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Recent Advances in Waste-to-Value Technologies for Sustainable Resource Recovery

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Abstract

The number and complexity of municipal, agricultural, industrial, plastic, electronic and organic wastes have increased, and there is a greater demand for resource-efficient alternatives to traditional disposal. This review examines recent advances in waste-to-value technologies and their role in sustainable resource recovery within a circular economy framework. It evaluates the recovery potential of major waste streams and compares thermochemical, biological, chemical, hybrid, and microbial electrochemical conversion pathways. Particular attention is given to the production of renewable energy, biofuels, biochemicals, recovered nutrients, biochar, functional carbon, and other value-added materials. The review also highlights the increasing use of artificial intelligence, machine learning, the Internet of Things, and digital twins for process monitoring, waste forecasting, automated sorting, predictive maintenance, and system optimization. Despite substantial technological progress, large-scale implementation remains constrained by feedstock heterogeneity, inadequate segregation, high capital requirements, limited infrastructure, regulatory uncertainty, and weak markets for recovered products. Sustainability therefore requires integrated assessment of environmental impacts, economic feasibility, technical performance, social acceptance, and institutional readiness. Global experiences further show that successful deployment depends on locally appropriate technologies, supportive policies, stakeholder participation, financing mechanisms, and market development. Waste-to-value systems generally have a high potential to decrease the reliance on landfill, strategic recovery, and decarbonisation in industry, and improve circular production, if complemented by technological innovation, appropriate governance and commercially viable implementation pathways.

Keywords- *waste valorization, resource recovery, circular economy, sustainable waste management, value-added products*

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1. INTRODUCTION

The volume and complexity of waste produced in the world have grown at a high rate due to the rapid growth of population, urbanization, industrial development and shifting consumption patterns. Lots of municipal, industrial, agricultural, plastic and electronic wastes are still piling up and exerting increasing stress on natural resources, environmental quality, and public health. The traditional waste management systems, in particular, landfilling and incineration, are becoming unsustainable due to resource depletion, greenhouse gas emissions, and ecosystem degradation. Thus, converting wastes to useful resources has become one of the most important measures of sustainable development and environmental protection (Abdel-Shafy & Mansour, 2018). Waste-to-value (WtV) is a concept that takes waste as a resource that can be recovered to produce energy, chemicals, fuels, nutrients and advanced materials using appropriate technologies. It encourages resource efficiency, material circularity and decreases reliance on virgin resources. The implementation and diffusion of circular economy principles have further sped up the utilization of industrial by-products and waste streams as economically valuable secondary resources, thus enhancing environmental sustainability and industrial competitiveness (Angstmann, 2025).

Waste valorization, in particular, has become significant in the agriculture industry where nutrients, organic amendments and bio-based products can enhance resource efficiency and decrease dependence on scarce natural resources. Waste recovery within agriculture production systems fosters sustainable agriculture, reduces disposal needs and boosts the circular bioeconomy by transforming biomass residues into valuable products (Haque et al., 2023). With increasing urbanization and economic growth, the volume of municipal solid waste (MSW) generated is also growing globally, posing significant problems for collection, processing and disposal facilities. The growing waste generation shows the demand for using new technologies for recovering valuable materials and energy, lessening the use of landfills, and minimising environmental pollution (Chen et al., 2020). Recent estimates indicate that the amount of MSW generation in the world might be significantly higher than previously assumed, thus reinforcing the need to improve waste management systems by increasing the integration of waste valorization and resource recovery, as well as by developing innovative technologies. The developments emphasize the need to shift the waste management paradigm from traditional disposal to sustainable waste-to-value approaches (Maalouf & Mavropoulos, 2023).

