Prod.* 2024;434:139989. <https://doi.org/10.1016/j.jclepro.2023.139989>
22. Jiang ZP, Li YR, Wei GP, Liao Q, Su TM, Meng YC. Effect of long-term vinasse application on physico-chemical properties of sugarcane field soils. *Sugar Tech.* 2012;14(4):412–17. <https://doi.org/10.1007/s12355-012-0174-9>
23. Ukanwa K, Patchigolla K, Sakrabani R, Anthony E, Mandavgane S. A review of chemicals to produce activated carbon from agricultural waste biomass. *Sustainability.* 2019;11(22):6204. <https://doi.org/10.3390/su11226204>
24. Romanovski V. Agricultural waste-based nanomaterials: green technology for water purification. In: *Aquananotechnology.* Elsevier; 2021. p. 577–95. <https://doi.org/10.1016/B978-0-12-821141-0.00013-6>
25. Karić N, Maia AS, Teodorović A, Atanasova N, Langergraber G, Crini G. Bio-waste valorisation: Agricultural wastes as biosorbents for removal of (in)organic pollutants in wastewater treatment. *Chem Eng J Adv.* 2022;9:100239. <https://doi.org/10.1016/j.ceja.2021.100239>
26. Hama Aziz KH, Mustafa FS, Karim MAH, Hama S. Biochar-based catalysts: An efficient and sustainable approach for water remediation from organic pollutants via advanced oxidation processes. *J Environ Manage.* 2025;390:126245. <https://doi.org/10.1016/j.jenvman.2025.126245>
27. Sridhar A, Kapoor A, Senthil Kumar P, Ponnuchamy M, Balasubramanian S, Prabhakar S. Conversion of food waste to energy: A focus on sustainability and life cycle assessment. *Fuel.* 2021;302:121069. <https://doi.org/10.1016/j.fuel.2021.121069>
28. Arora J, Ramawat KG, Mérillon JM. Disposal of agricultural waste and its effects on the environment, production of useful metabolites and energy: potential and challenges. In: Ramawat KG, Mérillon JM, Arora J, editors. *Agricultural waste: environmental impact, useful metabolites and energy production.* Singapore: Springer; 2023. p. 3–20. https://doi.org/10.1007/978-981-19-8774-8_1
29. Ivask M, Olle L, Nei L. Domestic organic waste treatment through vermitechnology. *Waste Manag Res.* 2013;31(8):878. <https://doi.org/10.1177/0734242X13493730>
30. Meena J, Singh D, Goel N, Shukla V, Gupta VK. Waste utilization and valorization: AI-driven approaches for creating value from food byproducts in India. In: *2024 4th International Conference on Innovative Sustainable Computational Technologies (CISCT);* 2024. p. 1–6. <https://doi.org/10.1109/CISCT62494.2024.11134224>
31. Kapoor R, Ghosh P, Kumar M, Sengupta S, Gupta A, Kumar SS. Valorization of agricultural waste for biogas-based circular economy in India: A research outlook. *Bioresour Technol.* 2020;304:123036. <https://doi.org/10.1016/j.biortech.2020.123036>
32. Bhamidimarri RB, Kommagalla PK, Bankupalli S, Kumari A. Thermo-catalytic transformation of indigenous agricultural waste into chemically diverse bio-oil: process refined through response surface optimization. *Biomass Convers Biorefinery.* 2025;15(12):18385–402. <https://doi.org/10.1007/s13399-024-06434-z>
33. Prasad M, Ranjan R, Ali A, Goyal D, Yadav A, Singh TB. Efficient transformation of agricultural waste in India. In: Naeem M, Ansari AA, Gill SS, editors. *Waste management in MENA regions.* Cham: Springer; 2020. p. 271–87. https://doi.org/10.1007/978-3-030-41552-5_13
34. Yadav VK, Sharma AK, Gacem A, Pandit J, Wany A, Kumar A. Emerging trends in the valorization of agricultural waste and their utilization in agricultural, pharmaceuticals and environmental cleanup. *Waste Biomass Valorization.* 2025;16(6):2779–833. <https://doi.org/10.1007/s12649-025-03002-y>
