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https://doi.org/10.1590/SciELOPreprints.16654

Submitted on: 2026-06-22
Posted on: 2026-09-16 (version 1)
(YYYY-MM-DD)

Declaration

Peer review status: This is a non-peer-reviewed preprint submitted to SciELO Preprints.

A version of the material presented in this manuscript is currently under consideration for publication as a book chapter.

Solid Waste Valorization: Concepts, Principles, Valorization Techniques, and Integrated Waste Management

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Abstract

Waste mismanagement challenges sustainability and harms the environment and public health – it contributes to water, soil, and air pollution. In this context, the waste valorization perspective views undesired streams as potential resources for protecting natural resources, generating wealth, preventing depletion, and reducing the negative externalities associated with improper disposal. This review introduces the main techniques for valorizing a broad spectrum of wastes, including recycling, bioconversion (e.g., composting and anaerobic digestion), and thermochemical methods (e.g., pyrolysis and gasification). The integration of waste valorization techniques is briefly discussed. The implementation of the waste valorization technique primarily depends on the waste characteristics and the process's technical, economic, and operational feasibility. The integration of multiple valorization techniques will not always boost resource recovery and energy efficiency. Besides, there is no one-size-fits-all management strategy, and the best option should be assessed on a case-by-case basis. Lack of infrastructure, incentives, or a legal framework to support recovery methods can hamper the full promotion of waste valorization and resource utilization, especially in developing economies. Technological development in the waste sector and digital transformation are still required to prompt the recovery of resources from waste streams.

Keywords: bioconversion; circular bioeconomy; municipal solid waste; recycling; resource recovery; waste treatment.

1.1 Introduction

Due to rising solid waste management costs, increasing product prices, and changing consumption patterns, the recovery of valuable, low-cost products, such as chemicals, energy, and fertilizers, has gained increasing attention (Malinauskaite et al., 2017). In this context, waste valorization has emerged as an alternative to the conventional waste management model, which involves the disposal of post-consumer materials in landfills and/or incineration (Cobo et al., 2018). Waste recovery is predicated on the principles of the circular economy, in which waste is returned to the production cycle as raw material for producing new materials (Cobo et al., 2018; Kanani et al., 2020). Herein, the term "re-emerged" is intended to reinforce that the principles of waste valorization are not a modern approach and have been practiced by societies for thousands of years. Ancient civilizations prioritized the repair, reuse, and recycling of materials, driven by the scarcity and high cost of feedstocks. Composting and the agricultural repurposing of urban excreta were common practices in ancient China and early farming communities (Barles, 2015).

The recovery of waste (valorization waste) offers numerous advantages, including a reduction in the consumption of natural resources, a decrease in the amount of waste disposed of, a decrease in the cost of final disposal, the creation of employment opportunities and income, the development of new waste recovery technologies, the fostering of environmental awareness in a society that learns to sort waste, a reduction in environmental impact, reduction risk of spreading infections, aesthetic concerns, a decrease in greenhouse gas emissions, and the mitigation of the impacts of climate change by replacing virgin raw materials and fossil fuels (Ambaye et al., 2023; Cobo et al., 2018; Prajapati et al., 2021). However, despite several benefits, the feasibility of implementing solid waste valorization technologies is intrinsically linked to overcoming economic, operational, social, and legal barriers (Ambaye et al., 2023; Makan et al., 2025).

Waste valorization is part of solid waste management policies in most countries, which adopt a waste management hierarchy. First is waste prevention, second is waste reuse, third is recycling, and fourth is waste recovery and/or waste-to-energy conversion (Ambaye et al., 2023; Cobo et al., 2018). Once all possibilities for transforming waste into resources have been exhausted, final disposal must be carried out appropriately. The waste hierarchy indicates that priority should be given to actions aimed at preventing waste generation; therefore, not generating waste is more important than treating it. At the same time, approaches that maximize resource recovery and minimize the need for final disposal should be prioritized in solid waste management. Public policies, economic incentives and sanctions, and technological innovations play a fundamental role in promoting waste recovery in a country (Ambaye et al., 2023; Makan et al., 2025; Rashad et al., 2026).

