

Sustainable Garden Waste Management: Innovative Strategies for a Circular Economy

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ABSTRACT

The waste resulting from landscaping and seasonal maintenance activities (such as grass clippings, leaves, prunings and other plant material) accounts for a significant portion of municipal solid waste, but is often landfilled, dumped or burned. That's a waste of a useful resource and contaminates the soil, water and air with methane and other pollutants, the environmental effects of which are increasing climate change. The review focuses on the innovative ways garden waste can be managed in the context of circular sustainability, using a narrative synthesis of the latest literature. Following the characterisation of the sources, physical and chemical properties and environmental impacts of garden waste, four main valorisation processes are compared: composting, mulching, bioenergy production, and resource recovery, with respect to their outputs, advantages, limitations and environmental profiles. The analysis demonstrates that these routes have the potential to turn the garden waste into compost, biochar, mulch, biogas and other high-value products, which leads to better resource efficiency, soil health, pollution reduction, carbon sequestration and economic opportunity. They are measured on four pillars: resource efficiency, pollution reduction, climate change mitigation and economic benefits. The review also identifies technical, economic and regulatory barriers to widespread adoption – feedstock heterogeneity, high capital costs, poor markets for recycled products and fragmented policy – and research gaps – complete life-cycle assessment, social acceptance, digitalisation of waste-management systems. Considering all the evidence, no single pathway is ideal; multiple pathways exist, which can be supported by a strong life-cycle approach and by clear policy for a circular economy, to make garden waste a valuable resource for more sustainable, resilient and resource-efficient communities.

Keywords- garden waste; circular economy; composting; bioenergy; resource recovery; valorization; sustainability.

I. INTRODUCTION

The handling of garden waste is at the crossroads between urban planning, environmental protection and the broader green economy, and is increasingly moving away from a single-use approach to managing waste to a focus on material recovery systems. The grass cuttings, leaves, prunings and other plant debris in question are a significant proportion of municipal solid waste, but their composition varies considerably with location (Eades et al., 2020a). The matching of the amount of waste produced on the household level with the amount actually collected remains a challenge in the design of workable management schemes, for example, in England, where household garden waste is a substantial proportion of the urban waste stream (Eades et al., 2020a). This organic matter is responsible for methane, a greenhouse gas that has a strong warming effect, when not handled properly, and landfilling is a big culprit, directly contributing to climate change (Blanchard et al., 2023). For this reason, recent research has focused on routes like composting, anaerobic digestion and recycling, reducing environmental load and contributing fertility to soils (Zhang et al., 2023).

The moisture content and carbon-to-nitrogen ratio of garden waste may vary depending on the proportion of the materials, ranging from high carbon wood chips to high nitrogen grass clippings (Dronia, Połomka, et al., 2023; Lelicińska-Serafin et al., 2024). This largely determines the type of treatment that is appropriate, with wet material like grass being well-suited for anaerobic digestion and drier, woodier material for heat energy recovery by drying or other heat energy recovery methods (Shi et al., 2013). The volume of the garden waste produced by single-family homes might be controlled by source

separation and offers real potential as an energy source in Central Europe (Lelicińska-Serafin et al., 2024). To maintain a clean waste stream, therefore, is highly reliant on public awareness and on compliance with the rules set out for residents for the waste collection (Fontaine et al., 2024).

Of the many possibilities, composting is the most widely used method for recycling garden waste, both on a large scale and in your own backyard. Huge windrow facilities can accommodate a larger quantity of material with high accuracy of temperature, moisture and aeration control and provide fast and sanitary decomposition (Mishra & Yadav, 2022a; Yao et al., 2024). Forced-aeration static piles with proper additives have been successfully used to stabilise the garden waste and to produce an acceptable product with agreeable physical and chemical characteristics such as moderately alkaline pH and moderate electrical conductivity (Yao et al., 2024). Maturity is important for agricultural use: A range of indicators is regularly monitored to ensure that the final compost will not damage plants, including the E4/E6 ratio of humic substances (Yao et al., 2024).

