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GREEN CHEMISTRY APPROACHES FOR SUSTAINABLE WASTE VALORIZATION AND RESOURCE RECOVERY: A COMPREHENSIVE REVIEW

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ABSTRACT

The increasing amount of agriculture, industry, municipality, food, plastic, and electronic waste has led to environmental degradation, which has only increased the need for sustainable management of resources. The concept of green chemistry, in its push to reduce hazardous materials, to be more resource-efficient and support circular materials use, has changed the way people see waste as an environmental problem, and profited as a resource. This in-depth review discusses the principles of green chemistry and their application in waste valorization and resource recovery in different waste streams. It covers the key green conversion technologies such as catalytic, biocatalytic, hydrothermal, electrochemical, microwave-assisted, ultrasound-assisted, mechanochemical and supercritical fluid processes, and explains their applications in bioenergy production, platform chemicals, bioplastics, biochar, advanced carbon materials, and biofertilizers. The review also delves into the methodology for sustainability assessment, industrial implementation and the role of green chemistry in the circular economy and sustainable development. Current up-and-coming technologies such as artificial intelligence, smart biorefineries, carbon capture and utilization and green hydrogen production are assessed to determine the potential for enhancing process efficiency and industrial scalability. While facing a number of technological hurdles due to feedstock variability, catalyst stability, economic viability, and regulatory support, sustained technological innovation and interdisciplinary research are expected to bring a boost to sustainable waste valorization. In conclusion, green chemistry offers a comprehensive approach to sustainable waste management, resource conservation, and long-term sustainable industrial processes.

KEYWORDS
Green chemistry, Waste valorization, Resource recovery, Circular economy, Sustainable waste management

1. INTRODUCTION

The world has seen rapid population growth, urbanization, industrialization and altered consumption patterns, which has led to increased agricultural, municipal, industrial, food, biomass wastes. These waste streams have a high proportion of organic materials, nutrients, polymers, minerals, and energy-rich compounds, many of which are either thrown in landfills, open dumped or burned in open fireplaces. This can result in greenhouse gas emissions, soil and water pollution, odour pollution, environmental damage and health risks. Concurrently, the fact that all of natural resources are finite, has intensified the demand for production systems that use less raw material and recover valuable raw materials from waste streams. As a result, the waste is gradually being rethought as a new resource and not as an environmental pollution. This shift has fueled greater interest in the valorization of waste, resource recovery, and in the adoption of models of circular bioeconomy, capable of keeping materials and energy in productive systems for as long as possible.

Green chemistry offers a vital scientific basis for transition, as it encourages the design of products and processes which decrease the use of hazardous substances, minimize waste generation and improve energy efficiency and the use of renewable feedstocks. In waste valorisation, green chemistry can play a role in the valorisation of waste to fuels, chemicals, fertilizers, adsorbents, polymers, biochar and other value added products in an environmentally responsible way. It is especially relevant to biomass and food waste which have carbohydrates, proteins, lipids, lignin, cellulose and other moieties that can be recovered or converted. By improving energy recovery from food waste and reducing reliance on traditional waste disposal and fossil energy, integrated processing systems can play a key role in improving the sustainability of food systems.The use of integrated processing systems can enhance energy recovery from food waste, reduce reliance on conventional waste disposal and fossil energy sources, thereby contributing to the sustainability of food systems (Talan et al., 2021). Likewise, biorefineries allow the cascading of the biomass residues into a series of products, enhancing the efficiency of the use of resources and the promotion of circular bio-economic development (Ubando et al., 2020). Bio-based materials are also becoming increasingly popular, leading to concerns about competition between industrial feedstocks and food production.

Therefore the use of food and feed crops in bio-based materials needs to be carefully evaluated and not be based on simplistic assumptions of food security, land use or resource allocation. Dammer et al. (2023) highlighted the importance of evidence-based evaluation as crop-based materials could pose risks and also offer benefits based on local conditions, agricultural practices and supply-chain configurations. This further underscores the need to use alternative feedstocks such as non-food biomass, agro-industrial residues and unavoidable organic wastes. Waste derived RM can help to alleviate the pressure on arable land and offer opportunities for material recovery, rural enterprise development and low carbon production.

Of the possible valorisation pathways, WtE technologies have been attracting much interest as they are capable of generating heat, electricity, gaseous fuels and liquid fuels from combustible and organic waste. There are various types of technologies like anaerobic digestion, gasification, pyrolysis, fermentation, thermal conversion, etc., that have several benefits depending on their feedstock and operating conditions. Raut et al. (2025) defined waste-to-energy as a significant process of converting waste into useful energy and Tshikovhi and Motaung (2023) noted the technological innovations that are enhancing biomass energy production. For example, fast pyrolysis can be used to generate bio-oil and biochar from agricultural residues and fruit-processing wastes. The use of agro-industrial residues such as avocado (Persea acuminata) seeds to produce bio-oil and biochar highlights the potential for transformation over the wastefulness of discarding a specific agro-techno-residue to create useful products, namely energy and carbon rich products (Izquierdo, 2023). The environmental potential of waste valorization, however, does not necessarily mean successful valorization.

Biorefineries and IRFs are often constrained by economic, institutional, technical and organizational factors. Commercialization may be delayed due to high capital costs, unreliable feedstock supply, limited infrastructure, market volatility and poor coordination among stakeholders (Chávez et al., 2024). Technological, financial, regulatory and public acceptance challenges can affect the long term viability of Biowaste-to-energy projects (Yadav et al., 2025). Another significant pathway of nutrient recovery and organic matter is through commercial composting, which relies on the successful segregation, quality control, capacity and demand for composts. (Saqib & Sadef, 2025). The consideration of waste valorization should not be limited to the broader ethical, social, and governance perspectives.