Due to its persistence and comparatively low recycling rate, plastic waste is one of the most critical environmental challenges. Much of the discarded plastic is still not being managed properly and is spilling into the terrestrial and marine environment, with detrimental effects on biodiversity and ecological balance. These challenges have driven a search for more advanced recycling and conversion technologies that can enable plastic waste to be converted into useful secondary material (secondary resource, SR) (Law et al., 2020). The food packaging industry is a significant contributor of plastic waste because they use a lot of single-use materials for food packaging. The valorization and recovery of post-consumer plastics through innovative recycling technologies is thus an important aspect of sustainable resource recovery and circular material management (Ncube et al., 2021). Electronic waste is also a waste stream that is quickly expanding with the advent of technology and product life cycles that are getting shorter. While e-waste may have recyclable components and contain valuable metals, the composition of e-waste and the presence of hazardous materials make recycling a complex process. Recovery technologies, therefore, need to be efficient to achieve the maximum material recovery with a minimum of environmental risk (Tansel, 2017). Despite technological advances, many developing countries still do not have proper waste collection systems and inadequate recycling systems, weak implementation, and limited investment. These obstacles undermine the action plan of resource recovery programs and impede the widespread implementation of sustainable waste-to-value programs (Ferronato & Torretta, 2019).

While there are several studies that focus on individual technologies for waste conversion and/or certain waste streams, there is limited literature summarizing recent developments in various waste-to-value technologies. Further, the fast progress of integrated conversion systems, digital process optimization and circular resource management requires a fresh review of the narrative, which is critical of technological advancement and its importance in sustainable resource recovery. Therefore, this review provides a comprehensive assessment of recent progress in waste-to-value technologies by discussing the prominent waste streams, emerging conversion technologies, value-added products, and sustainability implications of the technologies, and future directions for research and development that drive toward a circular and resource-efficient economy.

2. Waste Streams and Resource Recovery Potential

The success of a waste-to-value technology is highly reliant on the waste stream that it is applied to. Waste materials vary in their physical and chemical composition, moisture content, calorific value and contaminant composition, which affects the selection of the technology used for converting the waste and the quality of the product recovered. Therefore, comprehensive characterization of waste is crucial for achieving the maximum recovery efficiency, avoiding process limitations, and increasing the profitability of resource recovery systems (Li et al., 2024). Municipal solid waste is one of the most diverse waste streams, consisting of organics, plastics, paper, glass, metals, textiles and inerts. This diversity is a challenge for processing but also provides substantial opportunities for energy recovery, recovery of reusable materials and recovery of industrial feedstocks using integrated waste management solutions. ffective segregation and characterization improve valuable material recovery and conversion efficiency (Yadav & Shrotriya, 2024) due to effective segregation and characterization.

Mainly due to the abundance, renewability, and high amount of organic wastes, agricultural residues and biomass wastes have significant resource recovery potentials. Biological, thermochemical and chemical conversion technologies can be used to convert crop residues, forestry by-products, food processing waste and other lignocellulosic materials into biofuels, biochar, biochemicals, adsorbents and functional materials. The increasing importance of biomass valorization arises from its potential to be used as a substitute for fossil-derived resources, and to ensure sustainable development of the bioeconomy and low-carbon production systems (Zhou & Wang, 2020). Industrial waste streams are also valuable secondary resources with the presence of recoverable metals, minerals, polymers, solvents and specialty chemicals. The use of waste as raw material for producing valuable products has been achieved in an environmentally friendly way, thereby reducing waste generation, improving resource efficiency and minimizing environmental impacts in all industry sectors, thanks to the advances in green chemistry. These innovations serve to reinforce the sustainability of industries, and also to foster the circular use of production residues (Gutiérrez & Palos, 2023).

High carbon content and wide availability of plastic waste make it an increasingly important resource recovery target. Alongside the mechanical recycling of traditional methods, new polymer upcycling technologies also enable the recycling of waste plastics into higher value and higher performance materials. These approaches help to extend the life cycles of polymers, minimize the need for virgin raw materials from the petrochemical industry and play a major role in material circularity in today's manufacturing systems (Korley et al., 2021). The material characteristics alone are not enough to determine the recovery potential of waste streams. Apart from the suitability of the valorization pathways, other factors such as environmental performance, economic feasibility, energy efficiency, and impacts on the life cycle are also important. Integrated sustainability assessment frameworks offer a comprehensive basis for comparing different recovery technologies based on their technical, environmental and economic performance, which allows for informed decision-making for sustainable waste management, and resource use (Millward-Hopkins et al., 2018).