In addition to traditional composting, newer methods like vermicomposting and the production of biochar expand their toolbox. The earthworm *Eisenia fetida* transforms garden waste into a high-quality organic fertiliser, and the efficiency is further enhanced with the use of co-substrates in order to improve the nutrient content (Gong et al. 2019). The biochar produced from the pyrolytic decomposition of garden waste, on the other hand, can serve to sequester carbon and enhance the quality of soils because the best processing conditions result in a binding capacity of the biochar produced (Cui et al., 2024). Life-cycle work reinforces the overall message that the overall management burden (Oviedo-Ocaña et al., 2023; Rotthong et al., 2023) is significantly lowered by avoiding waste in the first place, and by recovering either materials or energy from what is waste. In the case of Thailand, the collaborative approach to organic-waste projects aimed to reveal the lowest environmental cost configuration and to emphasise the often context-specific nature of the solution (Rotthong et al., 2023).

A joined-up approach is required to integrate the folding of garden waste into the Municipal Operations, from generation to collection to end markets. This is because generation is also seasonal: at different times of the year, the grass may be at its peak and leaves may be at their peak (Dronia, Kostecki, et al., 2023; Dronia, Połomka, et al., 2023). If the compost and mulch product is to be economically sustainable, it is also important to build up durable demand for these products (Dronia et al., 2024). Here, regulatory instruments are essential instruments that can decide the fate of disposal, ranging from the prohibition of environmentally harmful disposal to the incentive of capturing the previously unmanaged material (Blanchard et al., 2023; Fontaine et al., 2024). Ultimately, the balance between technical innovations, community engagement and policy support will determine the success of garden-waste management, and will help to transform a waste problem into a resource for more sustainable cities (Kusch-Brandt, 2020; Zhang et al., 2023).

From a circular sustainability perspective, the garden-waste management encompasses both environmental and social and economic axis, namely resource efficiency, pollution control, climate mitigation and economic return, all within a single approach (Yang et al., 2023). Efficiency is realised by closing nutrient cycles – transforming waste into compost and biochar to boost soil and reduce the need for synthetic fertiliser (Cobo et al., 2018). Maintaining them within the local system translates to enhanced agricultural production and a cut in the reliance on imported inputs (Ghale et al., 2022). Pollution simply decreases by diverting material from landfill and open dumping; both aerobic composting and anaerobic digestion reduce GHG emissions and therefore help mitigate climate change (Muljaningsih et al., 2023). In the context of water treatment, biochar offers an added advantage: it not only sequesters carbon but also adsorbs contaminants (Samuel Olugbenga et al., 2024). When the compost and biochar is applied to land, it increases the soil organic carbon and allow soils to serve as a carbon sink, as agroforestry systems do (Ghale et al., 2022; Dmuchowski et al., 2024); and digital tools are now providing a closer connection between waste management and climate targets (Kurniawan et al., 2024). The economics that follow involve converting waste into marketable compost, reducing disposal costs, and generating new income streams that can foster green innovation to enhance firms' environmental and economic outcomes (Avilés-Palacios & Rodríguez-Olalla, 2021; Ciula et al., 2024; Cheng et al., 2025).

These threads are brought together in this review. It looks at creative applications of garden waste in the context of circular sustainable practices, such as its use as compost, mulch, bioenergy and recovered resources, and the corresponding decrease in pollution and increase in sustainable use of resources. Looks at the environmental and economic advantages of each pathway, identifies ongoing research and practice gaps, and synthesises current knowledge for future research and practice.

II. REVIEW METHODOLOGY

This paper is a narrative review. The literature was gathered from major academic databases using search terms covering garden and green waste, composting, mulching, anaerobic digestion, bioenergy and the circular economy. Retrieved records were screened against inclusion and exclusion criteria and de-duplicated, after which relevant information — waste sources, physical and chemical characteristics, treatment pathways and reported outcomes — was extracted. The evidence was then synthesized thematically around four valorization pathways, compared across outputs, advantages, limitations and

environmental impact, and finally evaluated for its contribution to circular sustainability before drawing out the remaining challenges and research gaps. The overall procedure is summarized in Figure 1.