Circular economy strategies do not only imply technical recycling practices, but also the responsibility of consumer use, the equity of the distribution of resources, and the welfare of the society for long term. The moral economic concepts with circular economy thinking, highlighting the need for sustainable production and responsible use of resources. Environmental justice is especially relevant in urban areas for communities that are being disproportionately impacted by waste-treatment facilities. As in Bantargebang in Jakarta, the capacity problem at the waste management site, social inequality and policy constraints can become tangled in urban waste systems (Tamba et al., 2025). Thus, the use of green chemistry in waste valorization must go beyond environmental efficiency, and social acceptance, policy integration and fairness in the distribution of benefits must be also included.

While significant advances have been made in waste conversion technologies, there is still a lack of integration of the literature in the fields of green chemistry, bioenergy, biorefining, waste management, and circular economy. A comprehensive synthesis is needed to link green chemical principles to particular waste streams, conversion processes, recovered products, benefits that the recovery provides for sustainability, and barriers to implementation. Such integration can help elucidate the role of green chemistry in the design of more resource efficient and safer valorization systems, and the conditions that would enable them to be implemented in industry. Hence, this review discusses the existing sustainable waste valorization and resource recovery strategies focusing on the technological routes, integration with the circular bioeconomy, environmental impact, and future challenges toward valorization. The objectives of this study are as follows:

1. To examine green chemistry principles supporting environmentally responsible waste valorization and efficient resource recovery.
2. To evaluate major technologies for converting diverse waste streams into energy, materials, and valuable chemicals.
3. To identify implementation barriers, sustainability opportunities, and future priorities for industrial-scale waste valorization

2. METHODOLOGY

2.1 Review Design

This article is a comprehensive narrative review to generate an integrated understanding of green chemistry approaches for the valorisation of waste and recovery of resources in a sustainable manner. The review is a qualitative and interpretative approach in order to investigate the existing science, technology, sustainability issues and industrial applications that have been reported in the literature (Ke et al., 2025). The review brings into focus some of the key developments, emerging research trends and future opportunities of the field through a synthesis of knowledge from various disciplines such as chemistry, environmental science, biotechnology and chemical engineering. This design allows for a wide and impactful examination of the field without relying on a structured framework for a review.

2.2 Literature Sources and Search Strategy

The sources of literature used in this review are scientific databases such as: Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, Taylor & Francis Online, ACS Publications, MDPI, IEEE Xplore and Google Scholar. The keywords used for the identification of relevant publications were: green chemistry, valorisation of waste, resource recovery, circular economy, biorefinery, bioenergy, green catalysis, biochar, sustainable waste management. In general, peer-reviewed publications from 2020 – 2026 were included in the review, while a few of the foundational studies (Effendy et al., 2023; Putra & Suhaimi, 2024) were consulted to explain the key concepts and technological evolution.

2.3 Literature Selection

The publications reviewed were chosen on the basis of their scientific relevance, contribution to the field and their suitability to offer sufficient knowledge about green chemistry and waste valorisation in a sustainable way. Priority was given to recent Journal articles (published in the last 10 years) and to authoritative reports in book chapters and reports that are linked to technological developments, biomass use, resource recovery, strategies for a circular economy and environmental sustainability. Various waste streams, conversion technologies and industrial uses were included in the representative studies to attain the balance of the topic (Mbola et al., 2024; Okereke et al., 2026). This allowed for the consideration of multiple perspectives in the review while maintaining the logical flow and scientific rigor of the discussion.

2.4 Thematic Analysis and Organization of the Review

The literature reviewed was synthesized by thematic organization, which highlights the main concepts and evolutions of the field of green chemistry and waste valorization (Ke et al., 2025; Sadikan, 2025). The main topics discussed were: principles of green chemistry, properties of waste streams, valorisation technologies, pathways for re-use of the resources, sustainability assessment, incorporation of circular economy, new innovations and future research directions. Information from various fields was collated, conceptual linkages were created and current developments, challenges and opportunities for further development were identified

(Table 1) (Figure 1). Thematic structure allows for a logical and comprehensive analysis from both the scientific and industrial perspectives, sustainable waste valorization (Figure 1).

Table 1: Scope and Organization of the Narrative Review

Review Component	Description	Purpose	References
Review design	Narrative and comprehensive review	Integrate current knowledge	Sadikan (2025)
Literature sources	Scopus, ScienceDirect, SpringerLink, Google Scholar	Broad literature coverage	Effendy et al. (2023)
Literature selection	Recent, relevant, peer-reviewed publications	Ensure topical relevance	Mbola et al. (2024)
Thematic organization	Green chemistry, technologies, applications, sustainability, future trends	Structured discussion	Ke et al. (2025)

