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Integrated Biorefinery Pathways for Organic Waste Valorisation: A Systematic Literature Review of Biological, Thermochemical, and Anaerobic Digestion Technologies

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Abstract: The increasing generation of organic and lignocellulosic waste has created significant environmental challenges, requiring sustainable and efficient waste management strategies. Biorefinery systems have emerged as a key approach within the circular bioeconomy framework, enabling the conversion of complex waste streams into value-added products such as biofuels, platform chemicals, animal feed, and fertilisers. **Objective***:* This study aims to systematically review recent developments in biorefinery-based waste valorisation technologies and evaluate their environmental and technological performance within a circular bioeconomy perspective. **Methods**: This research employs a qualitative systematic literature review (SLR) approach. Data were collected from peer-reviewed journal articles indexed in Scopus, ScienceDirect, Web of Science, and Google Scholar. The analysis was conducted using narrative synthesis and comparative evaluation of biological, thermochemical, and hybrid biorefinery technologies published between 2015 and 2026. **Results**: The results indicate that Black Soldier Fly (BSF) bioconversion can reduce organic waste mass by approximately 50% while producing high-value protein and lipid products. Hydrothermal Carbonisation (HTC) effectively converts wet biomass into hydrochar at 180–280 °C. Decentralised anaerobic digestion systems show superior environmental performance compared to incineration, particularly in reducing Global Warming Potential (GWP) and Fossil Fuel Depletion Potential (FFP). Lignin valorisation demonstrates strong potential for producing aromatic chemicals, although it remains constrained by feedstock variability and processing challenges. **Implications**: The findings suggest that integrated biorefinery systems supported by Life Cycle Assessment (LCA) offer a more sustainable pathway for organic waste management compared to single-process technologies. However, scalability, feedstock heterogeneity, and process optimisation remain key challenges for industrial implementation. **Originality**: The originality of this study lies in its integrated comparative analysis of biological, thermochemical, and hybrid biorefinery technologies within a circular bioeconomy framework, combining environmental performance assessment and technological evaluation to provide a comprehensive perspective for sustainable waste management development.

Keywords: Biorefinery; Waste Valorisation; Circular Bioeconomy; Black Soldier Fly; Hydrothermal Carbonisation

INTRODUCTION

The rapid increase in global population, urbanisation, and industrial activities has significantly intensified the generation of organic waste, particularly food waste and lignocellulosic residues. Global estimates indicate that solid waste generation will reach approximately 3.4 billion tonnes by 2050 (Kaza et al., 2018). In many countries, a large proportion of this waste is still managed through landfilling and incineration, which contributes to greenhouse gas emissions and environmental degradation. This situation highlights that organic waste management has shifted from a sanitation issue to a critical resource recovery challenge that requires sustainable technological solutions (Venkata Mohan, 2016).

In addition, increasing food consumption and agro-industrial activities continue to generate high-moisture organic residues that are difficult to treat using conventional disposal methods. These wastes contain valuable biomass fractions that are often lost due to inefficient management systems. As a result, there is growing attention toward technologies capable of converting waste into energy, materials, and bio-based chemicals within a circular economy framework (Fava, 2015).

Biological conversion technologies have been widely investigated as sustainable pathways for organic waste valorisation. Anaerobic digestion is one of the most established methods for converting organic waste into biogas and digestate, although its performance is strongly influenced by feedstock characteristics and operational stability (Tian, 2021). In parallel, Black Soldier Fly (BSF) bioconversion has gained attention as an efficient biological system for converting food waste into protein-rich biomass and organic fertiliser (Amrul, 2022).

Thermochemical conversion technologies such as hydrothermal carbonisation (HTC) and pyrolysis are increasingly applied for wet biomass and lignocellulosic waste treatment. HTC is particularly suitable for high-moisture biomass because it eliminates the need for energy-intensive drying processes and produces hydrochar with potential applications as solid fuel and adsorbent material (Petrović, 2024). Pyrolysis, on the other hand, enables the production of bio-oil and syngas, although its large-scale implementation remains limited by energy efficiency constraints and reactor design challenges (Ponnusamy, 2019).