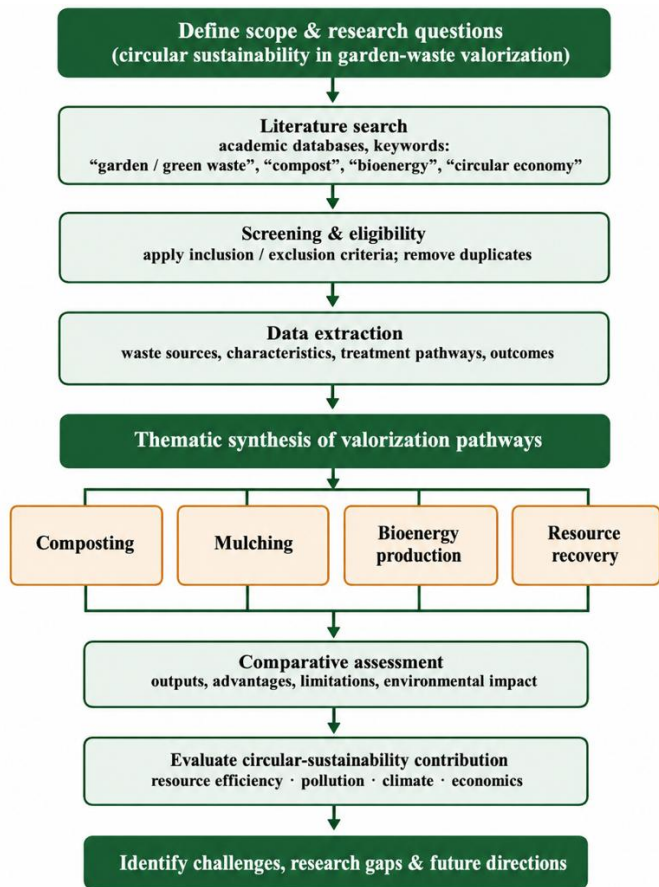


Figure 1. Methodological framework adopted for the review.

2.1 Garden Waste

Garden waste forms a large and steadily expanding slice of the world's municipal solid waste, pushed upward by urban growth, the appetite for green space and routine seasonal upkeep. Worldwide, food and garden waste together can account for as much as 44% of municipal solid waste, which makes efficient handling an urgent priority if environmental harm is to be limited (Yatoo et al., 2024). The picture varies by region: in Indonesia garden waste represented roughly 13% of unmanaged waste, some 4.2 million tonnes in 2022 alone, and that figure is set to climb as rules requiring more urban green space take effect (Supriatna et al., 2024). Modelling this stream accurately matters, because its chemistry differs from that of other organics such as food scraps, and those differences shape whether it is best landfilled, used for energy recovery, applied to land or fed into industry.

2.2 Sources of Garden Waste

Garden waste – also known as green waste or yard waste – is primarily from the natural growth of plants and from mowing and edging maintenance activities in public and private areas. Common materials include fallen leaves, twigs, tree and shrub prunings, and grass clippings or various other landscaping materials (Zhang et al., 2023). The materials are found in a variety of contexts such as private gardens, public parks, road verges, nurseries and farms (Osikabor et al. 2022). There are significant differences between the value of output produced in a town and in a rural area: such differences have been found in England, where detailed work revealed a substantial proportion of the value of output produced by private households in towns compared to rural areas (Eades et al., 2020b). The volume of organic waste generated by households in the apartments and single-family houses in Poland was also shown to vary, depending on the season of the year and the type of waste, and is particularly high during the fall and winter months, when leaves fall from plants, as well as depending on the size of the property (Dronia, Kostecki, et al., 2023b; Dronia, Połomka, et al., 2023b). The volumes often exceed the amount of collection capacity in rapidly urbanizing developing countries. In Nigeria, garden waste is a by-product of development activities with waste collected from gardens, day care centres, road side maintenance (Osikabor et al., 2022); while in Shanghai, municipal waste data from 2011 to 2019 showed a complex spatial and temporal distribution pattern that was associated with urban development and the changing land use (Shu et al., 2021). Others, however, are particularly

unique, like those of fruits from the tropics or sub-tropics like avocado, cherimoya and mango, which leave a characteristic footprint in areas where agriculture and urban gardening meet in southern Spain (Reyes-Martín et al., 2022). The range of variety makes the collection and processing of the material need to be adapted to the local combination of grass, wood chips and leaves, as the amount of these components affect the material's composition and behaviour significantly.