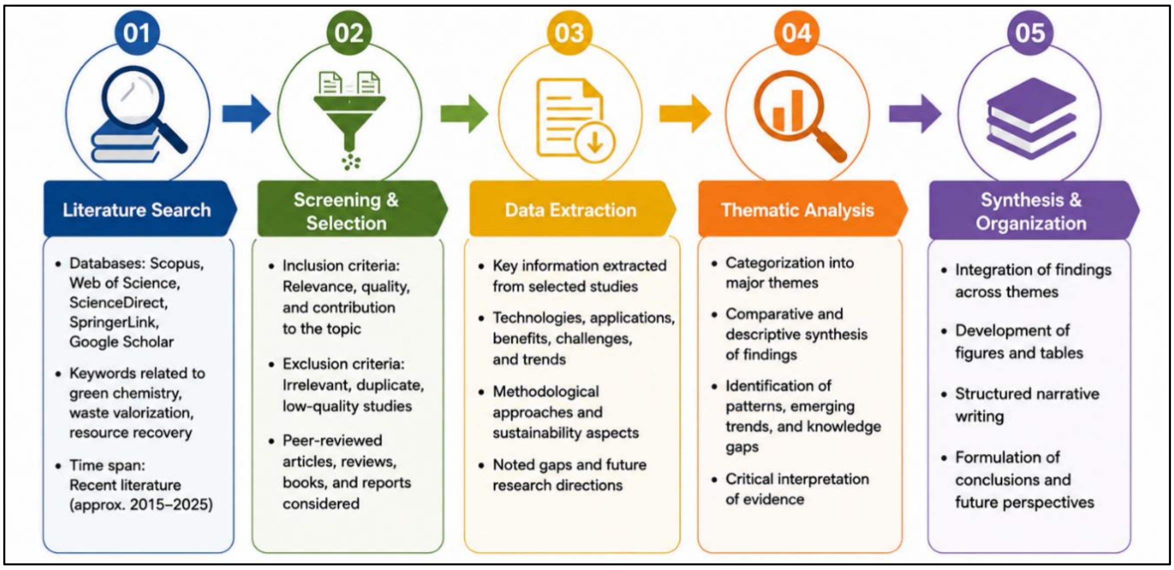

Figure 1: Methodology of review

3. FUNDAMENTALS OF GREEN CHEMISTRY FOR WASTE VALORIZATION

3.1 Evolution of Green Chemistry

Green chemistry has grown beyond pollution prevention to an integrated approach to the goal of designing chemicals and processes that are less toxic, more energy efficient and reduce the environmental impact of industrial operations. Originally, the idea was to reduce harmful chemicals in the manufacture of chemicals and has since grown to cover the entire lifecycle of materials, including using renewable feedstocks, energy efficiency, waste minimisation, and circular use of resources. Green chemistry is now being utilized in areas beyond sustainable laboratory synthesis, such as waste management, processing of biomass, environmental remediation and manufacturing of advanced materials. Green chemistry in the field of waste valorization aims at converting waste materials into useful products by applying environmentally friendly reaction routes which minimize environmental impacts and maximise the use of resources (Sheldon, 2024; Saraf et al., 2023). Recent developments also underscore the increasing role of green carbon, that encourages the use of renewable carbon sources rather than fossil-based feedstocks, thus contributing to low carbon industrial development and climate change mitigation. Hence, green chemistry has emerged as an integral component of sustainable manufacturing and circular resource management and offers scientific solutions that are also environmentally protective, economically viable and resource efficient.

3.2 The Twelve Principles of Green Chemistry

The 12 principles of Green Chemistry are scientific principles that can be used to design green chemical processes that reduce the environmental impacts associated with product development and manufacturing. These principles include minimization of waste; increased atom economy; use of less hazardous synthesis; design of safer chemicals; use of renewable feedstocks; catalysis; saving energy in processing; reducing the use of auxiliary substances; design for degradation; real-time process monitoring; and inherently safer chemicals. All of these principles promote an industry transition from end-of-pipe pollution control measures to measures that are taken at the source to reduce the amount of waste created. In waste valorization, these principles help transform agricultural residues, municipal solid waste, food waste, plastics, and industrial by-products into valuable chemicals, fuels, and functional materials with cleaner technologies (Sheldon, 2022; Tamargo et al., 2024). Green Chemistry is not only about yield, but it also looks at the conservation of resources, efficiency of processes, and minimizing environmental impact throughout the production process. Their implementation has been significant in the application of modern research on biomass conversion, catalytic processing and sustainable industrial chemistry, and led to the creation of greener technologies that can contribute to sustainable resource recovery and circular production processes.

3.3 Green Chemistry and Circular Economy

The principles of green chemistry and circular economy are aligned with the goal of using materials to their fullest extent and reducing material waste and the resulting environmental impact. While the circular economy aims to maximise the value of materials by reusing, recycling, remanufacturing and recovering them, green chemistry offers the molecular and process innovations to produce chemicals and materials with safer, cleaner and more efficient pathways. They allow waste streams to be seen as secondary raw materials, as opposed to landfilled or incinerated waste. Advanced catalytic processes, biomass valorisation, solvent recycling and renewable feedstock utilization illustrate green chemistry applications for circular material flows, which minimize reliance on virgin resources and fossil based chemicals (Sheldon, 2024; Nieto et al., 2026).. This synergy also inspires industries to re-engineer production systems that are based on sustainable use of resources, increased process efficiency, and lower environmental impacts. Thus, the implementation of green chemistry and circular economy principles offers an effective route to sustainable industrial development and to securing resources, resilience of the environment and sustainability of the economy in the long term.

3.4 Sustainable Resource Efficiency

Resource efficiency is one of the core principles of green chemistry, which aims to optimize the use of raw materials, water, energy and renewable resources in chemical production and waste valorization. Green Chemistry aims to reduce the use of linear production methods by optimizing processes, utilizing catalytic reactions, using renewable feedstocks, minimizing solvent use, and reducing the use of energy-intensive methods, thus maximizing the recovery of materials and minimizing waste generation. Resource-efficient approaches are especially important in the conversion of agricultural residues, food waste, industrial by-products and municipal solid waste to fuels, chemicals, fertilizers and advanced functional materials. Catalytic systems and biocatalytic processes are then used to further increase the selectivity of the reactions, yield, and reducing the overall energy consumption. The concept of Green chemistry is included by introducing various metrics like atom economy, reaction mass efficiency, E-factor and process mass intensity, which are indispensable for assessing the efficiency of resource usage and pinpointing potential process enhancements. These indicators enable the continuous optimization of industrial processes as well as the development of sustainable production systems that help to conserve natural resources and minimize environmental impacts (Martínez et al., 2022; Sheldon, 2022).