More recently, integrated biorefinery systems combining biological, chemical, and thermochemical processes have been proposed to maximise resource recovery and enable multi-product generation. However, most existing studies still focus on single-process systems rather than integrated frameworks. Limited comparative analysis exists regarding their environmental, economic, and technological performance within a unified circular bioeconomy perspective, indicating a clear research gap in current literature (Attard, 2020; Sarker et al., 2023).

This study aims to systematically review and synthesise recent developments in biorefinery-based waste valorisation by analysing major biological, thermochemical, and hybrid conversion technologies. The review focuses on anaerobic digestion, hydrothermal carbonisation, Black Soldier Fly bioconversion, and lignocellulosic biomass processing. Each technology is evaluated in terms of process characteristics, product outputs, advantages, limitations, and environmental implications. In addition, this study identifies key research gaps and provides future directions for developing integrated biorefinery systems that support circular bioeconomy implementation and sustainable waste management (Sarker et al., 2023; Tian, 2021).

It is hypothesised that integrated biorefinery systems combining biological and thermochemical processes provide higher overall sustainability performance compared to single-pathway waste treatment technologies. Such integration is expected to improve resource recovery efficiency, reduce environmental impacts, and enhance economic feasibility through multi-product valorisation. The novelty of this review lies in its comparative assessment of biorefinery pathways based on technological maturity, environmental performance, and scalability potential. This integrated perspective is expected to contribute to the development of next-generation sustainable waste management systems aligned with circular bioeconomy and net-zero emission targets (Fava, 2015; Venkata Mohan, 2016)

RESEARCH METHOD

The unit of analysis in this study is scientific literature related to biorefinery-based waste valorisation systems. The scope includes biological, thermochemical, and hybrid conversion technologies applied to organic waste such as food waste, agricultural residues, and lignocellulosic biomass. The analysed studies focus on process mechanisms, product outputs, environmental performance, and system integration within circular bioeconomy frameworks.

This study employs a qualitative systematic literature review (SLR) approach. This method is selected because it enables comprehensive synthesis and critical comparison of heterogeneous research findings across multiple biorefinery technologies. The qualitative design is appropriate for identifying patterns, research gaps, and technological trends without requiring primary experimental data. In addition, this approach allows integration of technical, environmental, and economic dimensions of waste valorisation systems.

The data used in this study are secondary data obtained from peer-reviewed scientific publications. Literature was retrieved from major academic databases, including Scopus, ScienceDirect, Web of Science, and Google Scholar. The selected documents consist of original research articles and review papers published between 2015 and 2026. All selected studies are directly related to biorefinery systems, waste valorisation technologies, and circular bioeconomy applications.

Data collection was conducted using a structured keyword-based search strategy. The keywords applied included "biorefinery", "waste valorisation", "organic waste", "hydrothermal carbonisation", "anaerobic digestion", "Black Soldier Fly", and "lignocellulosic biomass". The selection process followed three stages: identification of records, removal of duplicates, and screening based on title, abstract, and full-text eligibility. The initial search identified 412 records. After duplicate removal, 356 articles remained. A total of 112 articles were assessed for eligibility, and 64 articles were included in the final review.

Data were analysed using narrative synthesis and comparative analysis methods. The analysis focused on evaluating biorefinery technologies in terms of process characteristics, product yields, environmental performance, technological maturity, and scalability. Findings from selected studies were systematically compared and synthesised to identify similarities, differences, and research gaps. Data were further organised into tables and conceptual frameworks to enhance interpretation of feedstock types, conversion pathways, and final products. In addition, Life Cycle Assessment (LCA) results reported in previous studies were integrated to evaluate environmental impacts, particularly greenhouse gas emissions and resource efficiency.

RESULT

Current State of Biorefinery Technologies

The literature analysis shows that biorefinery development is primarily driven by the need to address increasing organic waste generation while simultaneously recovering valuable resources. The reviewed studies indicate a clear transition from single-process waste treatment systems to integrated biorefinery approaches that combine biological, thermochemical, and chemical pathways.

Recent research trends demonstrate that anaerobic digestion, hydrothermal carbonisation (HTC), and Black Soldier Fly (BSF) bioconversion are the most widely investigated technologies for organic waste valorisation. Anaerobic digestion is predominantly applied for energy recovery in the form of biogas, while HTC is more suitable for wet biomass conversion into hydrochar without pre-drying requirements. Meanwhile, BSF bioconversion has emerged as an effective biological system for converting food waste into protein-rich biomass and organic fertiliser.