2.3 Characteristics of Garden Waste

The treatment options available for garden waste depend on its physical and chemical composition, as well as the nature of the treatment: fermentation, biological digestion or thermochemical conversion. It is a lignocellulosic biomass, thus it is inherently renewable because of its lignin, cellulose and hemicellulose (Chen et al., 2023). The same structure can also prevent biological degradation and thus decelerate biological processes, but it also allows for recuperation via combustion and other means (Mašán et al., 2023). Moisture content, carbon to nitrogen ratio (C/N), organic-matter content and the composition of the material itself are the defining parameters. Untreated garden wastes have been measured recently with an average moisture content of 39%, a mean C/N ratio of 18.2 and an organic matter of 83% (Manu et al., 2021). The C/N ratio is critical to aerobic decomposition as it regulates the microbial activity and composting process. Garden waste composts have a slightly alkaline pH of about 1.42 to 1.50 mS/cm, which is considered to have a low salt load, beneficial for use in growing mediums (Yao et al., 2024b). The E4/E6 ratio is once more a quality and stability indicator of composts (Yao et al., 2024b). The particle size also plays a significant role in the breakdown of the product, smaller the particle size, more is the surface area available for action by the microorganisms, which results in faster breakdown and better final product (Mishra & Yadav, 2022b, 2021). However, if the fragmentation is too great the material may end up compacting and becoming oxygen deprived, so the pre-treatment must strike a balance. The nutrient content is dependent on origin, with urban garden waste high in nitrogen, phosphorus and potassium, and prunings from small fruit trees often high in magnesium, but the micronutrient content is low by all origins, so garden waste will not be a good source of micronutrients without amendment (Reyes-Martín et al., 2022). Another challenge is the contamination: when investigating selectively collected bio-waste, it was found that there is a high amount of non-organic foreign material which affects the quality of both compost and biogas (Dronia et al., 2024b). The variety of leaves, branches and clippings in different seasons and housing types highlights the importance of robust technologies capable of dealing with this "mixed feedstock".

2.4 Environmental Impacts of Improper Disposal

When garden waste is dumped in an unmanaged way, in landfills or dumps, its disposal has significant environmental costs including contributions to greenhouse gas emissions, degradation of soil and water quality, nutrient runoff and loss of biodiversity. After being buried with other organic waste, the decomposition of garden waste generates methane, a greenhouse gas whose warming potential is significantly greater than CO₂ (Nanda & Berruti, 2021). The mishandling of food and garden waste has a clear negative effect as verified in the life-cycle assessments of urban organic-waste systems in Thailand, which also highlight the importance of implementing proper treatment technologies (Rotthong et al., 2023). Organic waste continues to increase in Brunei Darussalam, where approximately 70% of waste is deposited in landfill, and this significantly contributes to the environmental impact and reduces energy security by failing to exploit waste-to-energy opportunities (Shams et al., 2024). The social and environmental impacts of poor waste management are wide-ranging: Cape Town in South Africa has experienced illegal dumping that polluted and marred the landscape and increased the burden on municipal waste disposal (Niyobuhungiro & Schenck, 2021). Where there is no alternative, garden waste is still burned, contributing to the air pollution stream with particulates and VOCs, which affect respiratory health (Lelicińska-Serafin et al., 2024b). In this light, material or energy recovery instead of landfilling helps to reduce carbon emissions and to enhance the urban environment by generating valuable land and renewable energy (Zhang et al., 2023). Based on the experiences from Central Europe and Warsaw, in particular, it can be concluded that the green waste collected from settlements could be a valuable energy feedstock if it is properly disposed of (Lelicińska-Serafin et al., 2024b). This is not only a good reason to move towards environmentally responsible management, but it also needs to be a management based on organics, with a waste avoidance objective in landfill (Mazzoli et al., 2024; Rotthong et al., 2023).

III. INNOVATION PATHWAYS FOR GARDEN WASTE MANAGEMENT

3.1 Composting: Biological Stabilization and Soil Amendment

Aerobic microbial activity is still continuing to play a prominent role in the composting of garden waste as a humus-like product. A large amount of recent research has focused on improving the process to achieve improved product quality and reduce emissions. The incorporation of nitrogen sources like sheep manure or food waste would result in a better C/N ratio, faster degradation and more stable product. A trial in which the vegetable waste was mixed with sheep manure resulted in a stable and mature compost after 120 days, which led to a good soil conditioner for agriculture (Ouelid Lhaj et al., 2024a). Integrating composting into SURA creates a circle, whereby processed waste is returned to be used in the production process, and the external input is minimized (Dsouza et al., 2021). Technical advances include aerobic processes for treating organic wastewater while recovering resources and real-time sensor networks to optimise temperature, moisture and aeration levels to boost efficiency and reduce processing times (Chang et al., 2024; Preethi et al., 2024). Nanotechnology-based techniques are also found to be beneficial, particularly in applications where traditional methods are ineffective (Preethi et al., 2024).

