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REVIEW

Optimization and Resource Utilization of Urban Solid Waste Classification and Recycling System under the Goal of Low Carbon Environmental Governance

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ABSTRACT

The classification and recycling of urban solid waste have become key channels to realizing a low-carbon environmental governance, enhance resource efficiency, and encourage a circular urban development. This review critically analyzes the existing status, optimization, governance and resource utilization strategies of urban solid waste classification and recycling systems. It emphasizes that the high performance of waste classification is based not just on the participation of residents, but also on coordination of source separation, classified collection, transportation, intelligent sorting, recycling technologies, market mechanisms and carbon accounting. Unstable classification behavior, fragmented management responsibilities, insufficient infrastructure, low-value recycling, weak life-cycle carbon assessment, and low level of demand of secondary resources are still challenges to the current systems. In order to overcome these barriers, this article offers an integrated optimization model comprising of digital monitoring, route optimization, sorting using artificial intelligence, life-cycle assessment, extended producer responsibility, economic incentives, participation of the populace, and green procurement. The review also highlights the fact that the utilization of the resources should focus on high-quality material recycling, organic waste recovery, industrial symbiosis, and verifiable reduction of carbon. In contrast to the traditional approaches to waste management, according to which the primary focus is on the disposal reduction or recycling rate, this article places the classification and recycling on the broader context of the low-carbon governance and urban material metabolism. The results offer both theoretical explanations and practical suggestions to implement effective, inclusive, and climate-oriented urban waste management systems.

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ARTICLE INFO

Received: 10 June 2026 | Revised: 21 June 2026 | Accepted: 10 July 2026 | Published Online: 12 August 2026

DOI: https://doi.org/10.30564/jees.v8i8.13632

CITATION

Zhang, C., Du, Y., 2026. Optimization and Resource Utilization of Urban Solid Waste Classification and Recycling System under the Goal of Low Carbon Environmental Governance. Journal of Environmental & Earth Sciences. 8(8): 587–603. DOI: https://doi.org/10.30564/jees.v8i8.13632

Keywords: Urban Solid Waste; Waste Classification; Recycling System Optimization; Resource Utilization; Low-Carbon Environmental Governance

1. Introduction

The management of urban solid waste has progressively developed into a traditional public service of sanitation and a strategic part of low-carbon environmental control, construction of a circular economy, and transformation of urban sustainability [1]. The generation of municipal solid waste is becoming more and more difficult and challenging in quantity and complexity, especially with the growth and acceleration of urbanization, growth in household consumption, and diversification of urban lifestyles [2]. According to the United Nations Environment Programme, the generation of municipal solid waste, both worldwide and domestically, is projected to increase, rather than decrease, not only from its current level of around 2.1 billion tonnes in 2023, but also to 3.8 billion tonnes in 2050; when externalities of pollution, health and climate are included on a global basis, the annual cost per capita of waste management could be dramatically higher than it currently is at about 102 dollars per person annually in 2023. Likewise, the World Bank has highlighted the fact that cities are in the centre of the global waste challenge with the generation of waste levels being expected to shoot up towards mid-century as income levels, population density and urban consumption will grow. These tendencies signify that urban solid waste is no longer addressed as an end-of-pipe environmental burden, but as an important area in which cities can mitigate emissions of greenhouse gases, extract valuable resources, and redesign material metabolism [3].

The classification and recycling of urban solid waste under the objective of low-carbon environmental governance offers a critical route to the reduction of emissions and enhancement of resource efficiency [4]. Recyclable material purity can be enhanced by waste sorting at the source, reducing contamination in the downstream recycling, and enhancing the technical and economic viability of downstream recycling. Conversely, mixed collection usually results in degradation of the material, increased costs in sorting, reduced recycling, and increased reliance on landfill or incineration. The carbon-reduction value of classification is hence not restricted to the avoidance of emissions during the disposal process; it also includes the replacement of virgin materials, the reduction of energy use during the primary production process, the mitigation of the methane emissions of organic waste, and the recovery of the secondary resources. Material circularity and organic waste treatment have been noted by the Intergovernmental Panel on Climate Change as important mitigation strategies, especially when waste systems do not produce methane, generate renewable energy, and replace synthetic fertilizers. In this way, the optimization of the waste classification and recycling systems can be interpreted as a multi-dimensional governance problem, which includes carbon accounting, resource circulation, technological innovation, behavioral regulation, and institutional coordination [5].