The variety of waste streams underscores the need for a variety of resource recovery solutions, rather than a one-size-fits-all approach. Combined, these approaches can helpto achieve higher recovery efficiencies, production of value-added products, and better integration of waste into the value creation process in the context of the circular economy, which will turn waste into a strategic resource for sustainable development. The principal waste streams, their properties, the most appropriate recovery methods and the most important value-added products of the waste streams have been summarised in Table 1.

Table 1. Major Waste Streams and Resource Recovery Potential

Waste stream	Key characteristics	Recovery pathway	Major products	References
Municipal solid waste	Heterogeneous mixed waste	Sorting, thermal and biological treatment	Energy, recyclables	Li et al. (2024); Yadav & Shrotriya (2024)
Agricultural biomass	Renewable lignocellulosic residues	Bioconversion, thermochemical conversion	Biofuels, biochar, biochemicals	Zhou & Wang (2020)
Industrial waste	Metals, minerals, solvents	Green chemical recovery	Secondary raw materials	Gutiérrez & Palos (2023)
Plastic waste	Carbon-rich polymers	Upcycling and chemical recycling	Polymers, fuels	Korley et al. (2021)
Diverse waste streams	Variable composition	Integrated recovery modelling	Optimized resource recovery	Millward-Hopkins et al. (2018)

3. Recent Advances in Waste-to-Value Technologies

With the current pace of technological development, the field of waste-to-value (WtV) systems is growing in number and scope, and is now capable of transforming a wide variety of waste materials into energy, fuels, chemicals, materials, and bio-based products. Recent advances in WtV technologies are increasingly focused on greater resource efficiency, reduced environmental impacts and enhanced process integration, all of which are key to the circular economy. The shift from conventional waste treatment to advanced resource recovery has led to the development of innovative conversion pathways that enable, for the most part, value extraction from diverse waste resources (Bazienė & Gargasas, 2025). Thermochemical conversion technologies have proven to be very promising for treating municipal, agricultural, industrial and plastic wastes. These processes, such as pyrolysis, gasification, hydrothermal treatment and combustion, can process different feedstocks with different compositions and generate syngas, bio-oil, biochar, and heat. Over time, the design of reactors, creation of new catalysts, and optimization of processes have improved the efficiency of conversion, selectivity of products, and energy recovery, making thermochemical technologies even more appealing for sustainable waste management (Durak, 2023). The thermochemical methods include pyrolysis, which has attracted specific attention to convert plastic wastes into liquid fuels, chemical feedstocks, waxes and carbon-rich materials in an oxygen-limited environment. The progress achieved in recent times in catalytic pyrolysis, reactor design and product upgrading has enabled the enhancement of the quality of the fuels and the increase in the yield of valuable hydrocarbons. These developments mean both reducing plastic waste and substituting fossil-based resources in industrial production processes (Papari et al., 2021).

The biological conversion technologies have also made significant progress with enhanced microbial processes that can convert organic wastes into renewable products. The anaerobic fermentation process has now advanced beyond the production of biogas to allow the production of biohydrogen, volatile fatty acids, organic acids and other valuable biochemicals. Conversion efficiency has been enhanced, and a wide spectrum of recoverable products from organic waste streams has been broadened through process optimisation, engineering of microbial communities and pretreatment of substrates (Litti et al., 2024). Agricultural biomass is emerging as an ever more promising raw material for bio-based chemicals, fertilizers, functional materials and renewable energy. There has been recent interest in maximizing the recovery of nutrients and nutrient cycles in a circular manner from biomass, which not only diminishes the amount of agricultural waste but also optimizes resource utilization and helps ensure the sustainability of food production systems (Ren et al., 2022). Bioconversion of organic waste has continued to be advanced, with the development of microbial biotechnology, enzyme engineering and integrated biorefineries. This progress allows the production of biofuels, biopolymers, enzymes, organic acids, etc., of commercial value from food waste, sewage sludge, and agricultural residues via efficient production processes. Including biological systems in such an integrated manner can enhance the utilization of resources and reduce the production of wastes and greenhouse gases (Reddy et al., 2026).