However, these benefits should be balanced against the methane and nitrous oxide emissions when there is not a complete aerobic condition (Rotthong et al., 2023).

3.2 *Mulching: Direct Application and Soil Conservation*

Mulching spreads shredded or chopped garden waste directly onto the soil, where it conserves moisture, suppresses weeds and slowly releases nutrients as it decomposes. Compared with composting or bioenergy, it delivers immediate benefits at very low energy cost. In forestry and agricultural settings, it offers a practical alternative to hauling biomass to distant power plants, particularly where transport costs would be prohibitive (Brás et al., 2024). The practice also improves soil structure and biodiversity, sheltering soil organisms and reducing erosion (H. Yang et al., 2024). Its effects depend on particle size and application rate; however, applying too little carbon-rich material can immobilize nitrogen and temporarily deprive plants of nutrients as microbes work through the residue (Oueld Lhaj et al., 2024b). Mulching is also unsuitable for waste carrying seeds or pathogens unless it is heat-treated first (Zhou et al., 2022). Even so, it remains a low-technology, high-impact option for both urban green space and rural farming, contributing ecosystem services such as climate regulation and soil conservation (Türkay & Tezer, 2024).

3.3 *Bioenergy Production: Energetic Valorization*

Bioenergy routes turn garden and agricultural waste into electricity, heat or fuel through thermochemical or biochemical means. Biomass power plants burning agricultural and forestry residues offer a workable option where centralized collection is feasible (Brás et al., 2024). Anaerobic digestion is another popular choice, generating methane-rich biogas that can be upgraded to biomethane for the gas grid or used in combined heat and power (Pasciucco et al., 2023). Recent work shows that digesting garden waste also produces volatile fatty acids, which can serve as feedstock for bioplastics and other high-value products, and that adding granular activated carbon strengthens hydrolysis and acidogenesis, helping overcome the recalcitrance of lignocellulose (Chen et al., 2023b). Advanced thermochemical conversions such as pyrolysis and gasification provide further routes, yielding biochar, syngas and bio-oil; biochar in particular doubles as a stable carbon sink and soil amendment (Kumari et al., 2024). Life-cycle calculations show the environmental balance of these routes varies widely with the technology used and the fossil energy displaced (Osman et al., 2024), and pairing waste-to-energy with carbon capture and storage can deliver very low-carbon outcomes, though the economics remain challenging (Materazzi et al., 2024).

3.4 *Resource Recovery and Valorization: Beyond Energy*

Modern recovery goes well beyond extracting bulk materials, drawing on enzymes, organic acids and nanomaterials within biorefining frameworks (Preethi et al., 2024; Usmani et al., 2020). Nanotechnology-based processing can isolate cellulose nanofibres and lignin derivatives destined for construction and pharmaceutical applications (Tang et al., 2024). An analysis of rice by-products in Sri Lanka illustrates how circular business models can knit together several revenue streams from a single agricultural waste (Illankoon et al., 2023). Multi-criteria decision analysis tools are increasingly used to weigh such options against environmental, economic and social criteria (Lombardi & Todella, 2023). Cost remains a real constraint, since the more sophisticated technologies often demand heavy financial and technical investment (Wine & Yang, 2025), but integrating garden waste into broader industrial symbiosis networks can substantially improve resource use and cut waste (Nogueira et al., 2023).

Table 1. Comparative Assessment of Innovation Pathways

Pathway	Output	Advantages	Limitations	Environmental Impact	Reference
Composting	Soil amendment	Nutrient recycling, better soil health, low technical barrier	Possible GHG emissions if mismanaged; needs space	Moderate; avoids landfill methane but demands careful aeration	Oueld Lhaj et al., 2024b; Rotthong et al., 2023
Mulching	Soil cover	Moisture retention, weed suppression, minimal processing	Risk of nitrogen immobilization; limited to certain waste types	Low; direct application cuts transport and processing energy	Brás et al., 2024; H. Yang et al., 2024
Bioenergy	Electricity / heat / biogas	Renewable energy, fossil-fuel displacement	High capital cost, technical complexity, possible air emissions	Variable; depends on technology and displaced energy source	Brás et al., 2024; H. Yang et al., 2024
Valorization	High-value chemicals / materials	High economic potential, diverse product range	Emerging technology, market	Potentially low; depends on	Tang et al., 2024;