Nonetheless, the present performance of solid waste classification and recycling systems in urban areas is still limited to several bottlenecks. To start with, the environmental awareness, convenience, incentive mechanisms, and trust in recycling system among residents are fundamental factors that determine the source classification [6]. In the areas where downstream treatment is more effective, the misclassification and poor attendance can undermine its effectiveness. Second, the systems of collection and transportation are frequently not properly organized with the demands of classification [7]. Once waste that has been classified separately is later mixed during collections or transfer, then people might be less willing to participate and lose the environmental benefits of classification. Third, recycling businesses are characterized by the unpredictable availability of materials, market prices, processing costs and the level of technology [8]. These aspects undermine high-value exploitation of recyclables and the resilience of the recycling industry chain. Fourth, the benefits of carbon emission reduction are not necessarily clearly quantified or included into policy analysis, which makes it hard to compare different waste treatment pathways on a life-cycle basis [9]. Review work on municipal solid waste management has in recent years been increasingly using life-cycle thinking and sustainability assessment to examine environmental impacts across waste systems, and has demonstrated the relevance of integrated assessment methods. However, classification behavior, recycling logistics, resource utilization, carbon reduction, and governance mechanisms are often still considered as an individual topic as opposed to an integrated system.

Plastic waste shows why there is the urgency to create a more efficient urban recycling system. The OECD recorded that the world plastic production doubled between 234 million tonnes in 2000 to 460 million tonnes in 2019, and plastic waste more than doubled between 156 million tonnes in 2000 to 353 million tonnes in 2019; and after taking into consideration the losses during the recycling process, only 9 percent of plastic waste was finally recycled across the globe. This low circularity exposes a structural issue: classification is not a sufficient condition to ensure that resources are used unless it is linked to stable collection networks, advanced sorting technologies, market demand of recycled resources and policy instruments that internalize environmental costs. The paper, metals, glass, textiles, kitchen waste, bulky waste, and construction-related urban waste streams have similar challenges. Hence, the optimization of urban solid waste classification and recycling incorporates a full-chain view, including the generation of waste, separation of sources, collection of classified waste, scheduling of waste transportation, intelligent sorting, cycling processing, resource product development, carbon accounting, and policy feedback [10].

This review is novel in its attempt to develop an integrated analytical framework to classify and recycle solid waste in urban areas within the narrower context of low-carbon environmental governance. Existing literature has been able to offer useful insights into each of the dimensions, including life-cycle assessment of municipal solid waste systems, recycling technology, community involvement, policy, the circular economy, and low-carbon waste treatment. As an example, the methods of life-cycle sustainability assessment of municipal solid waste management systems have been the topic of recent literature, and other reviews have focused on circular economy strategies to achieve low-carbon cities. Based on the contributions, this article is different in three ways. First, it connects classification and resource utilization as a continuous system instead of isolating the waste separation as a front-end behavior or recycling as a downstream industrial process [11]. Second, it integrates the optimization of the system into the context of the low-carbon governance, focusing on the relationship between the efficiency of recycling, the reduction of carbon emissions, the design of the policy, digital controls, and market incentives [1]. Third, it emphasizes the interplay of technological, institutional, economic, and social factors and argues that the effectiveness of waste classification depends not only on infrastructure and technological advancements but also on governance capacity and ability, and on the establishment of viable resource-recovery markets [12]. The integrated logic of this review, linking source classification, recycling optimization, resource utilization, and low-carbon environmental governance, is illustrated in **Figure 1**.