3.5 Life Cycle Thinking in Waste Valorization

Life cycle thinking is the extension of green chemistry to consider the environmental impacts of products and processes not just at the reaction level but also from the point of raw materials to the end-of-life stage. This comprehensive approach allows for the identification of opportunities to lower energy use, greenhouse gas emissions, waste generation and resource use while maximizing the recovery of valuable materials by researchers and industries. Life cycle thinking is particularly important in waste valorization to make informed decisions on how to choose the most appropriate waste conversion technologies, feedstocks, and pathways of resource recovery based on their overall sustainability performance. Green chemistry metrics help augment life cycle assessments by offering a quantitative assessment of process efficiency, waste production and environmental outcomes that can help guide fact-based improvements in industrial processes (Martínez et al., 2022; Tamargo et al., 2024). The application of life cycle thinking and the principles of green chemistry fosters the creation of environmentally responsible, economically viable and socially beneficial waste valorisation systems (Table 2). Life cycle thinking is still fundamental for the development of sustainable resource recovery and it contributes to the shift toward low carbon production systems (Figure 2).

Table 2: Green Chemistry Principles and Their Relevance to Waste Valorization

Green Chemistry Principle	Application in Waste Valorization	Sustainability Benefit	References
Waste prevention	Minimizes waste generation during conversion	Lower environmental pollution	Sheldon (2024)
Renewable feedstocks	Utilizes biomass and organic wastes	Conserves fossil resources	Sheldon (2024)
Catalysis	Improves conversion efficiency	Lower energy consumption	Sheldon (2022)
Safer solvents	Replaces hazardous chemicals	Reduced toxicity	Martínez et al. (2022)
Energy efficiency	Uses mild operating conditions	Reduced carbon emissions	Tamargo et al. (2024)
Life-cycle thinking	Optimizes resource use across the value chain	Supports circular production	Nieto et al. (2026)

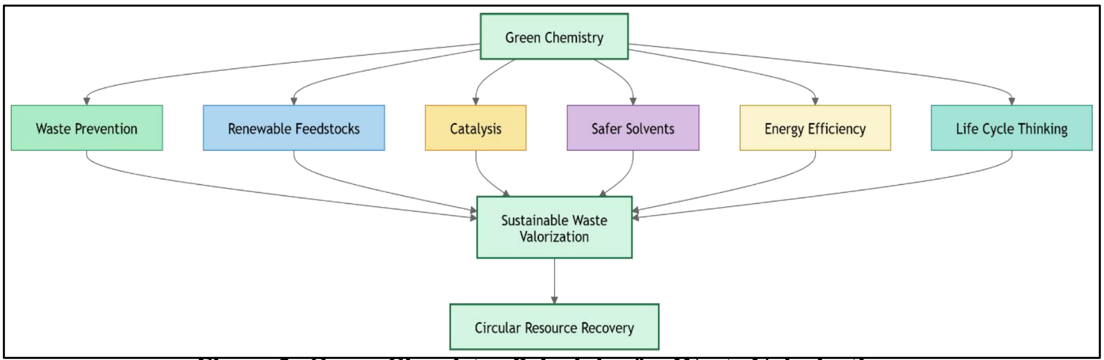

Figure 2: Green Chemistry Principles for Waste Valorization

4. MAJOR WASTE STREAMS AND THEIR VALORIZATION POTENTIAL

Agricultural, industrial, municipal, commercial and domestic waste streams offer a rich potential for the sustainable recovery of their resources via green chemistry valorisation technologies. Of these agricultural and forestry residues are one of the largest renewable biomass resources with crop straw, husks, bagasse, sawdust, pruning residues and lignocellulosic biomass being rich in cellulose, hemicellulose and lignin. Biofuels, biochar, biochemicals, biopolymers, enzymes, and biofertilizers can be extracted from these materials using environmentally friendly biorefinery and fermentation technologies, and thereby reducing open-field burning and improving resource use (Rocha et al., 2024; Lade et al., 2023). Food and organics from households, food processing industries, restaurants and markets are also a vast resource of biodegradable organics available for anaerobic digestion, composting, solid-state fermentation and biochemical conversion. A recent study has demonstrated that fruit and vegetable wastes can be used as valuable feedstocks for microbial metabolites, enzymes, organic acids and other high value bio-products in circular economy regime, which can reduce landfills, and lower GHGs (Ray et al. 2025; Umrao et al. 2024). The municipal solid waste (MSW) is a very complex material made up of biodegradable waste, paper, plastics, metals, glass, textiles, and other household waste products which need integrated segregation and processing methods in order to maximize material recovery. Green valorization technologies allow for the recovery of re-usable parts and the generation of renewable energy, compost or bio-based products from the bio-reducible parts, thus minimising environmental pollution and reliance on virgin resources. On the other hand, industrial wastes and by-products from agro-processing, food industry, chemical industries and other manufacturing processes often contain large amounts of recoverable organic compounds and nutrients. In recent years, these residues have been harnessed for microbial fermentation and enzyme production, providing an economically viable alternative to traditional raw materials and supporting industrial symbiosis and waste minimization (Yafetto et al., 2023; Oluwaseun et al., 2025). Plastic waste is one of the most difficult waste streams to manage due to its durability, sheer volume of usage and low rates of recycling. Green chemistry supports sustainable recycling and valorisation routes such as catalytic depolymerisation, solvent-assisted recycling, pyrolysis and generating alternative bio-based polymers that are less reliant on fossil based plastics and enhance material circularity. Similarly, electronic waste (e-waste) is a fast emerging concern around the world owing to its intricate cocktail of valuable metals, rare earth elements, polymers, and hazardous substances. The use of advanced techniques in green recovery, such as environmentally friendly leaching processes, selective extraction and biohydrometallurgical methods, enables the extraction of critical materials without the generation of toxic emissions that are associated with traditional metal recycling. In addition, the wastewater sludge and other emerging waste streams such as pharmaceutical residues, textile wastes, algae biomass, construction wastes, etc., have significant potential for the generation of renewable energy, biochar, adsorbents, fertilizers, and advanced functional materials using integrated green processing technologies. These various waste streams highlight that materials that have been thought of as environmental liabilities can be used as renewable feedstocks for sustainable resource recovery, which in turn helps to lower pollution, conserve natural resources, and generate value-added products by leveraging innovative green chemistry (Table 3) (Figure 3).