This chapter introduces the importance of waste valorization and the conceptual foundations of the main technologies available for recovering resources from solid waste. It then reviews the main waste recovery processes, categorized as follows: physicochemical processes (recycling, solidification/stabilization); bioconversion (composting, anaerobic digestion, and landfarming); thermochemical treatments (gasification and pyrolysis); and resource recovery based on integrated waste valorization systems and landfill mining. Prospects for integrated waste valorization are summarised.

1.2 Waste: Sources and Characteristics

1.2.1 Sources

It is imperative to comprehend the origins and attributes of solid waste when formulating waste management programs. This fundamental understanding enables the formulation of strategies for waste recovery, the development of minimization programs, the implementation of regular and selective collection projects, the determination of the most suitable modes of transport, and the design of transfer facilities and adequate final disposal sites (Tchobanoglous et al., 2003).

The genesis of solid waste in a community is typically associated with land use and location (Tchobanoglous et al., 2003). Consequently, waste can be classified by origin into the following categories, as shown in Table 1.

Table 1 – Classification of solid waste based on its sources (Barros, 2012; Tchobanoglous et al., 2003).

Waste type	Description	Examples
Household waste	This term is derived from the concept of daily life in residential settings.	Food waste, papers, newspapers, magazines, cans, glass, plastics, yard waste, and toilet paper, among others.
Public waste	Waste originating from municipal cleaning services. It includes street sweeping, beach cleaning, maintenance of open-air markets, alleys, squares, and parks.	Papers, packaging plastics, leaves, twigs, food, dust, sand, soil, and dirty paper.
Municipal solid waste	It includes household and public waste.	Paper, plastic, cardboard, glass, metals, wood, rubber, textiles, and leather. It may contain potentially hazardous materials, such as paints, solvents, batteries, healthcare waste, insecticides, lubricants, fluorescent lamps, and electronic waste (e-waste).
Commercial waste	Solid waste is generated in commercial and service establishments. Such establishments include, but are not limited to, shopping malls, stores, restaurants, supermarkets, and offices.	Paper, plastic, and other packaging materials are examples of commercial waste.

Healthcare waste	Waste originating from healthcare facilities, such as hospitals, clinics, laboratories, and pharmacies.	Needles, syringes, human tissue remnants, organs, pharmaceuticals, hormones, expired medications, and equipment effluents.
Industrial waste	Waste originating from production processes and industrial facilities.	Oils, acidic waste, organic waste, industrial sludge, ferrous and non-ferrous metals, glass, plastic, and toxic waste. Most of this category is hazardous.
Agricultural waste	Residues of various agricultural and livestock activities.	Fertilizers, pesticides, and crop biomasses.
Construction waste	It is generated from the construction and demolition of residential and commercial buildings.	Mixture of inert materials, stones, concrete, wood, ceramic, wires, soil, and broken glass.
Electrical and Electronic waste (e-waste)	Discarded electrical and electronic equipment, as well as their components, subcomponents, and consumables, which rely on electrical current or electromagnetic fields to function and have reached the end of their useful life or have been discarded by the user.	Computers, printers, cell phones, tablets, televisions, household appliances, cables, circuit boards, and batteries.
Mining waste	Waste that is produced during the exploration, extraction, or processing of minerals.	Removed rocks, processing tailings from bauxite, copper, iron, gold, mineral slurries or pulps, metallurgical slag, and chemical waste from mineral processing.
Sanitation services waste	Waste generated by sanitation services.	Residuals and sludge from sewage and water treatment facilities.

Recognizing the sources of solid waste facilitates the implementation of source-reduction strategies. The presence of hazardous, potentially valuable materials in some waste streams underscores the importance of properly identifying and segregating waste, as different fractions require selective collection, treatment, and environmentally sound disposal to reduce risks to public health and the environment (Barros, 2012; Tchobanoglous et al., 2003).

The implementation of programs aimed at reducing waste generation, as well as initiatives focused on community waste management strategies, has been shown to substantially reduce waste destined for final disposal (Tchobanoglous et al., 2003).

It is also important to note that municipal solid waste management is generally the responsibility of municipal administrations. The management of waste generated by industrial, healthcare, and sanitation facilities, as well as other activities, is the responsibility of the entities that produce it. However, the government may establish guidelines for its management through its policies, including waste from health services, civil construction, public services, and electrical and electronic waste (Barros, 2012, Monteiro et al., 2001; Tchobanoglous et al., 2003).