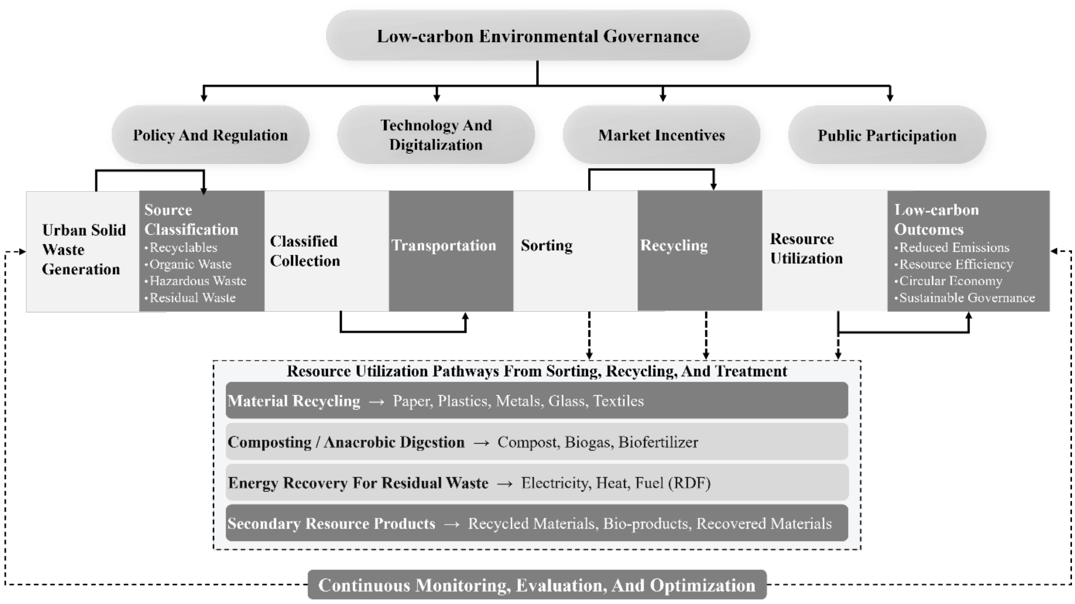

Figure 1. Integrated conceptual framework linking urban solid waste classification, recycling optimization, resource utilization, and low-carbon environmental governance.

The purpose of this review is thus to respond to three questions, which are interconnected. First, what are the big building blocks, operating behavior, and carbon emission implications of urban solid waste classification and recycling systems [13]? Second, to enhance the environmental and economic performance, how could the source classification, collection and transportation, sorting technologies, recycling processes, and resource utilization pathways be optimized [14]? Third, what governance systems will be required as the waste disposal management is replaced with the low-carbon resource management [15]? Through these questions, the article aims to offer a systematic source of information to researchers, policymakers, urban managers and recycling businesses. It also adds to the literature by suggesting that future development of urban solid waste systems should go beyond single-objective indicators like recycling rate or disposal reduction but adopt a comprehensive evaluation framework that will embrace carbon reduction, resource value, system cost, social participation and governance effectiveness.

Overall, solid waste classification and recycling in urban areas are critical elements in low-carbon urban environmental management [1]. With the ever-growing amount of waste produced globally, the pressure on cities to reduce emissions, increase resource efficiency, and improve environmental quality makes systematic optimization an increasingly urgent necessity. An effective classification and recycling system can turn urban waste into a secondary resource reservoir, helping mitigate carbon emissions, control pollution, and advance the circular economy. It is against this backdrop that this review discusses in a systematic fashion the current status, optimization pathways, governance mechanisms and future research directions of urban solid waste classification and recycling systems, with a specific concern to its role in ensuring low-carbon environmental governance.

2. Current Status of Urban Solid Waste Classification and Recycling Systems

2.1. Overall Development of Urban Solid Waste Management

The management of urban solid waste has reached a point where simple collection and terminal disposal measures are no longer sufficient to meet the demands of low-carbon environmental governance [16]. The volume of municipal solid waste has been increasing with urbanization, population concentration, and upgrading consumption. The Global Waste Management Outlook 2024 indicates that the generation of municipal solid waste is expected to grow starting at approximately 2.1 billion tonnes in 2023 to 3.8 billion tonnes in 2050, meaning that the cities will be under pressure in terms of collection, transportation, treatment and resource recovery. This trend demonstrates that waste management is not just a hygiene problem but a systemic challenge in terms of carbon emissions, land occupation, material loss, public health, and urban governance capacity.