New plastic valorization technologies are now available that go beyond traditional recycling processes, such as chemical depolymerization, catalytic upgrading, purification using solvents and hybrid conversion systems. These technologies are able to extract a higher-value product from a mixed and/or contaminated plastic stream that is otherwise hard to mechanically recycle. Their adoption helps to enhance material circularity and better utilize polymer resources (Udourioh et al., 2025). To recover as much biomass as possible from various kinds of feedstocks, multi-technology platforms are being developed. The thermochemical, biological, and chemical conversion pathways can be integrated into a single processing framework to achieve more flexibility and higher resource utilization and economic performance by matching waste fractions with the most appropriate conversion technologies (Al-Ansari et al., 2020). A recent development is the development of microbial electrochemical technologies that combine microbiology and electrochemistry to recover energy, valuable chemicals, clean water, and critical resources from waste streams. Such systems have great potential to facilitate sustainable water, material and energy cycles and provide an environmentally friendly alternative to standard treatment techniques (Schröder et al., 2026).

Recent innovations represent how waste-to-value technologies are advancing from stand-alone treatment solutions to integrated resource recovery solution platforms that can produce multiple value-added products. Waste valorization will continue to play a key role in the future of sustainable industrial development and circular resource management, due to the continued technological integration, optimization and innovation. Table 2 shows the main waste-to-value technologies recently developed and their main feedstock, product and technological benefits, and points to the diversification of modern resource recovery systems.

Table 2. Recent Waste-to-Value Technologies and Major Outputs

Technology	Feedstock	Major products	Key advantage	References
Thermochemical conversion	Mixed solid waste, biomass	Syngas, bio-oil, biochar	High energy recovery	Durak (2023)
Catalytic pyrolysis	Plastic waste	Liquid fuels, hydrocarbons	Improved product quality	Papari et al. (2021)
Anaerobic fermentation	Organic waste	Biogas, volatile fatty acids	Renewable biochemical production	Litti et al. (2024)
Bioconversion	Agricultural and food waste	Biofuels, enzymes, biopolymers	High-value bioproducts	Reddy et al. (2026)
Microbial electrochemical technology	Wastewater, sludge	Energy, chemicals, clean water	Simultaneous resource recovery	Schröder et al. (2026)

4. Value-Added Products and Industrial Applications

However, with the recent developments of waste-to-value technologies, the idea of waste disposal has been replaced by the generation of high-value products, which will help in achieving the objective of sustainability and resource efficiency in the industry. The utilization of organic, agricultural, municipal and industrial waste into commercially viable products not only reduces the environmental impacts but also opens new avenues for economic opportunities in the circular economy. A broad range of conversion technologies has been developed and broadened the range of products that can be recovered from waste, which can be a reliable source of renewable energy, bio-based materials, functional chemicals and industrial feedstocks (Popp et al., 2021). One of the biggest results of waste valorization systems is renewable energy. Organic residues and biomass wastes are more and more processed to generate power, heat, hydrogen, syngas and liquid biofuels by thermochemical and biological methods. Waste-derived energy is a key part of sustainable energy transitions, as these renewable energy carriers offer a way to decrease reliance on fossil fuels, enhance energy security, and support decarbonization plans (Østergaard et al., 2022).

Co-pyrolysis has been shown to be a promising emerging energy recovery route for mixed biomass feedstocks because it has the ability to produce a wide range of valuable products. Cogeneration of the three products (H2-rich syngas, bio-oil, and biochar) makes better use of resources and increases process efficiency and economic feasibility. These integrated conversion strategies not only maximize the value added from the different agricultural residues and wastes, but they also reduce the number of residues produced (Fassatoui et al., 2025). Biogas has emerged as one of the most proven waste-to-value technologies for the conversion of organic waste streams, including food waste from household waste, agricultural residues and wastewater sludge. In addition to the generation of renewable methane, modern biogas systems offer a positive energy balance, reduced greenhouse gas emissions and increased resource efficiency over traditional waste management. Hence, these systems are contributing significantly to renewable energy generation and sustainable waste management goals (Feiz et al., 2022).