1.2.2 Characteristics of solid waste

Solid waste exhibits a combination of physical, chemical, and biological characteristics. A comprehensive understanding of these properties is imperative for implementing an integrated waste management system, including waste valorization strategies (Tchobanoglous et al., 2003). However, obtaining representative waste samples is challenging due to the heterogeneity of the solid waste (van Elk et al., 2014).

Table 2 summarizes the main waste properties and provides brief descriptions of their relevance to the waste management system.

Table 2. Waste properties and their relevance for waste management (Barros, 2012, Boscov, 2007; Monteiro et al., 2001, Sowers, 1973, Tchobanoglous et al., 2003).

Category	Waste characteristic	Definition	Unit	Relevance for waste management
Physical properties	**Specific mass**	The mass of a given material relative to its volume. The specific mass of the waste material may vary depending on whether it is compacted or loose.	Mass per volume (kg/m^3, g/cm^3)	Data on specific mass are important for sizing the transportation system and waste collectors, and for quantifying the total waste weight and volume to be managed.
	Moisture content	The water content of the waste matrix. It is typically expressed as a percentage of its total (wet) mass or on a dry mass basis.	Percentage (%)	The moisture content of waste plays a pivotal role in biodegradation, acting as both an inhibitor and a facilitator. This dual functionality is particularly evident in both aerobic and anaerobic degradation processes. It

				directly influences leachate production and the design of the leachate collection system in disposal facilities.
	Field capacity	It is the amount of moisture a waste sample can retain under the force of gravity.	Percentage (%)	Field capacity is important for determining leachate formation in landfills.
	Gravimetric composition	Reflects the percentage values of each component (e.g., paper, plastic, glass, etc.) in a waste sample, relative to its total mass.	Percentage (%)	This characteristic is fundamental for determining waste management strategies. Enables the formulation of methods for waste treatment and valorization.
	Compressibility	It is the reduction in volume that the waste mass may undergo over time and under the action of load pressure. Compressibility results from mechanical processes (self-weight and loading of the waste layers) and from biodegradation of the organic matter present.	Length (e.g., mm, m, etc.)	It is an important characteristic for estimating the usefullife of the landfills, designing and implementing surface and leachate drainage systems, assessing landfill stability, and evaluating the performance of final cover systems.
Chemical properties	**Calorific value**	The amount of heat generated when the waste is subjected to a thermal process.	Energy per unit mass (MJ/kg, J/kg, etc.)	It is a pivotal parameter for evaluating and selecting thermal treatment technologies for solid waste.
	Carbon-to-nitrogen ratio (C/N)	Ratio of carbon to nitrogen content.	a.u	It may indicate the degree of decomposition of organic fraction waste during treatment processes,

				particularly biological processes. There are optimal C/N ranges that favor biological activity at different stages of treatment.
	Potential of hydrogen ions (pH)	It is a measurement of acidity or alkalinity in a substance. Waste materials are typically classified as acidic (pH < 7), neutral (pH ≈ 7), or alkaline (pH> 7).	a.u	This is a fundamental parameter for microbiological activity, as different groups of microorganisms have optimal pH ranges for growth. Furthermore, pH fluctuations are observed throughout the various stages of biological processes, including composting and anaerobic digestion, thereby reflecting the biochemical transformations occurring within the system.
Biological properties	**Biodegradability**	Biodegradability refers to the ability of organic waste to be decomposed by microorganisms.	–	Determines the efficiency of biological treatment processes.
	Microbial activity	Indicates the presence and intensity of microorganisms acting on the waste.	–	Controls the degradation rate and waste stabilization.

a.u = Adimensional unit

The characteristics of waste vary depending on social, economic, cultural, geographic, and climatic factors. These factors also differentiate communities from one another and cities themselves (Monteiro, et al., 2001).

Radioactive waste is generated throughout the nuclear fuel cycle—the sequence of activities associated with the operation of nuclear power reactors, beginning with uranium ore mining and continuing through the final disposal of the radioactive waste inevitably produced by these systems. The release of radioactive waste into the environment can result in severe consequences, including immediate fatalities, cancer, and genetic mutations on a catastrophic scale. Responsibility for managing these wastes lies not with municipal authorities but with specific agencies that report directly to each country's central government, with a clear separation between the implementing body and the regulatory authority (Beers, 1979).