Currently, many cities have developed waste classification systems, although their maturity and efficacy vary widely. In urban areas with comparatively high governance capacity, classification has, over time, shifted from pilot programs to an institutionalized management system. Nevertheless, in most cities, waste classification is policy-based as opposed to behavior-based, i.e., residents can only engage in waste classification under control or regulation. This undermines the stability of source separation and adds the doubt of the quality of recycling. The main issue is that classification systems frequently focus on front-end participation but fail to account for full-chain coordination. When classified waste is mixed during collection or when recycling businesses lack the necessary processing capacity, the environmental value of classification is greatly diminished [17].

2.2. Composition and Characteristics of Urban Solid Waste

Solid wastes in the city are extremely heterogeneous. It typically contains recyclable materials such as paper, plastics, metals, glass, and textiles; organic fractions (food and kitchen waste); hazardous household waste; residual waste; bulky waste, and, in some cities, construction and demolition-related waste [18]. The composition is directly connected to income levels, living conditions, consumption patterns, climatic conditions, and local industrial systems. Urban areas with high incomes usually generate more packaging waste, plastics, paper, and discarded consumer goods, but organic waste might account for a higher percentage in urban areas where household food preparation remains predominant. The major categories of urban solid waste, their dominant treatment pathways, potential for resource utilization, and relevance to low-carbon strategies are summarized in **Table 1**.

Table 1. Main categories of urban solid waste and their potential for resource utilization.

Waste Category	Typical Components	Main Management Pathway	Resource Utilization Potential	Low-Carbon Relevance
Recyclables	Paper, plastics, metals, glass, textiles	Source separation, collection, sorting, material recycling	Recovery of secondary raw materials for industrial production	Reduces virgin material extraction and manufacturing emissions
Kitchen/organic waste	Food residues, vegetable waste, fruit peels	Composting, anaerobic digestion, bioenergy recovery	Compost, biogas, biofertilizer, organic soil amendments	Avoids landfill methane and supports renewable energy production
Hazardous household waste	Batteries, lamps, chemicals, medicines	Separate collection and specialized treatment	Recovery of selected metals and safe disposal of toxic substances	Prevents secondary pollution and reduces environmental health risks
Residual waste	Contaminated materials, non-recyclable plastics, mixed waste	Incineration, landfill, mechanical-biological treatment	Limited energy recovery or final disposal	Requires emission control and should be minimized through classification
Bulky waste	Furniture, mattresses, large appliances	Dismantling, repair, reuse, recycling	Reusable products, wood, metals, plastics	Extends product life and reduces demand for new materials
Construction-related urban waste	Bricks, concrete, wood, ceramics, metals	Crushing, screening, recycled aggregate production	Recycled aggregates and construction materials	Reduces raw material mining and construction-sector emissions

This complexity in compositions directly impacts the design of classification and recycling systems. High-market-value recyclables like metals and clean paper are relatively easy to recycle economically, whereas low-market-value plastics, composite packaging, contaminated textiles, and mixed organic residues are more difficult to recycle economically. Plastic waste is particularly characteristic of the existing paradox between the growth of consumption and the recycling restrictions. The OECD reported that in 2000, global plastic waste exceeded 156 million tonnes, but only 9% of this waste was recycled in 2019, after accounting for losses during recycling. This implies that the availability of recyclable resources in waste streams does not necessarily translate into their successful recovery. The quality, cleanliness, separability, and the market demand of recovered materials are determinants [19].