Figure 1 illustrates the system boundary of integrated biorefinery pathways, showing the interaction between waste input streams, conversion technologies, and multi-product outputs including energy, fuels, and nutrient recovery. The system highlights the transition towards zero-waste frameworks in modern biorefinery research.

Figure 1. Tren and Research Focus

Figure 1 shows the system boundaries in this study, designed to fulfil several functions, including heat and electricity generation, transport fuel production, and nutrient recovery for agricultural purposes. As shown, all inputs into the system and all outputs from the system are traced from cradle to grave to ensure that all impacts of human activities and interactions between the system and the environment are included in the analysis.

Characteristics of Biorefinery Systems

The comparative characteristics of different biorefinery feedstocks and conversion processes are summarised in Table 1. The results indicate that each feedstock type requires specific processing technologies to optimise product yield and system efficiency.

Organic waste and food residues are mainly processed through BSF bioconversion, producing protein, lipids, and organic fertiliser. Lignocellulosic biomass is predominantly treated through chemical and thermochemical pathways to generate biofuels and platform chemicals. Wet biomass is effectively converted using hydrothermal carbonisation into hydrochar, while fruit and vegetable waste is commonly used for extraction of bioactive compounds.

Liquid waste streams such as wastewater sludge are primarily processed through anaerobic digestion for nutrient and energy recovery. These findings confirm that no single technology is universally applicable, but rather each system is highly dependent on feedstock characteristics.

Table 1. Characteristics of Biorefineries

Material Origin	Material Description	Process	Final Products	References
Organic Waste	Food waste, agro-industrial by-products, poultry and dairy manure	BSF larval bioconversion (*Hermetia illucens*)	Proteins and lipids (animal feed/aquaculture), biodiesel, organic fertiliser (frass), pigments (melanin, ommochrome)	(Amrul, 2022; De Smet, 2018; Nguyen, 2015; Zurbrügg, 2018)
Lignocellulosic Biomass	Lignin, cellulose, hemicellulose (e.g. straw, wood residues)	Pre-treatment (biological/chemical/hybrid); depolymerisation (oxidation, reduction, pyrolysis, hydrolysis)	Biofuels (liquid and gaseous), aromatic chemicals (phenol, cresol, eugenol, guaiacol, BTX), carbon fibres, polyurethane	(Ponnusamy, 2019)
Wet Biomass / Food Waste	Rice husk, grape pomace, municipal solid organic waste (OFMSW), potato waste	Hydrothermal carbonisation (HTC) (180–280 °C)	Hydrochar (solid fuel/biofuel), heavy-metal and dye adsorbents, soil conditioner	(Petrović, 2024)
Fruit and Vegetable Waste	Citrus peels, apple pomace,	Extraction (solvent, ultrasonic); fermentation	Carbohydrates (pectin, chitosan, cellulose), phenolic	(Das, 2015; Piwowarek, 2016; Sarker et al., 2023)

Material Origin	Material Description	Process	Final Products	References
	banana peels, beet pulp		compounds (chlorogenic acid), organic acids (acetic, fumaric, lactic acids), essential oils	
Liquid Waste (WWTP)	Faecal sludge, nutrient-rich wastewater (N, P)	Nutrient recovery models; anaerobic digestion	Biofertiliser, nutrient-rich biomass, biofuel	(Tian, 2021; Venkata Mohan, 2016)

System Boundary of Waste Treatment Scenarios

Table 2 presents the system boundary characteristics for different food waste treatment scenarios. The analysis compares incineration, decentralised anaerobic digestion, and centralised anaerobic digestion systems. The results show that incineration systems are associated with higher environmental burdens due to transport requirements and lower energy efficiency. In contrast, anaerobic digestion systems demonstrate better resource recovery efficiency, particularly through biogas production and nutrient recycling via digestate utilisation. Decentralised systems reduce transportation needs, while centralised systems offer higher energy conversion efficiency but require more complex infrastructure.