By-products from the biological conversion processes are also of great industrial interest. The digestates and biogases generated during digestion have become a focus as a new source of recoverable nutrients like nitrogen and phosphorus that can be utilized in agriculture as fertilizers. The use of advanced nutrient recovery technologies leads to better fertilizer production, lower nutrient losses, and closed-loop resource management, which positively affects sustainable agriculture (Zielińska & Bułkowska, 2024). Apart from energy products, wastes are also used for the production of advanced carbon materials that have wide industrial applications, derived from wastes as biomass. Functional carbon, obtained from biomass has desirable physicochemical properties which make it useful in energy storage devices, water purification systems, catalysts, environmental remediation, sensors, and composite materials. These are high-value products and the potential for commercialization has increased due to ongoing advances in material engineering, alongside the economic viability of biomass valorization (He et al., 2023).

As the diversity of value-added products shows, waste-to-value technologies have matured to multi-functional systems of resource recovery that can simultaneously yield renewable energy, industrial materials and agricultural inputs. Technological innovations and the implementation of valorization processes will enhance the role of waste valorization in sustainable industrial development, in the development of resource security and in the circular economy, through the expansion of commercialization possibilities. Figure 1 shows the conversion of key waste streams into renewable energy, bio-based products and advanced materials, respectively, using biological and thermochemical conversion technologies, contributing to industrial sustainability and the circular economy.

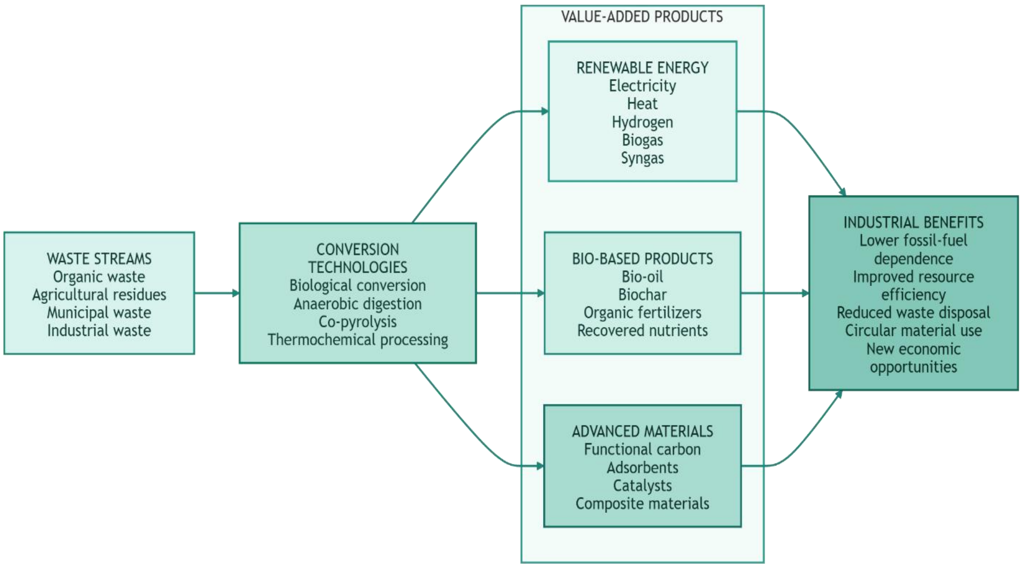

Figure 1. Waste-to-value conversion pathways for generating value-added products and industrial benefits

5. Sustainability Assessment of Waste-to-Value Systems

The sustainability assessment is a key element when deciding if waste-to-value systems can be economically, socially and environmentally successful over the long-term, in addition to the effective treatment of waste. The conversion efficiency is not the only metric that can be used to measure the success of a valorization technology, as other factors such as resource use, energy demand, emissions, operating costs, and product quality will also affect the overall sustainability of the valorization technology. The current trend is therefore to assess waste recovery systems using a broad spectrum of performance indicators, such that the increased value from the recovery of a waste resource is not just about moving environmental burdens. Comprehensive assessment frameworks are therefore increasingly used to evaluate waste recovery systems across many performance indicators so that recovery of a waste resource adds value to sustainable development rather than merely crowds out environmental burdens. Common measures of environmental sustainability include greenhouse gas emissions, displacement of fossil resources, energy efficiency, water usage, and waste reduction. Organic waste-to-energy technologies have been proven to be promising in diverting waste away from landfill and producing renewable energy and reducing emissions. Still, their environmental performance relies on the characteristics of the feedstock, the degree of conversion, the level of emission control, and management of the process residues, thus making it imperative to consider the full life cycle of waste valorization systems (Zueva et al., 2024).