Table 2: Major Waste Streams and Their Valorization Potential

Waste Stream	Major Valorization Route	Representative Products	References
Agricultural waste	Biochemical and thermochemical conversion	Biofuels, biochar	Ray et al. (2025)
Food waste	Anaerobic digestion, fermentation	Biogas, organic acids	Yafetto et al. (2023)
Municipal solid waste	Recycling and waste-to-energy	Energy, recovered materials	Lade et al. (2023)
Industrial waste	Catalytic and chemical recovery	Chemicals, secondary raw materials	Rocha et al. (2024)
Plastic waste	Chemical recycling and pyrolysis	Fuels, monomers	Umrao et al. (2024)
Electronic waste	Metal recovery and recycling	Critical metals	Oluwaseun et al. (2025)

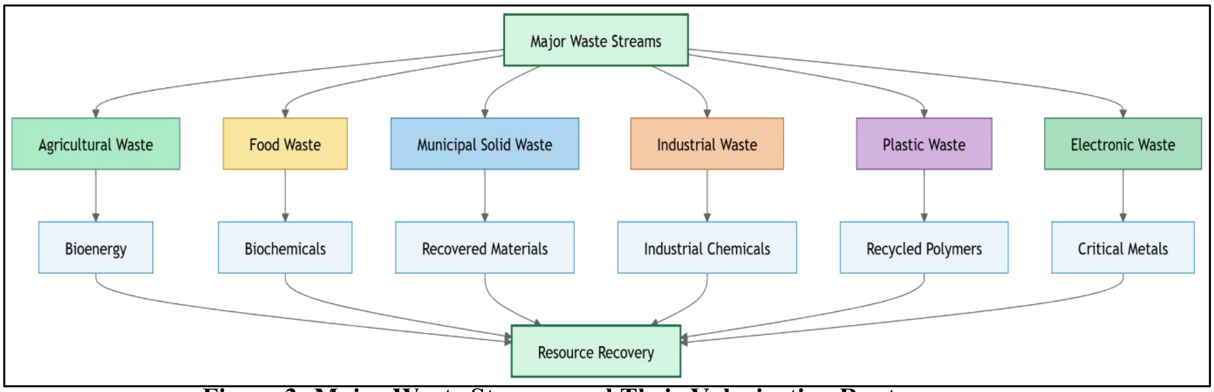

Figure 3: Major Waste Streams and Their Valorization Routes

5. WASTE VALORIZATION INVOLVING GREEN CHEMISTRY TECHNOLOGIES

The use of green chemistry technologies has revolutionized waste valorization technologies by making it possible to efficiently convert a variety of wastes into energy, chemicals, fuels and value added materials, and reduce the use of environmental resources and impacts. Homogeneous, heterogeneous and bio-inspired catalytic systems represent the key approaches of green catalysis to achieve sustainable chemical transformation with better selectivity, energy efficiency and the lower usage of hazardous reagents. In addition to the catalytic processes, biocatalytic and enzymatic processes involve the use of microorganisms and enzymes to convert biomass, food waste, and agricultural residues into biofuels, organic acids, enzymes, and specialty chemicals under mild operating conditions, which helps to reduce energy consumption and chemical waste. Hydrothermal and solvothermal conversion technologies are excellent methods to process high-moisture biomass and organic wastes without needing to intensively dry them and generate bio-oil, hydrochar, platform chemicals and nutrient-rich by-products under elevated temperatures and pressures. Photocatalytic processes use semiconductor materials which are excited by ultraviolet or visible light to destroy pollutants, extract valuable compounds and activate chemical reactions by sunlight, and are especially promising for wastewater treatment and environmental remediation. Similarly, electro-chemical technologies have been developed as environmentally friendly options for resources recovery, since they allow selective oxidation and reduction, metal recovery, hydrogen production and wastewater purification, with a relatively low consumption of chemicals and high process control. Green chemistry has also attracted a considerable interest towards physical process intensification techniques. During biomass conversion, microwave heating can shorten the reaction time, increase product yield, improve energy efficiency and reduce solvent consumption, due to the direct interaction between microwave (electromagnetic radiation) and reaction media. Likewise, ultrasound-assisted processing is emerging as a new area of green technology due to the ability to create high temperatures and pressures in localized areas which will increase mass transfer, cell disruption, extraction efficiency, emulsification and reaction kinetics without resorting to harsh processing conditions. The high potential of using ultrasound in environmental engineering, biomass processing, pollutant degradation and sustainable manufacturing has been enhanced by recent developments in the field of ultrasonic engineering (Baptista-Pereira et al., 2025; Ensminger & Bond, 2024). Over time, ultrasonic systems are also increasingly capable of achieving more process control and operational efficiency, as well as greater scalability, enabling them to be incorporated into industrial waste valorization and resource recovery systems (Feeney, 2024; Kahraman et al., 2025). In addition, the cavitation performance has been continuously improved through the advancement of ultrasonic power amplification and high-intensity ultrasonic transducer technologies, which has contributed to the extraction efficiency, activation of the catalyst, and chemical conversion in various green processing applications (Choi, 2023; Asfandiyarov et al., 2024). Another solvent free green technology is the mechanochemical processing method, where mechanical energy from grinding and/or milling is used to trigger chemical reactions, thereby reducing the need for solvents, energy consumption and the possibility of efficient synthesis of advanced materials based on industrial and mineral waste. Lastly, supercritical fluid technologies, especially with supercritical CO_2, are used to extract, fractionate, purify and process material without many of the organic solvents traditionally used, and have excellent mass transfer properties and easy product recovery. These complementary technologies, taken together, illustrate the versatility of green chemistry and how it can combine catalytic, biological, thermal, electrochemical, mechanical and physical processing techniques to maximize the recovery of resources in processes, minimize environmental impacts, optimize process efficiency, and enable sustainable valorization of waste in a circular economy (Table 2).