Table 2. System Boundary Characteristics

Treatment Scenario (FU: Disposal of 1 tonne of FW)	System Boundary (Key Inclusions)	References
Incineration (Business-as-Usual scenario)	Includes food waste (FW) transport (average 25 km), electricity and diesel consumption, electricity output efficiency of 19%, leachate treatment, and disposal of bottom ash to landfill involving road transport (11 km) and water transport (30 km).	(Tian, 2021; Tong, 2018)
Decentralised Anaerobic Digestion	Includes small-scale systems (capacity: 2 tonnes/day) in which FW transport to the site is assumed to be zero. Accounts for grid electricity consumption, water use, biogas purification (Fe_2O_3), and utilisation of digestate as biofertiliser (substituting N, P, and K). Biogas utilisation: electricity generation (25% efficiency) or cooking fuel.	(Cheong, 2020; Khoshnevisan, 2018; Tong, 2018)
Centralised Anaerobic Digestion	Includes small-scale systems (capacity: 300 tonnes/day) with FW transport (average 30 km). Accounts Accounts for electricity consumption (18	(Cheong, 2020; Tian, 2021)

Treatment Scenario (FU: Disposal of 1 tonne of FW)	System Boundary (Key Inclusions)	References
	kWh per tonne FW), methane yield of 75%, and fugitive emissions pf 0.9%. Biogas utilization: electricity generation (35% efficiency) or upgrading to biomethane for transport fuel.	

Figure 2 illustrates the comparative system boundary of food waste treatment scenarios, highlighting differences in energy input, output efficiency, and environmental impact across the three systems.

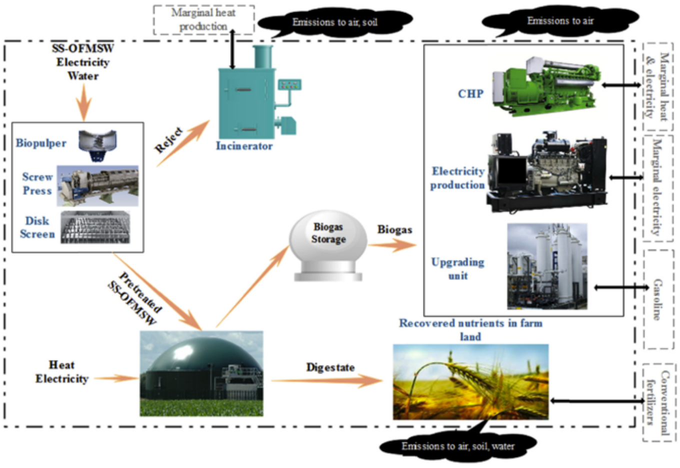

Figure 2. Boundary System of Scenario (Khoshnevisan et al., 2018)

Current State of Biorefinery Development

Amrul argue that the development of biorefineries is motivated by the necessity to manage the growing amount of waste generated and to identify alternative carbon sources that are different from petroleum (Amrul, 2022). Main trends and research focus:

- Research has transitioned from single-technology solutions to integrated valorisation approaches that combine biological, chemical, and thermal processes to optimise value extraction and attain zero-waste systems.
- Contemporary research is dominated by anaerobic digestion, hydrothermal carbonisation, and enzymatic conversion for the purpose of valorising food refuse.
- Hydrothermal carbonisation: HTC is known to be very effective in turning wet biomass to hydrochar at moderate temperatures without the need of pre-drying.
- Lignin valorisation: In an effort to enhance the efficacy of lignin depolymerisation, hybrid chemical-biological biorefineries are being investigated progressively.

- The role of Black Soldier Fly larvae is to be increasingly employed as efficient organic waste converters, capable of reducing waste mass by up to 50% within shorter timeframes than conventional composting.

DISCUSSION

The results of this study indicate that biorefinery systems for organic waste valorisation are increasingly shifting toward integrated multi-pathway approaches. Biological technologies such as anaerobic digestion and Black Soldier Fly (BSF) bioconversion are widely used for energy and protein recovery, while thermochemical processes such as hydrothermal carbonisation (HTC) are effective for converting wet biomass into hydrochar. In addition, lignocellulosic conversion technologies remain important for producing high-value chemicals despite their higher processing complexity. Overall, the findings show that no single technology is sufficient to address the complexity of organic waste management.