Many tools exist to assess the environmental footprint of waste-derived products and to compare them to traditional fossil-fuel-based products, and one of the most popular is life cycle assessment (LCA). For instance, sustainable methanol production from sewage sludge is an example of how waste materials can be used as alternative carbon sources and mitigate the resource concerns of using virgin materials. However, the sustainability of such processes relies on the energy resources needed upstream, on the transportation, on the need for pre-processing and recycling, and on the need for end-of-pipe use downstream, which makes it important to test processes by life cycle evaluation to assess what environmental hot spots exist in the process and what opportunities there are to improve it (Kexel et al., 2025). Economic sustainability is also of great importance as it is proven that the sustainability of waste-to-value technologies is dependent on the investment costs, the operational efficiency, the value of the product (market value), the availability of the feedstock and the policy support. The economic performance of agro-livestock waste management systems is heavily affected by uncertainties in the biomass supply, logistics in getting to and from the facilities and the location of the facilities. These variables can be optimized by sustainable network design approaches, which can improve resource use, minimize operational risks, and make bioenergy production systems more economically viable (Zarrinpoor, 2024). In addition to environmental and economic aspects, social and institutional issues play a crucial role in the success of waste-to-value technologies. For resource recovery systems to be adopted at scale, they must be effective, involve stakeholders, be accepted by the public, be technically capable, and be ready for the market. To achieve such transitions, however, governance must enable it; there needs to be investments in infrastructure, and policy needs to foster innovation, circular resource management and commercialization of recovered products as well as technological advancements (Morone et al., 2020).

Maximizing resource recovery is not enough for the sustainability of Waste-to-Value systems, and balancing the three pillars of environmental protection, economic feasibility and social acceptance is key. Combining LCA, techno-economic assessment and institutional factors is a holistic approach to choose valorization pathways that are scalable and resilient in order to embrace the transition towards a circular and resource-efficient economy. Table 3 provides an overview of the key dimensions of sustainability assessment applied to waste-to-value systems, and indicates that the selection of technology should take into account environmental, technical, economic and social dimensions.

Table 3. Sustainability Assessment Indicators for Waste-to-Value Systems

Sustainability aspect	Evaluation indicator	Assessment approach	Primary objective	References
Environmental	Emissions, energy use	Life Cycle Assessment	Minimize environmental impacts	Zueva et al. (2024)
Technical	Process efficiency, product yield	Process simulation	Improve system performance	Liu et al. (2022)
Economic	Investment and operating costs	Techno-economic analysis	Assess financial feasibility	Zarrinpoor (2024)
Life-cycle performance	Energy use and environmental burdens	Life-cycle assessment	Identify process hotspots	Kexel et al. (2025)
Social and institutional	Policy, stakeholder acceptance	Sustainability transition assessment	Support large-scale implementation	Morone et al. (2020)

6. Emerging Innovations, Challenges, and Future Directions

Digitalization, intelligent process control and integrated resource recovery systems are becoming more and more important in driving the evolution of waste-to-value technologies, enabling better operational efficiency and environmental performance. New technologies are changing the way waste is traditionally managed to make it data-driven and automated, optimising waste collection, segregation, processing and product recovery. These are some of the advances that help achieve the goals of the circular economy by improving resource use in the waste management chain while minimizing operating costs and environmental impacts (Tawo & Mbamalu, 2025). Artificial intelligence (AI) is a major enabler in the modern era of waste management, enhancing decision-making, predictive analysis and process optimization. AI models can predict the amount of waste, plan the most efficient collection routes, automatically classify waste, keep track of the performance of waste management facilities and increase the efficiency of waste resource recovery by analysing data in real time. These can facilitate proactive and effective waste management systems, sustainable urban development and circular resource utilization (Fang et al., 2023). Intelligent waste management is further enhanced by machine learning algorithms, which can categorize waste, forecast equipment issues, fine-tune recycling processes, and aid AI-powered sorting systems. The implementation of modern computing algorithms can be combined with sensor technologies for more precise and faster waste processing and help increase recycling rates and operational efficiencies in resource recovery facilities (Gupta et al., 2019).