Pathway	Output	Advantages	Limitations	Environmental Impact	Reference
			uncertainty, complex processing	substitution for virgin materials	Usmani et al., 2020

Taken together, the evidence suggests that the best results come from a holistic strategy combining several pathways rather than relying on any one. Composting and mulching deliver immediate environmental gains, while bioenergy and higher-value valorization create opportunities for energy security and economic growth. Future work should concentrate on operational systems that maximize material recovery with minimal environmental cost, underpinned by robust life-cycle assessment and policy that rewards sustainable practice (Abdallah et al., 2024; Adhikari et al., 2024).

IV. CONTRIBUTION TO CIRCULAR SUSTAINABILITY

Bringing circular-economy thinking into waste management marks a real departure from linear disposal, replacing it with systems that improve material performance, cut pollution and ease climate pressure. The shift is not only environmentally sensible but economically attractive, treating waste as a key input for farming and energy. The approach rests on the 9R hierarchy: Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose and Recycle, which together promote resource efficiency, minimise waste and extract maximum value across a product's life (Avilés-Palacios & Rodríguez-Olalla, 2021; Muljaningsih et al., 2023). By regarding garden waste as a nutrient-rich resource rather than a nuisance, municipalities and private operators can close material loops, reduce demand for virgin resources and shrink the footprint of disposal (Cobo et al., 2018; Yang et al., 2023).

4.1 Resource Efficiency

In a circular system, efficiency comes mainly from optimizing material flows and extending product life. Garden organics — trimmings, leaves and clippings — make up a notable share of municipal solid waste, especially in urban and suburban areas (Kumareswaran et al., 2024). Conventional handling, whether collection-and-disposal or burning, strips out vital nutrients such as nitrogen, phosphorus and potassium (Cobo et al., 2018). Converting this biomass instead into compost, biochar and organic fertilizers retains that value (Greeshma et al., 2025; Samuel Olugbenga et al., 2024). Compost rebuilds soil organic matter, improves structure, moisture retention and microbial diversity, and lowers the need for chemical fertilizer and irrigation (Greeshma et al., 2025). Keeping nutrients circulating within the local ecosystem raises agricultural output and reduces dependence on outside inputs (Cobo et al., 2018). Purpose-built models, such as the M-GRCT framework, further help identify recoverable streams in low-income areas so that recovery is both technically sound and socially acceptable (Vargas-Terranova et al., 2022a).

4.2 Pollution Reduction

Diverting garden waste from landfill and open dumping directly cuts pollution. Under the anaerobic conditions typical of landfills, organics decompose to release significant methane and nitrous oxide, both potent greenhouse gases (Muljaningsih et al., 2023), while leachate from rotting waste can carry excess nutrients into groundwater and surface water, driving eutrophication and the oxygen-starved dead zones that follow (Delgado et al., 2024). Aerobic composting and anaerobic digestion sharply reduce these pollutants or turn them into useful by-products (Kumareswaran et al., 2024). Anaerobic digestion, for example, captures methane for energy and produces a digestate usable as fertilizer, keeping the gas out of the atmosphere (Cobo et al., 2018). Biomass-derived biochar used in water treatment delivers a twin benefit — sequestering carbon while removing waterborne contaminants — showing how versatile circular solutions can be (Samuel Olugbenga et al., 2024). A systematic review of liquid organic waste reinforces the potential of processing technologies to convert waste into useful materials and so lower the risks of poor disposal (Kumareswaran et al., 2024).

4.3 Climate Change Mitigation

Climate mitigation links to waste management through lower greenhouse gas emissions and greater carbon storage. With industry still heavily dependent on fossil energy and solid-waste volumes rising, strategies are needed that can cut emissions by 45% by 2030 and reach carbon neutrality by 2050 (Yang et al., 2023). Sound waste management contributes by avoiding emissions from land degradation and by reducing the energy needed to make virgin materials (Gallego-Schmid et al., 2020; Yang et al., 2023). Applying compost and biochar to soil increases stored organic carbon and lets soils function as carbon sinks (Greeshma et al., 2025; Samuel Olugbenga et al., 2024), an effect that agroforestry systems strengthen by sequestering carbon while delivering ecosystem services (Dmuchowski et al., 2024; Ghale et al., 2022). Indonesian case studies show that economically viable waste management can reduce methane from open dumps (Muljaningsih et al., 2023), and renewable-energy initiatives in Zimbabwe demonstrate how integrating waste management supports a low-carbon circular economy (Kumba et al., 2024). Digital transformation is accelerating this convergence by sharpening planning and lifting operational efficiency (Kurniawan et al., 2024).