Table 2: Comparison of Green Chemistry Technologies Used in Waste Valorization

Technology	Typical Feedstock	Major Products	Key Advantage	References
Green catalysis	Biomass, plastics	Chemicals	High selectivity	Sheldon (2022)
Biocatalysis	Organic waste	Organic acids, enzymes	Mild reaction conditions	Sheldon (2022)
Hydrothermal conversion	Wet biomass	Bio-oil, hydrochar	No drying required	Sheldon (2022)
Microwave processing	Agricultural waste	Biofuels, chemicals	Rapid heating	Baptista-Pereira et al. (2025)
Ultrasound processing	Food and biomass waste	Extracts, bioactive compounds	Enhanced mass transfer	Kahraman et al. (2025)
Supercritical fluids	Biomass	High-purity extracts	Green solvent system	Ensminger & Bond (2024)

6. RECOVERY OF RESOURCES AND VALUE ADDED PRODUCTS

6.1 Bioenergy and Biofuels

Bioenergy and biofuels are among the most well-developed green chemistry resource recovery strategies, allowing agricultural residues, food waste, forestry biomass and agro-industrial by-products to be converted to renewable energy carriers. Biogas, bioethanol, biohydrogen, biodiesel, bio-oil and biooils are produced by anaerobic digestion or fermentation and thermochemical technologies such as pyrolysis and gasification and can be used to replace part of the fossil fuels (Yin et al., 2026; Bułkowska & Zielińska, 2025). The integrated biorefinery systems further enhance energy recovery by using different fractions of biomass within the same processing chain, thus optimising energy recovery and minimising production of waste. Sustainable valorization strategies are also beneficial in terms of greenhouse gases mitigation and energy security and development of circular bioeconomy.

6.2 Platform Chemicals

Waste biomass is also a valuable renewable feedstock for the production of platform chemicals which can be used as intermediates for a wide range of industrial chemicals. Organic wastes can be converted to organic acids, alcohols, furans, phenolic compounds and other intermediates which can be used in the production of pharmaceuticals, polymers, solvents and specialty chemicals by biological, catalytic, and thermochemical conversion. Green chemistry enables these conversions by making the reactions more efficient and less hazardous and energy intensive (Yin et al., 2026; Blasi et al., 2023). Advancements in biorefineries have seen a growing number of integrated conversion processes to achieve high chemical yields from lignocellulosic biomass and agro-industrial wastes, aiming for a more sustainable, less petroleum feedstock-based manufacturing process.

6.3 Bioplastics and Biopolymers

Reevaluating waste for use in the production of bioplastics or biopolymers is seen as a more environmentally-friendly alternative to the petroleum-based plastics. Biodegradable polymers can be synthesized by microbial fermentation and/or green chemical synthesis using agricultural residues, food-processing wastes, and lignocellulosic biomass. These materials are less persistent in the environment, more circular and less contribute to the GHGs from plastics that are derived from fossil fuels (Pal et al., 2024; Blasi et al., 2023). The continued development of waste biorefinery technologies is enhancing polymer yield, quality, and process efficiencies, and ultimately delivering greater value for waste-derived bioplastics for use in packaging, agriculture, biomedical, and consumer-product applications in sustainable production systems.

6.4 Biochar and Activated Carbon

The thermochemical conversion of biomass and organic wastes generates high value carbonaceous materials such as biochar and activated carbon (Blasi et al., 2023; Yin et al., 2026). These materials have many applications including soil improvement, carbon sequestration, wastewater treatment, air purification and environmental remediation, due to their high surface area, porosity and adsorption capacity. Green Chemistry: Sustainable production processes, maximizing carbon recovery with minimum emission during pyrolysis and activation processes. Agricultural residues and agro-industrial wastes are abundant sources of feedstocks for their production, reducing agricultural wastes and developing functional products for a circular use of resources.

6.5 Organic fertilizer production and use of biofertilizers

The valorisation of green waste allows to recover the primary plant nutrients (N, P, K and beneficial microorganisms) from food waste, vegetable residues and organic biomass (Pal et al., 2024; Yin et al., 2026). The nutrients recovered are then converted into biofertilizers and soil amendments to enhance soil fertility, productivity, and nutrient cycling and minimize reliance on synthetic fertilizers. Biological conversion technologies like composting, anaerobic digestion, and microbial fermentation provide better nutrient availability and help to sustain agriculture. Nutrient recovery is also resource efficient, reducing waste disposal and promoting environmental protection and long-term soil health in circular bioeconomy systems.

6.6 Advanced Carbon Materials and Nanomaterials

Waste derived biomass has emerged as an increasingly critical raw material for the production of advanced carbon materials and nanomaterials for use in catalysis, environmental remediation, energy storage and advanced manufacturing (Maciel et al., 2023; Yin et al., 2026). Controlled thermal conversion and activation processes allow for the production of porous carbons, carbon composites and functional nanostructured materials with desirable physicochemical properties. Processing residues of coffee, especially spent coffee grounds, have been shown to be very promising as raw material for ceramic porous supports and other functional materials, for use in industry. These innovative valorization pathways contribute to the economic value of wastes and to the reduction of environmental burdens related to their disposal.

6.7 Industrial Feedstocks from Waste

Waste materials are gaining more and more attention as sustainable industrial feedstocks, that can be used to substitute virgin raw materials in several manufacturing sectors. Environmental friendly processing technologies can turn agricultural biomass, food-processing wastes, forestry wastes and coffee-processing by-products into food products, construction materials, chemicals, polymers, ceramics and other industrial commodities (Oliveira Batista et al., 2023; Maciel et al., 2023). In this respect, spent coffee grounds have been used to successfully incorporate into gluten-free bakery products to enhance the nutritional and technological properties, highlighting the versatility of waste derived materials for high valued applications. These resource recovery actions not only enhance the sustainability of the industries but also boost material efficiency and contribute to the shift toward circular production systems (Figure 4).