1.3 Concepts and Principles of Waste Valorization

Waste valorization (WV) refers to any strategy that involves reuse, recycling, recovery of materials and energy from solid residues in lieu of disposal and landfilling (Kanani et al., 2020). This is a strategic approach that may reduce pressure on natural resources and help meet energy demands. Transforming solid waste into value-added products is a key strategy for achieving sustainable development goals across multiple sectors, such as industrial, municipal waste management, commercial, and agricultural activities (Aït-Kaddour et al., 2024; Puntillo, 2023).

The WV approach helps reduce waste pollution and create high-value-added products from waste streams. It is important to note that the WV concept includes minimizing residues through improved resource efficiency and consumption practices, as well as energy capture and production from waste, which provide an alternative for transitioning to a more sustainable energy matrix (Kumar & Samadder, 2017).

Figure 1 illustrates the principles of the solid waste management hierarchy to achieve a circular economy within the waste management chain. To this end, coordinated implementation across all hierarchical levels should be fostered, rather than isolated interventions at single stages (Sharma et al., 2026).

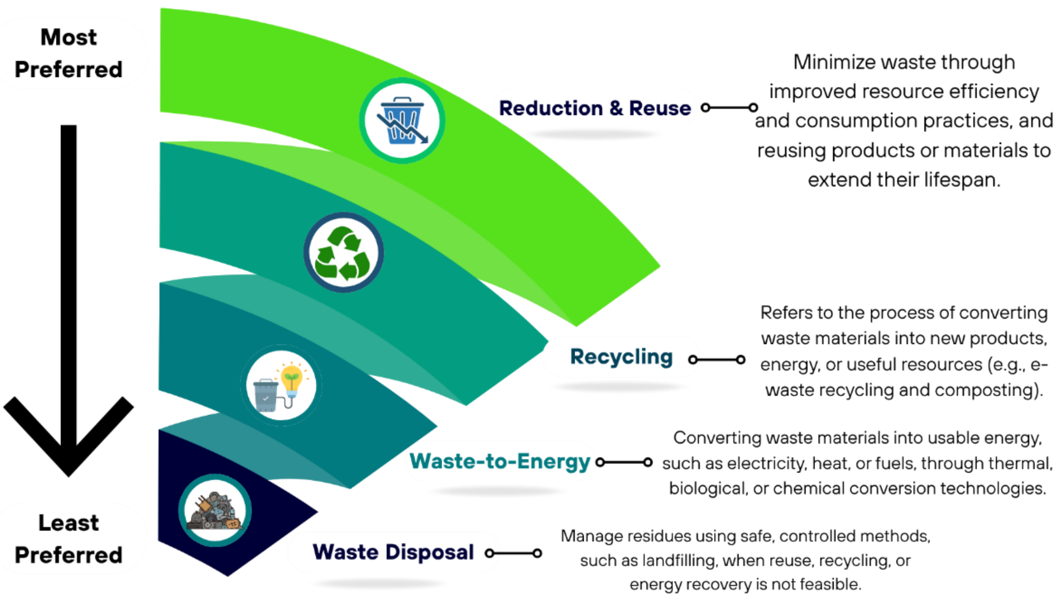

Figure 1. Solid waste management hierarchy. Based on (Sharma et al., 2026).

From waste reduction at the source and reuse to waste disposal of residues that cannot be managed by reuse, recycling (e.g., physicochemical recycling and composting), or energy recovery strategies (e.g., anaerobic digestion and thermochemical conversion), the WV perspective views undesired streams as potential resources. In the following sections, methods and integrated techniques are introduced and discussed to give the reader an overview of the main technologies for waste valorization.

1.4 Valorization Techniques and Integrated Approaches

1.4.1 Physico-chemical Processes

1.4.1.1 Recycling

Recycling is the process of collecting and reintegrating unwanted materials or energy into the production system. Thus, the recycling concept includes both recovered materials and energy production (energy recycling) (Coelho et al., 2011).

Recyclable products include glass, paper, cardboard, metal, plastic, tires, textiles, batteries, and electronics, which come from diverse waste sources, such as industrial activities, municipal solid waste, and agroindustries (Peng et al., 2025).