The Internet of Things (IoT), Artificial Intelligence and Digital Twin technologies are a major step forward for smart waste management. Low-cost digital twins represent a virtual inference of waste management infrastructure to facilitate continuous monitoring, simulation and optimization of system performance. Such technologies enable better operational planning, resource utilization, predictive maintenance, and enhanced service efficiency, especially in smart city settings where real-time decision-making is crucial (Shah et al., 2025). There is also technological advancement in using hybrid waste conversion systems using complementary processing techniques for higher resource recovery. By combining anaerobic digestion with gasification, organic wastes can be used much more efficiently, as both biological energy and thermochemical energy products can be recovered from the same feedstock material. The overall energy efficiency, less process residues, and more production of renewable fuels are enhanced with such hybrid systems compared to standalone conversion technologies (Inayat et al., 2025). Even with these technological advances, there are still a number of obstacles to the deeper penetration of waste-to-value systems. A few key challenges to overcome for commercialization are feedstock heterogeneity, inconsistent waste segregation, high capital costs, technological complexity, regulatory uncertainty, low number of plant facilities, and limited market demand for the recovered products. To overcome these challenges, technological innovation and policy support, investment in infrastructure and inter-governmental collaboration between research institutions, industries, and government are required. The new digital technologies, such as artificial intelligence, machine learning, IoT, digital twins and hybrid conversion systems, enable the intelligent execution of waste management tasks, and solving implementation problems is crucial to ensure the efficient recovery of resources and sustainable industrial development, as shown in Figure 2.

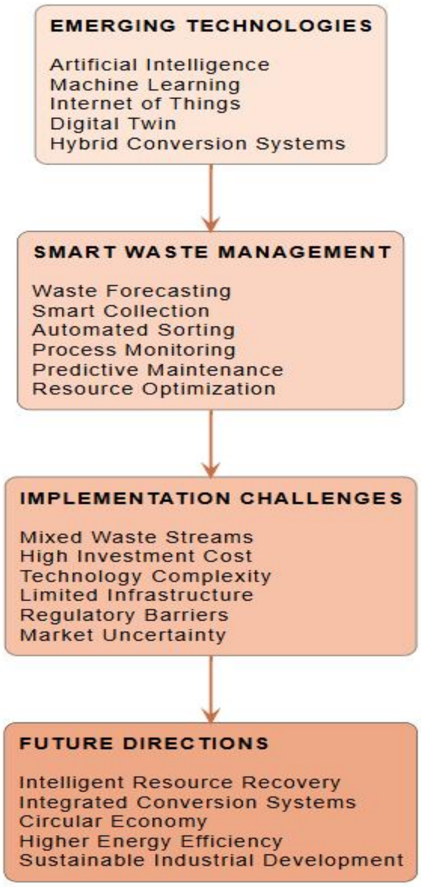

Figure 2. Emerging digital innovations, implementation challenges, and future directions for intelligent waste-to-value systems

Future research is needed to develop both a scalable and cost-effective, integrated waste valorization system that can process a variety of waste streams and reduce environmental impacts. The adoption of intelligent resource recovery systems is anticipated to accelerate with increased focus on various aspects of intelligence such as the use of artificial intelligence, digital twins, hybrid conversion technologies, automation, and circular economy principles. The further development and transfer of interdisciplinary research and technology will play a key role in bringing innovations developed at the lab scale to commercial use that helps with sustainable industrial development and global resource security. The promise of waste-to-value technologies is in combining digital intelligence with sophisticated conversion technologies to develop adaptive, efficient, and circular resource recovery systems. Technical, economic and institutional barriers will be key in achieving widespread implementation and maximizing the contribution of waste valorization to sustainable development.