35. Zhang Z, Malik MZ, Khan A, Ali N, Malik S, Bilal M. Environmental impacts of hazardous waste and management strategies to reconcile circular economy and eco-sustainability. *Sci Total Environ.* 2022;807:150856. <https://doi.org/10.1016/j.scitotenv.2021.150856>

36. Santagata R, Ripa M, Genovese A, Ulgiati S. Food waste recovery pathways: challenges and opportunities for an emerging bio-based circular economy. *J Clean Prod.* 2021;286:125490. <https://doi.org/10.1016/j.jclepro.2020.125490>
37. Muhammad S, Abdul Khalil HPS, Abd Hamid S, Albadn YM, Suriani AB, Kamaruzzaman S. Insights into agricultural-waste-based nano-activated carbon fabrication and modifications for wastewater treatment application. *Agriculture.* 2022;12(10):1737. <https://doi.org/10.3390/agriculture12101737>
38. Atabani AE, Tyagi VK, Fongaro G, Treichel H, Pugazhendhi A, Hoang AT. Integrated biorefineries, circular bio-economy and valorization of organic waste streams with respect to bio-products. *Biomass Convers Biorefinery.* 2022;12(3):565. <https://doi.org/10.1007/s13399-021-02017-4>
39. Casau M, Dias MF, Matias JCO, Nunes LJR. Residual biomass: A comprehensive review on the importance, uses and potential in a circular bioeconomy approach. *Resources.* 2022;11(4):35. <https://doi.org/10.3390/resources11040035>
40. Ajila CM, Brar SK, Verma M, Prasada Rao UJS. Sustainable solutions for agro processing waste management: An overview. In: *Environmental protection strategies for sustainable development.* 2012. p. 65–109. https://doi.org/10.1007/978-94-007-1591-2_3
41. Ahmad A, Priyadarshini M, Yadav S, Ghangrekar MM, Surampalli RY. The potential of biochar-based catalysts in advanced treatment technologies for removal of persistent organic pollutants from wastewater: A review. *Chem Eng Res Des.* 2022;187:470–96. <https://doi.org/10.1016/j.cherd.2022.09.024>
42. Guo Z, Yan N, Lapkin AA. Towards circular economy: Integration of bio-waste into chemical supply chain. *Curr Opin Chem Eng.* 2019;26:148–56. <https://doi.org/10.1016/j.coche.2019.09.010>
43. Kumar M, Ambika S, Hassani A, Nidheesh PV. Waste to catalyst: role of agricultural waste in water and wastewater treatment. *Sci Total Environ.* 2023;858:159762. <https://doi.org/10.1016/j.scitotenv.2022.159762>
44. Chhandama MVL, Chetia AC, Satyan KB, Supongsena Ao, Ruatpuia JV, Rokhum SL. Valorisation of food waste to sustainable energy and other value-added products: A review. *Bioresour Technol Rep.* 2022;17:100945. <https://doi.org/10.1016/j.biteb.2022.100945>
45. Sharma A, Kuthiala T, Thakur K, Thatai KS, Singh G, Kumar P. Kitchen waste: sustainable bioconversion to value-added product and economic challenges. *Biomass Convers Biorefinery.* 2025;15(2):1749–70. <https://doi.org/10.1007/s13399-022-02473-6>
46. Gavrilas S, Chereji BD, Munteanu FD. Agricultural waste valorization via biochar-based supermaterials: linking process design to sustainability. *Processes.* 2026;14(7):1076. <https://doi.org/10.3390/pr14071076>
47. Dadrasnia A, de Bona Muñoz I, Yáñez EH, Lamkaddam IU, Mora M, Ponsá S. Sustainable nutrient recovery from animal manure: A review of current best practice technology and potential for freeze concentration. *J Clean Prod.* 2021;315:128106. <https://doi.org/10.1016/j.jclepro.2021.128106>
48. Sheik Shalik S, Sivakumar G, Meyyappan M. Assessing the influence of bio-digested bone sludge compost on root morphology in rice cultivation. *Ecol Environ Conserv.* 2024;30(Suppl Issue):S369–72. <https://doi.org/10.53550/EEC.2024.v30i06s.054>