The observed dominance of integrated biorefinery approaches can be explained by the heterogeneous nature of organic waste streams. Food waste typically has high moisture content, making it more suitable for biological or hydrothermal processes rather than direct thermal conversion. Similarly, lignocellulosic biomass requires intensive pretreatment due to its rigid structural composition. These intrinsic feedstock characteristics drive the need for multi-technology systems that can adapt to different waste properties. Furthermore, economic and environmental constraints also encourage the combination of processes to maximise resource recovery efficiency and minimise residual waste generation.

The findings of this study are consistent with previous research that highlights anaerobic digestion as a mature and widely implemented technology for organic waste treatment (Tian, 2021). Similarly, BSF bioconversion has been reported as an efficient biological system for waste reduction and protein production (Amrul, 2022). However, this study extends previous works by systematically comparing biological, thermochemical, and hybrid systems within a unified framework.

Unlike earlier studies that tend to focus on single technologies such as HTC or anaerobic digestion in isolation (Petrović, 2024; Ponnusamy, 2019), this review demonstrates that integrated systems provide superior flexibility and broader sustainability potential. This represents the main novelty of the present study, as it bridges the gap between fragmented technological assessments and system-level biorefinery evaluation.

The results of this review suggest that biorefinery systems are not merely waste treatment technologies, but part of a broader transition toward a circular bioeconomy. The integration of multiple conversion pathways reflects a shift from linear waste disposal models to circular resource recovery systems. This transformation has significant implications for sustainability, as it enables simultaneous production of energy, materials, and nutrients from waste streams.

From a broader perspective, the findings also indicate that waste should no longer be considered as an environmental burden, but as a strategic resource for supporting energy security, material innovation, and sustainable agriculture. This paradigm shift is essential for achieving long-term sustainability goals and reducing dependency on fossil-based resources.

From a functional perspective, biorefinery systems offer multiple benefits, including waste reduction, energy recovery, and production of value-added products. Integrated systems can significantly reduce landfill dependency and improve resource efficiency. However, several dysfunctions remain evident, particularly related to technological complexity, high capital costs, and limited scalability.

In addition, social acceptance issues, especially for insect-based bioconversion systems such as BSF, may hinder large-scale adoption. Regulatory uncertainty and lack of standardisation further complicate the implementation of integrated biorefinery systems. These challenges indicate that technological advancement alone is insufficient without supporting institutional and societal readiness.

The findings of this study suggest several important implications for policy and future development. First, governments should promote integrated waste management policies that support multi-technology biorefinery systems rather than single-treatment approaches. Second, investment incentives are needed to accelerate the commercialization of emerging technologies such as BSF and hydrothermal carbonisation.

Furthermore, research funding should prioritise techno-economic analysis, life cycle assessment, and pilot-scale demonstration projects to bridge the gap between laboratory research and industrial application. Finally, regulatory frameworks should be updated to recognise waste as a resource, thereby facilitating the development of circular bioeconomy-based industries.

CONCLUSION

This review highlights that biorefinery-based waste valorisation represents a promising strategy for addressing the growing challenge of organic waste management. The findings indicate that biological systems (anaerobic digestion and Black Soldier Fly bioconversion), thermochemical processes (hydrothermal carbonisation), and lignocellulosic conversion technologies each offer distinct advantages depending on feedstock characteristics. However, the results consistently show that integrated biorefinery systems provide superior potential in terms of resource recovery efficiency, environmental performance, and multi-product generation compared to single-pathway approaches.

The main scientific contribution of this study lies in its integrated comparative framework of biorefinery technologies across biological, thermochemical, and hybrid pathways. Unlike previous studies that tend to focus on individual technologies, this review synthesises multiple conversion routes within a unified circular bioeconomy perspective. In addition, this study provides a structured comparison of technological performance, environmental implications, and scalability potential, thereby offering a more comprehensive understanding of waste valorisation systems. This work also identifies key research gaps and proposes future directions for the development of sustainable and integrated biorefinery systems.

Despite its contributions, this study has several limitations. First, the review is based on secondary data from published literature, which may introduce bias due to variations in methodologies and reporting standards across studies. Second, although multiple databases were used, some relevant studies outside indexed journals may not have been included. Third, this review does not include quantitative meta-analysis or experimental validation of the reported findings. Therefore, future research is recommended to incorporate techno-economic analysis, life cycle assessment-based meta-analysis, and pilot-scale experimental studies to strengthen the applicability of integrated biorefinery systems in real-world conditions.

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