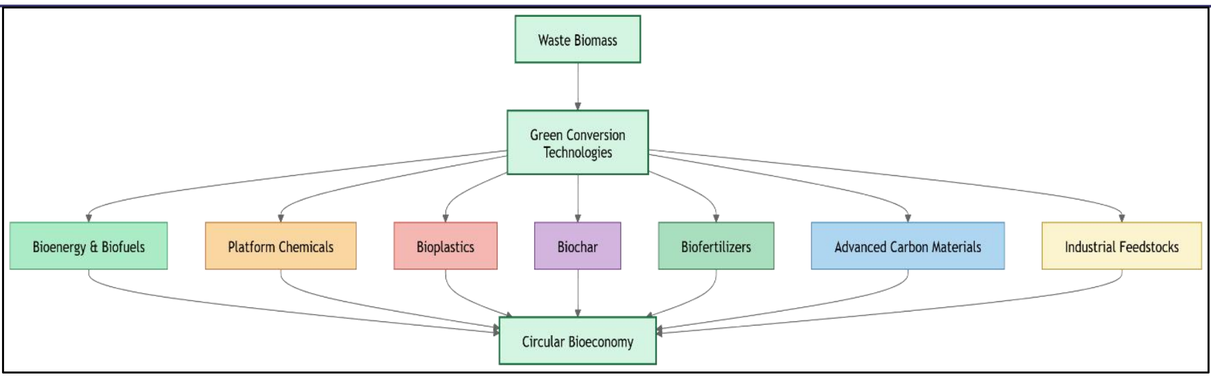

Figure 4. Green Waste-to-Resource Conversion Pathways

7. SUSTAINABILITY ASSESSMENT AND INDUSTRIAL APPLICATIONS

7.1 Environmental Benefits

Green waste valorization technologies offer significant environmental advantages, such as reducing waste disposal, saving natural resources, and reducing greenhouse gas emissions and pollution from traditional waste management methods. Energy, chemicals and materials recovery from agricultural residues, municipal and industrial by-products and organic biomass reduces reliance on virgin resources and encourages efficient material circulation (Oliveira Batista et al., 2023; Maciel et al., 2023). Cleaner production pathways, resource use, and energy reduction further minimize hazardous emissions, through the use of green chemistry technologies. The environmental benefits of waste valorisation play a critical role in mitigating climate change, safeguarding ecosystems and ensuring sustainable resource management, thus underscoring its significance to sustainable industrial development and environmental management.

7.2 Economic Feasibility

The economic viability of waste valorization is based on the feedstock availability, the efficiency of waste conversion, the maturity level of the technology, operational costs, market demand, and market value of the waste valorized products. Green chemistry allows industries to find new revenue streams and lower waste management costs by converting waste to commercially valuable fuels, chemicals, fertilizers, adsorbents, and advanced materials, among others (Oliveira Batista et al., 2023; Maciel et al., 2023). Multiple products can be recovering from a single waste stream, further increasing the profitability of the integrated biorefineries and resource recovery facilities. Waste valorization will gain increasing value, especially in terms of reducing production costs and increasing competitiveness, thanks to continuous improvement of technology, process optimisation and industrial integration.

7.3 Life Cycle Assessment (LCA)

To assess the environmental performance of waste valorization technologies, Life Cycle Assessment (LCA) is widely applied, taking into account environmental impacts along the whole product and process life cycle, from raw material extraction to final disposal or reuse. LCA is a method that facilitates a comprehensive evaluation of the energy use, greenhouse gas emissions, water use, resource depletion, and environmental burden for various conversion pathways. New research has broadened the scope of LCA for assessing new technologies prior to commercialization, offering valuable information for sustainable process design and technology selection (Arvidsson et al., 2024; Marson et al., 2025). These assessments enable evidence-based decision making process providing an identification of environmentally optimal waste valorisation routes and minimisation of unwanted environmental trade-offs.

7.4 Techno-Economic Assessment (TEA)

Environmental evaluation is complemented by a Techno-Economic Assessment (TEA) that focuses on the technical performance and economic viability of waste valorization technologies. Commercial viability is established through consideration of capital investment, operating costs, process efficiency, product yield, market value, and scalability with TEA. By combining TEA with environmental assessment, a more comprehensive assessment of sustainability can be achieved, which takes into account financial and ecological performance (Oliveira Batista et al., 2023; Maciel et al., 2023). These analyses help industries, investors and policy makers identify economically competitive technologies and aid investment decisions and strategies for commercialization. Environmental and economic evaluations enable the creation of waste valorization systems which are efficient in resource usage and can be made sustainable in the long-term in industry.

7.5 Industrial Case Studies

The implementation of the green waste valorization technologies in the industrial sector is proof of the possibility of using these technologies in various sectors, such as agriculture, food processing, municipal waste management, chemical production and production of renewable energy. The conversion of waste materials into bioenergy, platform chemicals, biofertilizers, and advanced materials has been successfully done by commercial biorefineries, anaerobic digestion plants, biomass conversion facilities, and recycling industries, which have significantly reduced the environmental impacts. Prospective environmental assessment tools have become more and more used to assess the sustainability of new industrial technologies before they are scaled up, aiding process optimization and technology development in a responsible way (Zinke et al., 2025; Spreafico et al., 2025). The experiences are from industry, and illustrate the increasing shift from lab-scale innovation to commercially viable waste valorisation systems.