4.4 Economic Benefits

The economic case rests on turning garden waste into marketable products while trimming the costs of disposal and remediation. A circular economy converts waste into reusable materials that re-enter the economic cycle, opening income streams and creating jobs (Avilés-Palacios & Rodríguez-Olalla, 2021). For small and medium-sized enterprises, adopting circular supply-chain principles can improve performance and long-run sustainability, even if upfront costs run higher (Tseng et al., 2025a). Producing compost, biochar and biogas yields tangible returns, particularly in agricultural markets that demand such inputs (Cobo et al., 2018; Greeshma et al., 2025). In Poland, managing municipal waste streams for energy has shown that thermal treatment of high-calorific fractions offers a viable economic alternative to disposal (Ciula et al., 2024). Circular-economy policies can also spur green innovation that lifts both economic and environmental performance (Cheng et al., 2025), while coordination between levels of government and active public participation strengthen environmental protection and economic gains alike (Jiang, 2024). Evidence from EU agricultural employment under circular conditions further indicates that regional strategies can build economic resilience and stability (Matysik-Pejas et al., 2023).

V. CHALLENGES AND FUTURE OPPORTUNITIES

The move towards sustainable waste management runs into a broad set of obstacles spanning technology, economics and regulation, and tackling them calls for a comprehensive approach. Despite clear potential for resource recovery and climate mitigation, progress is often held back by organizational barriers, financial limits and fragmented rules (Avilés-Palacios & Rodríguez-Olalla, 2021; Kurniawan et al., 2024). Clearing these hurdles requires not just new technology but systemic change in governance and markets so that solutions can be sustained and scaled (Tseng et al., 2025a; Wang et al., 2024).

5.1 Technical Constraints in Garden Waste Valorization

Technical difficulties stem largely from the heterogeneity of garden waste and the efficiency of the systems that process it. Mixtures of leaves, branches, clippings and other organics vary widely in composition, moisture and degree of decay, which complicates smooth operation (Ciula et al., 2024; Kumareswaran et al., 2024). That variability feeds through to inconsistent compost and biochar quality and so to uneven agricultural performance (Greeshma et al., 2025). Contaminants such as plastics or heavy metals in mixed streams can further compromise compost quality and marketability (Iuga, 2016). Many advanced treatments remain constrained by energy and resource demands (Cobo et al., 2018), and implementing them well requires modelling and monitoring systems for real-time control that many cities simply lack (D'amico et al., 2021; Esguícero et al., 2021). Digital tools could help overcome some of these barriers by improving data capture and processing, but their uptake is limited by high initial costs and complexity (Jemal et al., 2023; Kurniawan et al., 2024). Urban-metabolism and modelling tools, for instance, can improve management yet demand expertise and collaborative programmes that are unavailable in many regions (D'amico et al., 2021; Jemal et al., 2023). Logistics add to the strain, since collecting and transporting dispersed garden waste is especially costly in rural or sparsely populated areas (Matysik-Pejas et al., 2023; Tseng et al., 2025a).

5.2 Economic Challenges and Market Viability

Economics is a major brake on adoption. Building treatment facilities — composting plants or digesters — demands substantial upfront investment, while returns hinge on volatile markets for end products such as compost and biogas (Ciula et al., 2024; Kumba et al., 2024). The small and medium-sized enterprises that often anchor local waste management face high implementation costs despite the long-term payoff (Tseng et al., 2025a). Weak and uneven demand for recycled products undermines viability further, as buyers frequently favour cheaper virgin materials (Avilés-Palacios & Rodríguez-Olalla, 2021; Iuga, 2016). Economic appraisals also tend to omit externalities such as environmental and social value, understating the true worth of circular systems (Cheng et al., 2025; Matysik-Pejas et al., 2023). Without incentives such as subsidies, tax relief or carbon credits, many circular initiatives stay uncompetitive against linear disposal (Jiang, 2024; Wang et al., 2024). Developing business models that internalize these externalities and build value chains for recovered resources is essential, and doing so requires concerted effort between government and local businesses to align profit with sustainability (Ciula et al., 2024; Kumba et al., 2024; Tseng et al., 2025b).