Recycling can be categorized into two groups: closed-loop and open-loop. Closed-loop recycling refers to a production system in which the waste or by-product of a process is reused to produce the same product or a similar component, theoretically allowing repeated cycles without the need for virgin materials. Open-loop recycling occurs when a material from one product is recycled into a different product, typically involving post-consumer materials and often different products and manufacturers (Coelho et al., 2011).

Besides, the International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) have standardized the classification of recycling processes into four categories. Mwanza (2021) has summarized each of them, as described in Table 3.

Table 3. Recycling processes, their advantages and disadvantages. (Mwanza, 2021).

Recycling type	Description	Advantages	Disadvantages
Primary	Direct reintroduction of pre-consumer scrap/residues into the extrusion cycle (Closed-loop)	Simple and low-cost; highly energy- and resource-efficient.	Requires a single, pure waste source; limited number of possible cycles
Secondary (Mechanical)	Physical processing (sorting, washing,	Most economical and ecological option; widely	Potential for polymer degradation; difficult to process contaminated

	grinding) to create substitutes for virgin polymers	used for commercial products	or complex wastes.
Tertiary (Chemical)	Chemical breakdown of polymer chains into small molecules for fuels or new polymers	Recovers high rates of monomers; suitable for food-grade packaging	High operational costs; requires harsh conditions (high temperature/pressure); can be slow
Quaternary (Energy recovery)	Incineration of plastic solid wastes to generate heat or electricity	Ideal for highly contaminated or toxic wastes that cannot be mechanically recycled	Produces toxic air emissions that need to be managed; does not result in a new material product

Overall, primary and secondary (mechanical) recycling are more cost-effective for pure waste streams; tertiary (chemical) and quaternary methods are recommended for managing complex or contaminated non-wanted materials that would otherwise end up in disposal sites.

The recycling process provides benefits such as conserving natural resources, mitigating greenhouse gas emissions, reducing energy use, preventing waste and water pollution, and socioeconomic inclusion of vulnerable populations. However, logistical complexities, the absence of robust end-markets for recovered materials, negative consumer perceptions, manufacturer reluctance to integrate end-of-life design, and the limitations of current legislative frameworks and traditional business models appear as barriers that need to be addressed to advance recycling as a waste valorization business model (de Almeida et al., 2021; Rahimifard et al., 2009).

1.4.1.2 Solidification/stabilization

Solidification and stabilization (S/S) technologies refer to a group of cleanup methods that use reagents (e.g., cement, fly ash, clay, or geopolymers) to immobilize and prevent the release of toxic substances from hazardous sludge, radioactive, and industrial wastes (Liang et al., 2024; Petrillo et al., 2025)

Solidification involves the physical encapsulation of harmful substances within a monolithic mass with high structural integrity, thereby trapping them in place and restricting their migration into the surrounding environment. In contrast, stabilization relies on chemical interactions with contaminants to decrease their solubility and mobility, thereby lowering the risk of contamination of soil and water resources (Chen et al., 2023).

From a waste valorization perspective, S/S is a simple, and low-cost process for transforming S/S-treated hazardous waste into useful materials such as pavement, road bases, or concrete fillers (Liang et al., 2024). (Karayannis et al., 2017) investigated the S/S process of hazardous metals from various solid wastes into ceramic and glass-ceramic materials. The research demonstrated the feasibility of inertizing potentially hazardous metals into environmentally-friendly ceramics and glass-ceramics for safe use as building materials.

Recently, advanced methods such as thermal treatments (vitrification, sintering) and molten salt processes have been explored to further improve both immobilization efficiency and the potential for the recovery of valuable metals (He et al., 2025).

However, technical and regulatory barriers still limit the full promotion of S/S as a waste valorization technique. Variability in waste composition and the long-term stability of immobilized waste contaminants can limit the reliability and acceptance of S/S products. From a regulatory perspective, many frameworks still classify S/S-treated materials as waste rather than secondary resources, restricting their reuse in construction, urban, and industrial applications (Liang et al., 2024; Petrillo et al., 2025).

1. 4.2 Biological Treatments

Biological treatments for solid waste can be applied to the organic fraction of waste generated in households, restaurants, farmers' markets, retail establishments, and industrial activities, such as food processing and agro-industrial production.