7.6 Contribution to Circular Economy and Sustainable Development Goals

Green waste valorization is directly in line with the principles of circular economy, because the preservation of the value of the materials, through recovery, recycling and reuse, rather than disposal. Conversions that are efficient with resources lower the consumption of virgin raw materials and facilitate sustainable production and responsible consumption. These also help to achieve a number of United Nations Sustainable Development Goals (SDGs), including SDG7 Affordable and Clean Energy, SDG9 Industry, Innovation and Infrastructure, SDG11 Sustainable Cities and Communities, SDG12 Responsible Consumption and Production, and SDG13 Climate Action. Green chemistry-based waste valorization can be an effective approach to reach long term sustainable development goals and global sustainable development targets, by combining environmental protection, economic growth and efficient resource management (Table 3).

Table 3: Sustainability Benefits and Industrial Applications of Green Waste Valorization Technologies

Technology	Sustainability Benefit	Industrial Application	References
Anaerobic digestion	Renewable energy recovery	Biogas production	Yin et al. (2026)
Biorefinery	Maximum resource utilization	Bio-based chemicals	Pal et al. (2024)
Biochar production	Carbon sequestration	Soil amendment	Blasi et al. (2023)
Nutrient recovery	Reduced fertilizer demand	Agriculture	Pal et al. (2024)
Carbon materials	Waste minimization	Energy storage, adsorption	Maciel et al. (2023)
Waste-derived feedstocks	Circular material use	Food, ceramics, polymers	Oliveira Batista et al. (2023)

8. EMERGING TRENDS AND FUTURE PERSPECTIVES

New technologies are revolutionizing green chemistry–based waste valorization, with increased efficiency in process, resources recovery and industrial sustainability. Artificial intelligence (AI), as a tool of predictive analytics, automatic waste classification, process monitoring, and intelligent decision-making, has emerged as an important component in optimizing waste management systems. Machine learning and deep learning algorithms are used to improve the characterization of feedstocks, control of the process, and its efficiency and to minimize the use of resources and environmental impacts (Radwan & Khan, 2023; Singh et al., 2025). Smart biorefineries are another step forward towards sustainable use of waste, combining biotechnological, thermochemical and digital approaches to efficiently convert different waste streams into biofuels, chemicals, fertilizers and high-value materials simultaneously. Besides these developments, the integration of CCS with waste valorization plants is gaining relevance, as a way to reduce carbon emissions and to convert CO2 to useful chemicals and fuels, which contributes to the carbon neutral industrial production. Another promising direction is the development of green hydrogen from waste resources, in which biomass, organic waste and municipal waste are used as renewable raw materials for hydrogen production based on biological, thermochemical and electrochemical processes. It also has the potential to contribute to low carbon energy systems and to energy, water and carbon efficiency of integrated waste biorefineries. With the advancement of material science, new applications of material prepared from agricultural and industrial wastes, which can be used for energy storage, environmental purification, catalytic reaction, and other applications, have emerged. In addition to technological innovations, sound policy frameworks and scale-up of industries are important to drive up commercial adoption (Shahab et al., 2022; Fotovvatikhah et al., 2025). Regulations that support, financial incentives, a standardised sustainability assessment and public and private partnerships can enable technology transfer and investment and encourage circular economy. Research efforts should focus on optimizing processes with the integration of AI, scaling up green conversion technologies, developing resource-efficient biorefineries, and fostering interdisciplinary and cross-sectoral collaboration to enhance economic sustainability, environmental impact, and industrial application. All these developments highlight the key importance of green chemistry in developing sustainable waste valorization and resource recovery in the future circular bioeconomy systems.

9. CHALLENGES AND RESEARCH GAPS

Although considerable achievements have been made in green chemistry-based waste valorization, it is still not widely used in industries due to numerous challenges. Processing is affected by the feedstock heterogeneity due to differences in composition, moisture content, and contaminants of waste materials directly affecting conversion efficiency, product quality, and process consistency. Another important challenge is the maintenance of the catalyst performance and stability during prolonged operation, as the performance reduction, fouling and decreased selectivity may drive up the cost of operation and reduce the efficiency of resource recovery. In addition, efficient scaling up of process from laboratory to commercial scale demands better reactor design, process integration, and reliability of operation with no loss of environmental and economic efficiency. The significant capital investment, operating costs and market uncertainty over the supply of waste-derived products can be a deterrent to large-scale deployments. Further, there are regulatory and policy challenges, including the lack of harmonized waste management regulations, inadequate financial incentives, and no unified sustainability assessment frameworks, that constrain technology commercialization between regions. Further investigation should focus on the development of robust catalysts, consistent feedstock pre-processing methods, integrated biorefinery systems, advanced process optimizations and complete sustainability assessment. Also, increased collaboration between researchers, industries and policy makers will be key to speed up technology transfer, increase economic competitiveness, and facilitate transition towards a circular and resource efficient bioeconomy.

10. CONCLUSIONS

Green Chemistry is emerging as a game-changer in the field of sustainable waste valorization and resource recovery. Different waste streams can be converted to bioenergy, platform chemicals, biofertilizers, biochar or advanced carbon materials, and a variety of other value added products, using green catalytic systems, biocatalytic processes, hydrothermal conversion, electrochemical technologies and other advanced technologies. These technologies help reduce natural resource dependency and lower generation of waste, greenhouse gas emissions and environmental pollution, thereby enabling the shift from linear to circular bioeconomy. Although significant technological advances have been made, different kinds of challenges remain, such as the variability of the feedstock, the durability of the catalysts, the scalability of the process, the economics and the support from the regulation regarding the large-scale implementation of sustainable waste valorization systems. To overcome these challenges, researchers from multiple disciplines, technology innovation, supportive policy design, and academia, industry and government need to work together. Future developments of artificial intelligence, smart biorefineries, carbon utilization and production of renewable hydrogen will further enhance the process efficiency and industry sustainability. Overall, green chemistry offers a solid scientific base for achieving global goals through environmentally responsible and economically-worthy waste management solutions, while simultaneously offering a comprehensive scientific basis for waste as a valuable resource, for circular resource management, and for enhancing the competitiveness of industry.

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