Organic waste deserves particular attention from a low-carbon perspective because, when disposed of in landfills, it decomposes under uncontrolled anaerobic conditions and can generate methane that escapes as a fugitive greenhouse gas emission. This landfill pathway should be clearly distinguished from controlled biological treatment. Composting is predominantly an aerobic process in which adequate aeration promotes the conversion of organic matter into CO_2, water, heat, and stable compost or soil amendments, thereby reducing the risk of methane formation. Anaerobic digestion, by contrast, is an intentionally anaerobic process operated in closed reactors; it converts organic waste into methane-rich biogas that is captured and used for heat, electricity, or upgraded fuel, while digestate may be further treated or used as a biofertilizer. Therefore, source-separated organic waste can reduce climate impacts either through aerobic composting that stabilizes organics or through anaerobic digestion that captures methane as a renewable energy resource. In both cases, separation from plastics, metals, and hazardous residues is essential to maintain treatment efficiency, product quality, and low-carbon benefits [20].

2.3. Development of Classification Systems and Source Separation Practices

Urban waste classification systems generally follow two major pathways: mandatory classification, driven by government regulation, and voluntary classification, supported by environmental awareness and incentives [6]. Mandatory systems can rapidly improve participation rates through laws, inspections, penalties, and community supervision. However, if residents perceive classification as inconvenient or symbolic, compliance may remain superficial. Voluntary systems rely more heavily on public awareness, trust, and social norms, but they often suffer from unstable participation and limited coverage. In practice, effective classification usually requires a hybrid governance model that combines legal obligation, behavioral incentives, infrastructure convenience, and transparent feedback.

Source separation is the foundation of recycling efficiency, yet it is also the weakest link in many cities [14]. Classification accuracy depends not only on residents' willingness but also on the clarity of classification standards. Overly complex categories may increase cognitive burden, while overly simplified categories may reduce downstream recycling value. A practical classification system should balance scientific precision with operational simplicity. For example, separating recyclables, kitchen waste, hazardous waste, and residual waste is easier to communicate than highly detailed material-based categories, but downstream recycling still requires further sorting and refinement.

Another major challenge is the "trust gap" between residents and waste management systems. When residents observe that classified waste is later mixed during transportation, their motivation to classify declines. This reflects a deeper governance problem: classification cannot be treated as an isolated household responsibility. It must be supported by separate collection vehicles, transfer stations, sorting facilities, data monitoring, and stable recycling channels [21]. Without this chain, source separation becomes performative rather than functional.

2.4. Recycling and Resource Utilization Pathways

The current concept of recycling urban solid waste encompasses material recovery, biological treatment, energy recovery, and final disposal [22]. Recycling of materials remains the most desirable channel for clean, high-value recyclables, as it can reduce demand for virgin raw materials and prevent emissions from primary production. The recycling markets for metals, paper, glass, and some plastics are relatively mature, but their recovery rates are highly dependent on contamination levels and price volatility. Recyclables that do not command high prices may need policy support or a subsidy, since collection and processing costs may exceed market returns.

The utilization of organic waste resources primarily involves composting, anaerobic digestion, and the production of bio-based materials [23]. Composting can restore nutrients to soil, and anaerobic digestion can produce biogas and reduce methane emissions compared to an uncontrolled landfill. However, these channels must be closely monitored for quality. When organic waste contains plastics, heavy metals, or other hazardous residues, the resulting compost or digestate would face safety and marketability issues. Thus, the recycling of organic waste also depends on the quality of source separation and the quality of downstream products.

Incineration is a common method of energy recovery in certain urban centers to reduce waste and recover energy as electricity or heat [24]. Nevertheless, its participation in the governance of low-carbon is controversial. Incineration has the potential to reduce landfill dependency and avoid methane emissions, but it may also create lock-in effects in case cities overbuild incineration capacity. Lock-in of this kind can undermine the incentives to reduce, reuse, and recycle materials. Thus, energy recovery must be framed as an option for treating non-recyclable residual waste rather than as an alternative to high-quality recycling.

2.5. Carbon Emission Characteristics of Waste Management Processes

Urban solid waste systems generate carbon emissions at various stages, including collection, transportation, sorting, treatment, disposal, and secondary pollution control [7]. The emissions from landfills are primarily methane from organic waste decomposition, and those from incineration are linked to both the fossil-fuel component of the waste and the ancillary energy use. The route length, vehicle type, loading efficiency, and the location of waste facilities determine the emissions from collection and transportation. Even though transportation emissions are not always huge in large metropolitan areas with scattered recycling facilities, they can still be significant.