The field of study known as "food waste recovery" has seen a marked increase in research, particularly on the organic fraction of municipal solid waste (Roy et al., 2023). The focus of this growing field is on converting organics into valuable resources (Sarker et al., 2024).

Biological treatment processes can be broadly classified into two main categories: aerobic and anaerobic. Composting is the primary aerobic treatment method, while anaerobic digestion is the main process used in anaerobic treatment (Saravanan et al., 2022). The following is a review of the processes:

1.4.2.1 Composting

Composting is an aerobic biological degradation process in which the microbial community transforms the organic content of waste into a stable form, generating heat (Saravanan et al., 2022). Composting is an ancient technology that remains one of the most widely used approaches for recovering organic matter from residues, especially in areas with limited infrastructure for more complex technologies (Mehta et al., 2014; Rashid & Shahzad, 2021). In developing countries, the largest fraction of organic waste is sent to landfills (Catorza et al., 2022).

Composting offers several environmental and operational advantages. Notably, it mitigates leachate generation and greenhouse gas (GHG) emissions associated with the anaerobic decomposition of organic matter in landfills (Catorza et al., 2022). Additionally, composting reduces the volume of waste sent to landfills, decreases the need for synthetic fertilizers, conserves natural resources, and improves soil health (Rashid & Shahzad, 2021; Saravanan et al., 2022). Another relevant aspect is the potential to generate carbon credits in developing countries through projects linked to international climate mitigation mechanisms, such as those under the Paris Agreement (Catorza et al., 2022).

Additionally, removing the organic fraction from waste destined for final disposal improves the geotechnical stability of landfills. The degradation of this fraction can generate pore pressures that compromise the structural integrity of the landfill and the waste it contains (van Elk et al., 2014).

Composting has many advantages, but it also has limitations. It is relatively slow, taking several weeks to months to produce compost. It also requires large areas (Rashid & Shahzad, 2021). If not properly managed, the process can produce nitrous oxide, a GHG (Cucina, 2023).

The composting process has four phases: mesophilic, thermophilic, cooling, and maturation (Ho et al, 2022). At the beginning of the process, the mesophilic phase occurs when the compost temperature is approximately 20-40 °C (Ho et al., 2022). As the temperature rises to approximately 40-70 °C, thermophilic microorganisms proliferate, promoting the rapid degradation of organic matter and the elimination of pathogenic agents, thereby marking the onset of the most critical stage of the process: the thermophilic phase (Ho et al., 2022). Over time, the temperature drops to 40–45 °C, mesophilic microorganisms begin to grow again and predominate during the cooling and maturation phases (Mehta et al., 2014).

Several factors influence the composting process, including aeration, temperature, pH, moisture content, the carbon-to-nitrogen ratio, the nature of the feedstock, and compost technology (Barros, 2012; Ho et al., 2022).

1.4.2.2 Anaerobic digestion (AD)

Anaerobic digestion (AD) is a biochemical process in which the organic fraction of solid waste is converted, under non-toxic conditions, into biogas (mainly methane (CH_4) and carbon dioxide (CO_2) and digestate – a nutrient-rich byproduct with vast potential for resource recovery. In AD, about 10% of the organic fraction of waste is converted into digestate, and the remaining 90% into biogas (Jacob et al., 2025; Swaminaathan et al., 2024).

The AD occurs in four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. AD relies on syntrophic interactions among microorganisms that, under limited-oxygen conditions, hydrolyze complex organic matter into soluble monomers such as amino acids, fatty acids, sugars, and glycerol. Understanding these biological processes and their associated chemical reactions is essential for optimizing AD performance (Volschan Junior et al., 2021).

Historically, the AD is used to stabilize primary and secondary sludges from wastewater treatment plants; However, it is a viable application for any organic waste, such as food leftovers, agricultural residues, and lignocellulosic biomasses (de Souza Guimarães & da Silva Maia, 2023; Swaminaathan et al., 2024; Volschan Junior et al., 2021).

The main products of AD are biogas and digestate, which are used as energy sources and soil conditioners, respectively. However, AD can extend beyond the basic production of these value-added products. Several studies have demonstrated that using organic waste for energy generation and the production of value-added materials can contribute to the development of more sustainable and resilient economies (Cucina, 2023). In this context, implementing more stringent regulations to divert organic waste from landfills, along with incentive policies that support the development and adoption of AD technology for organic waste valorization, is also essential (Jacob et al., 2025).