49. Upadhyay SK, Singh G, Rani N, Rajput VD, Seth CS, Dwivedi P. Transforming bio-waste into value-added products mediated microbes for enhancing soil health and crop production: perspective views on circular economy. *Environ Technol Innov.* 2024;34:103573. <https://doi.org/10.1016/j.eti.2024.103573>
50. Wibisono DAS, Saw CY, Wu TY, Chau CF. Advancing industrial food byproduct management: strategies, technologies and progress in waste reduction. *Processes.* 2025;13(1):84. <https://doi.org/10.3390/pr13010084>
51. Polipalli K, Suraboyina S, Kashimalla M, Polumati A. A review on value addition of agricultural residues by chemical and biochemical processes to abate environmental pollution. *Green Technol Sustain.* 2025;3(4):100241. <https://doi.org/10.1016/j.grets.2025.100241>
52. Silva TAL, Varão LHR, Pasquini D. Lignocellulosic biomass. In: *Handbook of biomass.* Singapore: Springer; 2024. p. 1–39. https://doi.org/10.1007/978-981-19-6772-6_5-1
53. Sama DK, Tomczyk-Nazarczuk A, Szweczek-Karpisz K. Modification directions of agricultural waste biochars to improve their effectiveness as amendments for degraded soils. *Sustain Mater Technol.* 2025;45:e01529. <https://doi.org/10.1016/j.susmat.2025.e01529>
54. Blasi A, Verardi A, Lopresto CG, Siciliano S, Sangiorgio P. Lignocellulosic agricultural waste valorization to obtain valuable products: An overview. *Recycling.* 2023;8(4):61. <https://doi.org/10.3390/recycling8040061>
55. Reddy AS, Kasa VP, Samal B, Dubey BK, Yadav V, Pandey DS. Sustainable agricultural waste management in India: innovations, challenges and future perspectives. *Biomass Bioenergy.* 2025;202:108261. <https://doi.org/10.1016/j.biombioe.2025.108261>
56. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ.* 2021;372:n71. <https://doi.org/10.1136/bmj.n71>
57. Ogbu CC, Okey SN. Agro-industrial waste management: the circular and bioeconomic perspective. In: *Agricultural waste – new insights.* IntechOpen; 2023. <https://doi.org/10.5772/intechopen.109181>
58. Dhaliwal SS, Sharma V, Verma V, Kaur M, Singh P, Gaber A. Impact of manures and fertilizers on yield and soil properties in a rice–wheat cropping system. *PLoS One.* 2023;18(11):e0292602. <https://doi.org/10.1371/journal.pone.0292602>
59. Jayabal R, Prabhakar P. Advanced strategies in food and agricultural waste valorisation: integrating nanoengineering, artificial intelligence and smart bioconversion for sustainable resource recovery. *J Sci Food Agric.* 2025;105. <https://doi.org/10.1002/jsfa.70311>
60. Huzir NM, Asmadi AA, Rosly MB, Tamunaidu P, Amin ANR. Composting as a pathway for organic waste valorization: substrate performance, process strategies and quality benchmarks. *J Mater Cycles Waste Manag.* 2026;28(2):815–33. <https://doi.org/10.1007/s10163-025-02460-9>
61. Sajid U, Aslam S, Hussain A, Mumtaz T, Kousar S. Pressmud compost for improved nitrogen and phosphorus content employing *Bacillus* strains. *Recycling.* 2024;9(6):104. <https://doi.org/10.3390/recycling9060104>
62. Pandey AK, Thakur S, Mehra R, Kaler RSS, Paul M, Kumar A. Transforming agri-food waste: innovative pathways toward a zero-waste circular economy. *Food Chem X.* 2025;28:102604. <https://doi.org/10.1016/j.fochx.2025.102604>
63. Ravindran B, Mnkeni PNS. Bio-optimization of the carbon-to-nitrogen ratio for efficient vermicomposting of chicken manure and waste paper using *Eisenia fetida*. *Environ Sci Pollut Res Int.* 2016;23(17):16965–76. <https://doi.org/10.1007/s11356-016-6873-0>