Recycling has the potential to reduce carbon emissions by substituting materials. By using recovered metals, paper, plastics, or glass instead of virgin materials, it is possible to save on energy use and industrial emissions [25]. But these advantages cannot be taken for granted. They rely on the quality of recovery, processing efficiency, the actual rate of substitution, and the energy structure of recycling industries. A low-quality recycling process that uses high levels of energy or yields low-quality materials may provide minimal carbon benefits. Consequently, life-cycle assessment is becoming increasingly significant for comparing landfill, incineration, composting, anaerobic digestion, and recycling of materials in a uniform manner. The World Bank has also stressed the importance of not just looking at waste systems in terms of their disposal capacity, but also at their long-term environmental performance.

2.6. Key Limitations of Current Systems

Although there have been improvements in classification policy and recycling infrastructure, the current urban solid waste systems still face structural constraints [26]. Various actors commonly manage collection logistics, sorting facilities, recycling enterprises, and carbon governance without adequate coordination. The second limitation is that the resource recovery value is low. Technically recyclable materials are economically unattractive, so selective recycling of economically viable fractions and neglect of problem fractions result. Carbon accounting is very weak; this is the third limitation. Most cities report recycling or disposal reduction levels but lack a robust life-cycle carbon assessment, making it challenging to determine the most climate-effective pathways.

In general, the modern situation regarding urban solid waste classification and recycling reflects a shift toward resource-oriented governance at the expense of disposal-oriented governance [27]. However, this transition has not been fully implemented. Persuading residents to classify waste is not the main challenge; the main challenge is creating an integrated system in which classification, collection, recycling technology, market mechanisms, and carbon governance support each other. Urban waste classification can only serve as a real impetus for low-carbon environmental governance when the entire system chain functions coherently.

3. Optimization of Urban Solid Waste Classification and Recycling Systems

3.1. Optimization of Waste Classification at the Source

The initial stage of recycling solid waste in urban areas is source classification, yet its success is not guaranteed by residents' readiness to sort waste [6]. The primary challenge in most cities is not the lack of a classification policy, but the vagaries of classification behavior and the low purity of separated waste streams. When asked to categorize waste based on complex or constantly shifting criteria, participation can become a symbolic act that does not genuinely reflect actual conditions. Thus, it should be kept in mind that, to optimize source classification, both simplifying the classification logic and ensuring compatibility with downstream treatment requirements should be considered. An effective system must enable residents to learn categories with minimal difficulty and generate waste streams that are beneficial to recycling businesses and treatment plants.

The best way to optimize source separation is to switch from a command-based to a feedback-based governance. Traditional publicity campaigns commonly focus on environmental responsibility but seldom inform residents whether their behavior in classifying has delivered quantifiable benefits. Digital solutions, including QR code tracing, community-level data platforms, smart bins, and household feedback systems, can help bridge this gap. Recent research on smart municipal solid waste management demonstrates that Internet-of-Things-based devices and machine-learning models can monitor bin status, predict waste generation, and improve pickup timing, indicating that digital infrastructure can bridge the gap between household behavior and system-level optimality [28].

Nonetheless, the application of digital technology cannot be regarded as an alternative to social governance. Smart bins and recognition systems can enhance supervision but will also increase management costs and exacerbate access inequality in older communities or low-income areas. Therefore, optimizing source classification requires integrating technology with behavioral incentives, social trust, and community involvement. Participation can be reinforced by pay-as-you-throw systems, reward systems, volunteer supervision, school education, and public disclosure of recycling results, but the effectiveness of these measures varies depending on whether residents believe that classified waste will be separated after collection. The greatest lesson is that source classification cannot be optimized solely at the household level; it requires an integrated chain of collection, transportation, sorting, and resource utilization [21].

3.2. Optimization of Collection and Transportation Systems

Collection and transportation are important links between source classification and downstream recycling [7]. Although the residents may sort the waste properly, the environmental value of classification may be sacrificed when the different waste streams are mixed during collection or when logistics systems are inefficient. Thus, the three goals that should be pursued simultaneously through optimization of the collection and transportation processes are maintaining the integrity of the classification, reducing operational costs, and decreasing carbon emissions.