1.4.3 Thermochemical routes

Thermochemical conversion is promising for waste valorization and has been extensively investigated in recent years. It enables the use of low-quality and mixed raw materials, reducing waste and improving resource recovery (Yangin-Gomec et al., 2025). In thermochemical processes, waste is chemically converted at temperatures ranging from 180 °C to above 1000 °C, producing value-added products such as fuels, chemicals, and biochar. In this sense, long-chain, high-molecular-weight hydrocarbons are transformed into shorter, lower-molecular-weight hydrocarbons (Janabi et al., 2024; Lewandowski et al., 2020).

Thermochemical processes include gasification, pyrolysis, and combustion. In summary, pyrolysis thermally degrades wastes, in the absence of oxygen, to produce bio-oil, char, and gases; gasification converts carbonaceous materials into syngas (mainly H2, CO, CO2, and CH4) using limited oxidizing agents at high temperatures, and combustion burns organic materials to release energy (Swaminaathan et al., 2024).

Combustion involves the thermal conversion of materials into carbon dioxide and water. Incineration is a combustion-based method of waste disposal that has become increasingly popular. It reduces the hazard and volume of waste. Nonetheless, incineration presents several disadvantages, including high operating costs, substantial capital investment, management challenges, and the potential for air pollution (Jack et al., 2026; Rahil et al., 2023). Combustion is not discussed in this chapter because the conversion of carbon-rich feedstocks into energy and valuable chemicals via pyrolysis and gasification offers several advantages over combustion. Let us explore two main thermochemical processes for waste valorization: pyrolysis and gasification.

1.4.3.1 Pyrolysis

Pyrolysis is a thermochemical process that converts organic materials, such as biomass and waste, into biochar, bio-oil, and syngas in the absence of oxygen through thermal decomposition. This process involves subjecting organic material to high temperatures in a controlled environment, breaking down organic polymers (e.g., cellulose, hemicellulose, lignin, or plastics) into simpler molecules by a series of radical-driven reactions, including depolymerization, cracking, and secondary recombination (Swaminaathan et al., 2024). Readers are referred to

Naqvi et al. (2021) for more detailed information on pyrolysis kinetics and mechanisms.

Common feedstocks include biomass, municipal solid waste, plastic waste, and industrial waste (Yangin-Gomec et al., 2025). Key operational parameters influencing pyrolysis include temperature (typically 350–700 °C, with slow pyrolysis 350 – 700 °C and fast pyrolysis between 450–700 °C), heating rate ranges from ≤ 25 ºC min-1 (slow pyrolysis) and ≥ 10 ºC min-1 (fast pyrolysis), and residence time is generally higher than 30 min for slow pyrolysis and about 1 seg for fast pyrolysis. Feedstock characteristics (e.g., moisture content, particle size, and composition) also influence the pyrolysis performance (Ong et al., 2019). The main products generated are biochar (a solid with high carbon content), bio-oil (a liquid fuel), and syngas (a combustible gas mixture) (Swaminaathan et al., 2024).

1.4.3.2 Gasification

Gasification is a thermochemical process that converts carbonaceous materials, such as biomass, coal, or waste, into synthesis gas (syngas), primarily consisting of hydrogen (H_2) and carbon monoxide (CO), along with other trace gases (Swaminaathan et al., 2024).

Mechanisms of gasification involve heterogeneous and homogeneous reactions, such as partial oxidation, the water–gas reaction, the Boudouard reaction, and the water–gas shift, which primarily produce a synthesis gas (syngas) rich in CO and H_2 (Babatabar & Saidi, 2021). (Lewandowski et al., 2020) provide a discussion of reaction mechanisms, kinetics, and gasification devices.

Gasification occurs at high temperatures (>700 °C) and under controlled oxygen or steam at atmospheric pressure (Ong et al., 2019). Typical feedstocks include biomass, municipal solid waste, plastic waste, and industrial waste (Jung & Ro, 2023; Yangin-Gomec et al., 2025). Key operational parameters for gasification include temperature (typically above 700 °C), pressure (near atmospheric or slightly elevated), and residence time (Ong et al., 2019). The primary product of gasification is syngas, a versatile fuel gas mixture that can be used for power generation, heating, industrial processes, or as a feedstock for producing various chemicals and transportation fuels (Swaminaathan et al., 2024).