7. Global Case Studies and Policy Perspectives

The adoption of waste-to-value technologies in practice around the world highlights the importance of both technological innovation and an enabling policy environment, infrastructure, institutional capacity, and market readiness for resource recovery to be successful. The results from various regions indicate that waste valorization programs need to be tailored to the specific waste characteristics, socio-economic context and regulation in order to be sustainable over time. These region-specific solutions have helped to accelerate the implementation of circular economy principles and enhance the use of waste resources in the region (Elizabeth et al., 2025). To tackle the rising volume of waste and enhance energy access, environmental protection, and economic development, several countries in the Global South have adopted waste-to-value projects. Biogas projects based on agricultural residues, food waste and organic municipal waste have shown that decentralized recovery systems can supply renewable energy, and simultaneously decrease waste disposal, as well as sustain the livelihoods of the rural population. The relevance of community involvement, technical training, guaranteed financing and efficient operational management to make waste valorization projects a success in the long-term is also underlined in these case studies (Somorin et al., 2025). The integrated resource recovery in urban wastewater management is increasingly being approached with advanced sewage sludge valorization. Internet of Things (IoT) enabled monitoring, bioleaching and anaerobic digestion will help to further maximize nutrient recovery, renewable energy generation and valuable metal recovery, in addition to optimizing the process continuously. These multi-functional systems demonstrate the potential of digital technologies to make wastewater treatment plants a sustainable resource recovery system that can help create sustainable circular urban infrastructure (Giwa et al., 2025).

The ability to turn specific waste streams into high-value commercial products is also evidenced in case studies across different sectors. Fish processing wastes are generally considered as waste disposal problems, but have been identified as one of the significant sources of omega-3 fatty acids for the food supplement and nutraceutical industries. Besides the energy value of waste products, the valorization of marine waste towards the production of bioactive products is also expanding the possibilities of waste valorization, as it is a way to decrease the environmental pollution caused by marine waste while also producing products of high economic value (Alfio et al., 2021). A number of policy and technological advances have also led to the transformation of carbon rich solid waste to advanced materials with environmental applications. The creation of composites of graphene from waste to capture the carbon dioxide is an innovative approach for circular economy that tackles not only waste management but also climate change mitigation. The prospect of high-value waste-derived materials in future low-carbon industrial systems is increasing, but commercialization is still in early stages, as these approaches show (Samuel, 2025).

The experiences of the reviewed countries in the world show that the key to effective WtV implementation is both policy support and technological development. Therefore, the key elements of successful case studies have been highlighted and defined as the use of suitable technologies, enabling regulations, engagement and commitment of stakeholders, investment of funds and market development to optimize resource recovery and achieve circular economy goals. To scale up sustainable waste valorization practices in various geographic and economic environments, it would be crucial to improve these enabling conditions.

8. Conclusion

Waste-to-value technologies have evolved from single disposal-based application to multi-faceted resource recovery systems that generate renewable energy, fuels, nutrients, chemicals and advanced material solutions. This review demonstrates pathway suitability based on the characteristics of waste, process efficiency, product quality, and things that happen locally. In addition to thermochemical processes, there are alternative technologies including biological, chemical and microbial electrochemical processes and hybrid processes that can be used, with hybrid processes providing the most flexibility and product recovery. Technical performance is not sufficient, though, for sustainability. Life cycle impacts, capital and operating costs, social acceptance, infrastructure, regulatory support, and market demand must be considered in conjunction. Digital technologies such as artificial intelligence, IoT, machine learning, and digital twins will further enhance process monitoring, automation, forecasting and resource optimization. However, there are significant problems of feedstock diversity, ineffective segregation systems, high start-up costs, and small market scale. Scalable technologies, supportive policy instruments, increased public–private partnership and locally adapted implementation models will play a critical role in future progress. In general, waste valorisation can play a significant role in the implementation of the circular economy, on resource security, on the decarbonization of industrial processes, and on sustainable waste management, provided that technological innovations are in line with environmental, economic and institutional interests.

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