One of the most straightforward ways to enhance the efficiency of the collection process is through route optimization [29]. There are also fixed routes and schedules that waste collection vehicles may follow, but these systems may not align with actual patterns of waste generation. The effects of this can include partially loaded vehicles, route duplication, fuel consumption in traffic, and overfilled bins in high-density areas. Unnecessary travel distance can be minimized and vehicle loading efficiency enhanced using vehicle routing models, geographic information systems, real-time monitoring, and heuristic algorithms. In a 2024 study on municipal solid waste collection and routing using ant colony algorithm models, an improved ant colony-shuffled frog leaping algorithm was proposed, and it was reported that the optimized multi-vehicle model reduced the total collection distance and increased the average loading rate compared with less optimized methods. This suggests that optimizing logistics can have positive economic and low-carbon impacts.

The increasing use of IoT sensors also alters the rationale for garbage collection. Cities can shift to demand-sensitive collection based on bin fill, waste type, traffic, and vehicle availability [30]. These systems are particularly applicable to recyclable waste, kitchen waste, and hazardous household waste, as each stream requires different collection frequencies, odor and contamination risks, and storage needs. However, the demand-responsive collection also presents new challenges. It involves the ability to transmit data reliably, maintain sensor equipment, integrate between departments, and use uncertainty-capable algorithms. In cases of poor maintenance of digital systems or low-quality data, optimization models can produce unrealistic routes.

Transportation on a low-carbon basis also requires vehicle technology and facility design. Emissions can be reduced through electric collection vehicles, optimization of transfer stations, and decentralized collection points for recyclables [31]. Still, these strategies must be implemented based on local urban density and energy structure. In urban areas with a narrow road network and local-level collection, small electric vehicles may be better suited due to their compact size and low weight. In contrast, large transfer vehicles may be more efficient due to their low weight and large size. The best model is thus not a universal one. Cities require spatially heterogeneous logistics systems that are proportional to waste generation density, the road system, the location of treatment facilities, and carbon reduction.

3.3. Optimization of Sorting and Recycling Technologies

The sorting technology can determine whether it is possible to convert the classified and collected waste into high-quality secondary resources. Manual sorting remains prevalent in most recycling systems, particularly for mixed recyclables and low-value materials. Nonetheless, manual sorting is labor-intensive, inconsistent, and may frequently subject workers to health and safety hazards. The use of automated sorting technology based on optical sensors, near-infrared spectroscopy, hyperspectral imaging, computer vision, robotics, and artificial intelligence is increasingly considered a significant tool to enhance recycling efficiency [32].

Research on the use of AI-powered waste management technologies demonstrates that advanced sensors, computer vision, hyperspectral cameras, IoT devices, and robots can assist in identifying materials, detecting objects, and sorting materials in a material recovery facility [30]. These technologies can help divert materials from landfills for value addition across sectors such as packaging, textiles, metals, glass, transportation, and electronics. The use of hyperspectral imaging has been of particular interest, as it can identify materials by their spectral properties and detect contaminants in complex waste streams; more recently, its non-destructive nature, high spectral resolution, and usefulness in distinguishing between material types and contamination have been highlighted.

Despite these benefits, technological optimization needs to be evaluated critically. The automated sorting systems can usually work well under controlled conditions, but municipal waste streams are heterogeneous, wet, dirty, broken, overlapping, and locally variable. The use of AI models that are trained on small datasets can also fail when exposed to new packaging types, mixed materials, or contaminated surfaces. Robotics might also not work with irregularly shaped objects, soft plastics, cloth, or items partially concealed on conveyor belts. The future of automated sorting, therefore, lies not only in the accuracy of the algorithms but also in the diversity of the data, sensor fusion, mechanical stability, and the system's constant adaptation to the composition of local waste [33].