64. Hansen JH, Hamelin L, Taghizadeh-Toosi A, Olesen JE, Wenzel H. Agricultural residues bioenergy potential that sustain soil carbon depends on energy conversion pathways. *GCB Bioenergy.* 2020;12(11):1002–13. <https://doi.org/10.1111/gcbb.12733>
65. Saady NMC, Hernández AV, Flores Servín KL, Rodríguez JZ, Haque MA, Owusu MK. Valorization of agro-food plant wastes: bioactive compound profiles and biotechnological potential of twenty crops. *Recycling.* 2026;11(1):7. <https://doi.org/10.3390/recycling11010007>
66. Waqas M, Hashim S, Humphries UW, Ahmad S, Noor R, Shoaib M. Composting processes for agricultural waste management: A comprehensive review. *Processes.* 2023;11(3):731. <https://doi.org/10.3390/pr11030731>

67. Folina A, Kakabouki I, Baginetas K, Bilalis D. Integration of bioresources for sustainable development in organic farming: A comprehensive review. *Resources*. 2025;14(7):102. <https://doi.org/10.3390/resources14070102>
68. Prasanna Kumar DJ, Mishra RK, Chinnam S, Binnal P, Dwivedi N. A comprehensive study on anaerobic digestion of organic solid waste: A review on configurations, operating parameters, techno-economic analysis and current trends. *Biotechnol Notes*. 2024;5:33–49. <https://doi.org/10.1016/j.biotno.2024.02.001>
69. Sathiyapriya S, Prabhakaran J, Sheeba S, Anandham R, Ilamaram M. Nutrient recycling through composting: harnessing agricultural wastes for sustainable crop production. *Plant Sci. Today*. 2024;11 (Suppl 4). <https://doi.org/10.14719/pst.5627>
70. Ungureanu N, Vlăduț V, Biriș SS, Gheorghe N, Ionescu M. Biomass pyrolysis pathways for renewable energy and sustainable resource recovery: A critical review of processes, parameters and product valorization. *Sustainability*. 2025;17(17):7806. <https://doi.org/10.3390/su17177806>
71. Gao Y, Wang M, Raheem A, Wang F, Wei J, Xu D. Syngas production from biomass gasification: influences of feedstock properties, reactor type and reaction parameters. *ACS Omega*. 2023;8 (35):31620–31. <https://doi.org/10.1021/acsomega.3c03050>
72. Osman AI, Lai ZY, Farghali M, Yiin CL, Elgarahy AM, Hammad A. Optimizing biomass pathways to bioenergy and biochar application in electricity generation, biodiesel production and biohydrogen production. *Environ Chem Lett*. 2023;21(5):2639–705. <https://doi.org/10.1007/s10311-023-01613-2>
73. Makwana J, Dhass AD, Ramana PV, Sapariya D, Patel D. An analysis of waste/biomass gasification producing hydrogen-rich syngas: A review. *Int J Thermofluids*. 2023;20:100492. <https://doi.org/10.1016/j.ijft.2023.100492>
74. Clauser NM, Felissia FE, Area MC, Vallejos ME. A framework for the design and analysis of integrated multi-product biorefineries from agricultural and forestry wastes. *Renew Sustain Energy Rev*. 2021;139:110687. <https://doi.org/10.1016/j.rser.2020.110687>
75. Jayaraman S, Yadav B, Dalal RC, Naorem A, Sinha NK, Srinivasa Rao C. Mushroom farming: A review focusing on soil health, nutritional security and environmental sustainability. *Farming Syst*. 2024;2 (3):100098. <https://doi.org/10.1016/j.farsys.2024.100098>
76. Shafaghat AH, Merenda A, Seccombe D, Phuntsho S, Shon HK. From waste to high-value fertilisers: harvesting nutrients from liquid anaerobic digestate for a circular bioeconomy. *Desalination*. 2025;596:118266. <https://doi.org/10.1016/j.desal.2024.118266>

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonpublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc. See https://horizonpublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (<https://creativecommons.org/licenses/by/4.0/>)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.