5.3 Policy and Regulatory Challenges

Policy and regulation often trail behind technology, breeding uncertainty and friction. In many countries, frameworks still emphasize recycling over genuine material recovery, raising legal and administrative barriers to circular systems (Iuga, 2016; Wang et al., 2024). Rigid legal definitions of waste versus product, for example, can impede the sale and distribution of recovered materials (Avilés-Palacios & Rodríguez-Olalla, 2021a; Iuga, 2016). Fragmented oversight, with several agencies governing different facets of waste management, frequently produces conflicting and ineffective rules (Tseng et al., 2025b; Wang et al., 2024). Effective circular strategies need supportive instruments — extended producer responsibility, landfill taxes, and mandatory recycling targets — that reward waste reduction and recovery (Kurniawan et al., 2024; Wang et al., 2024), yet designing and enforcing them often meets industry resistance and political instability (Jiang, 2024; Wang et al., 2024). Disparities in standards between countries can also hamper the cross-border spread of best practice

and technology (Matysik-Pejas et al., 2023; Wang et al., 2024). Aligning policy and strengthening international cooperation are, therefore, key to enabling the transition (Avilés-Palacios & Rodríguez-Olalla, 2021; Wang et al., 2024).

5.4 Research Gaps and Future Directions

For all the growing interest, important gaps still limit our grasp of these systems. Comprehensive life-cycle assessments are needed to gauge environmental impact across different settings and scales (Cobo et al., 2018; Yang et al., 2023), since many studies focus narrowly on single methods or local conditions and generalize poorly (Dmuchowski et al., 2024; Kumareswaran et al., 2024). The social dimension — community acceptance, behaviour change, the effects of source separation — is under-researched yet central to designing systems people will actually support (Greeshma et al., 2025; Tseng et al., 2025b; D'amico et al., 2021).

Looking ahead, integrated approaches that connect waste management with agricultural energy and urban planning hold particular promise (Ghale et al., 2022; Yang et al., 2023). Linking waste systems with recycling can enhance carbon sequestration and biodiversity while generating economic value (Dmuchowski et al., 2024; Ghale et al., 2022). Emerging options such as engineered biochar and advanced anaerobic digestion could improve resource use and lower impacts further (Cobo et al., 2018; Samuel Olugbenga et al., 2024), and digitalizing management with artificial intelligence and the Internet of Things would sharpen monitoring and decision-making (D'amico et al., 2021; Jemal et al., 2023; Kurniawan et al., 2024). Finally, collaboration among scientists, policymakers, business leaders and communities is vital for navigating the many challenges garden-waste management presents (Tseng et al., 2025b; Wang et al., 2024). Closing knowledge gaps and learning together can move communities towards waste systems that are sustainable, resilient and dependable, helping to mitigate climate change and protect public health (Kurniawan et al., 2024; Yang et al., 2023).

VI. CONCLUSION

This review makes the case that garden waste is a valuable biomass resource that can underpin a circular economy when it is directed along the right valorization pathways. Traditional handling of landfilling, open burning and dumping — not only wastes recoverable material but also drives environmental degradation and greenhouse-gas emissions. The literature shows that innovative routes such as composting, mulching, anaerobic digestion and bioenergy generation, combined with resource-recovery technologies, can transform garden waste into compost, biochar and renewable energy. These pathways improve resource efficiency and soil health, reduce pollution, increase carbon sequestration and create economic opportunity, advancing genuinely sustainable practice. Considerable barriers to wide adoption nonetheless remain, including variable feedstocks, technical limits, economic constraints and weak policy support. Progress will depend on developing integrated, scalable systems, on more rigorous life-cycle assessment, on digital technologies, and on policy frameworks built for a circular economy. Meeting the challenges that lie ahead and accelerating the move towards a more sustainable approach to garden waste will require closer collaboration among researchers, policymakers, industry and local communities. Circular strategies for garden-waste valorization offer a workable route to greater environmental sustainability, reduced climate impact and more resilient, resource-efficient communities.

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