1.4.5 Integrated and Hybrid Valorization Systems

Given the multiple sources and diverse characteristics of solid waste, an integrated treatment chain and/or the application of hybridized systems may be recommended to promote full resource recovery from waste streams.

Waste sorting, collection, transportation, pretreatment or conditioning, and resource utilization are key components to consider from a technical perspective (Zhang et al., 2022). As discussed in previous items, several methods are available for extracting material and/or energy from residues (e.g., recycling, composting, anaerobic digestion, combustion, pyrolysis, and gasification). For resource recovery, the implementation of the technique should consider waste composition, available infrastructure, economics, environmental impacts, and market demand for the recovered products, among other factors.

(de Almeida & Lúcio de Souza Teixeira, 2024) highlight that integrated waste valorization should also be practiced at a micro-level, incentivizing home composting and small-scale anaerobic digesters to increase treatment rates of organics, which does not require waiting for any municipal infrastructure to be implemented.

On an industrial scale, recovery methods could be integrated and/or hybridized to diverse value-added products. (Hidalgo et al., 2014) aimed to demonstrate the concept of 'mixed plant' integrating anaerobic digestion (AD) and pyrolysis to the management of a broad spectrum of wastes (livestock, industrial, agri-food, agricultural, and non-recyclable fraction proceeding from waste treatment plants) in an integrated facility. Biogas and syngas would be used as fuel, whereas digestate could be employed as a slow-release fertilizer. Pyrolysis can also provide additional bio-oil and carbon material for solid fuel production. According to the authors, integrating energy across the main process streams can optimize the utility's overall consumption.

In another study, a hybrid AD and gasification waste-to-energy system showed economic feasibility for valorizing paper, plastics, and the organic fractions of municipal solid waste. The main factors that may affect its operability include energy prices and capital costs, which could influence the investment decision (Mabalane et al., 2021).

When treating sewage sludge from sanitation services, (Li & Feng, 2018) pointed out that integrated AD and pyrolysis can be an alternative for high-content organic sludge. However, the integrated pathway would not be recommended for low-organic sludge due to the high energy input required to operate this route. In this case, standalone AD must be preferred. This case illustrates that each investment decision should be made through proper evaluation, with diverse options considered to support the optimal choice.

Besides, the successful application of recovery technologies, or their integration, will depend not only on their technical and economic performance but also on the availability of adequate management frameworks that enable their implementation within the waste management chain (Rahimifard et al., 2009).

1.5 Conclusions

Population growth, human activities, and industrial production are the driving forces of increased waste generation. In that direction, integrated waste valorization is no longer a utopian philosophy but a necessity to be implemented, especially given energy demands and the need to add value to waste. To this end, integrated systems that encompass source separation, collection, transportation, processing technologies, and evaluation methods, such as life cycle analysis, life cycle costing, energy balancing, and techno-economic assessment, are required to support decision investment. There is no one-size-fits-all management strategy, and the best option should be assessed on a case-by-case basis, considering the particularities and circumstances of each application. Recent technological advances have prompted the digital transformation in the waste sector. The use of

Artificial Intelligence (AI) and AI tools in the waste management system can be particularly relevant for improving waste valorization and better resource utilization.

Author contributions

Conceptualization, R.A; Methodology, R.A and A.G.H.P.E.; Validation, R.A and A.G.H.P.E.; Formal Analysis, R.A and A.G.H.P.E.; Data Curation, R.A and A.G.H.P.E.; Writing – Original Draft Preparation, R.A and A.G.H.P.E.; Visualization, R.A and A.G.H.P.E.; Writing – Review & Editing, R.A and A.G.H.P.E.; Funding Acquisition, R.A.

Acknoledgement

Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro – FAPERJ (E-26/204.425/2024).

Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

The authors declare that the data supporting the findings of this study are available within the manuscript.

Declaração de Disponibilidade de Dados (In Portuguese)

Todo o conjunto de dados que sustenta os resultados deste estudo está apresentado no corpo do manuscrito.

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