In the case of recycling technologies, the main issue is to shift low-value recovery to high-value resource utilization. Mechanical recycling would be effective for cleaning plastics, paper, metals, and glass, but contamination and material degradation reduce product quality. Various technologies can expand resource pathways, such as chemical recycling, biological treatment, composting, anaerobic digestion, and waste-to-energy. To illustrate, energy recovery can minimize landfill volume and recover heat or electricity, but it may undermine incentives to recycle materials if the capacity to burn materials becomes excessive. Thus, the optimization of sorting and recycling should be organized, not in competition, but in accordance with the priorities of waste reduction, reuse, high-quality material recycling, biological resource recovery, and residual treatment [30].

3.4. System-Level Optimization Models

The classification of solid waste and the recycling systems of urban solid waste are complex socio-technical systems. Optimization in one phase might cause problems in another unless the entire chain is taken into account. For example, adding more classification categories could enhance theoretical recycling accuracy but also decrease resident compliance and raise collection costs. Similarly, the construction of advanced sorting facilities can enhance material recovery. Still, if source separation is poor or the market is not keen on recycled products, the investment may fail to deliver the intended returns. Thus, system-level optimizations are required to ensure a balance among environmental, economic, technical, and social goals [5]. **Table 2** summarizes the major optimization strategies across the full waste-management chain, showing how each system link contributes to recycling efficiency, emission reduction, and resource recovery.

Table 2. Optimization strategies for urban solid waste classification and recycling systems.

System Link	Major Optimization Measures	Expected Benefits	Key Limitations
Source classification	Simplified classification standards, smart bins, QR-code tracing, and resident feedback systems	Improves separation accuracy and public participation	High cost of digital infrastructure; uneven public compliance
Collection and transportation	Separate collection, route optimization, electric vehicles, demand-responsive scheduling	Reduces mixing, fuel consumption, labor cost, and transport emissions	Requires real-time data, vehicle coordination, and infrastructure support
Transfer and storage	Dedicated transfer stations, sealed containers, odor control, temporary storage zoning	Maintains waste-stream purity and reduces secondary pollution	Space constraints in dense urban areas
Sorting facilities	AI recognition, optical sorting, robotic sorting, sensor-based separation	Improves material recovery rate and recycling quality	Performance may decline with wet, contaminated, or mixed waste
Recycling processing	Mechanical recycling, biological treatment, anaerobic digestion, and high-value material recovery	Converts waste into secondary resources and energy products	Market instability and quality-control challenges
Carbon evaluation	Life-cycle assessment, carbon accounting platforms, emission-reduction verification	Supports climate-oriented decision-making	Requires reliable data and standardized accounting boundaries

Life-cycle assessment provides a significant methodological foundation for system optimization, as it evaluates environmental impacts across waste generation, collection, transportation, treatment, recycling, and final disposal [9]. Recently reviewed research on life-cycle sustainability assessment of municipal solid waste management systems indicates the growing significance of life-cycle thinking in evaluating environmental, economic, and social burdens across waste management stages. To govern low-carbon governance, this method is necessary, as the carbon benefit of recycling is based not only on avoided disposal emissions but also on substitution effects, energy consumption in processing, transport distance, and the quality of recovered materials.

Multi-objective optimization models are particularly appropriate in waste management because cities must balance multiple objectives [34]. These are the reduction of carbon emissions, cost minimization, increased recycling rate, service coverage, reduced health risks, and increased public satisfaction. A single-objective model that minimizes cost may favor large-scale centralized treatment, whereas a model that maximizes the recycling rate may overlook economic feasibility. A carbon-oriented model will be more inclined towards diverting organic waste and replacing materials, but it still has to take into account public involvement and infrastructure capacity. Thus, carbon accounting, economic cost, technological viability, and social acceptability should be included in a single decision-support model in the future.

System-level optimization can be further enhanced with the aid of big data and artificial intelligence. Research on AI-powered municipal solid waste management has highlighted the potential of genetic algorithms, reinforcement learning, route optimization, real-time bin monitoring, AI-driven life-cycle assessment, techno-economic analysis, and end-to-end system design to enhance waste management performance [30]. Nonetheless, governance risks also arise in data-driven optimization. The waste data can be discontinuous among sanitation departments, recycling businesses, platform companies, and treatment facilities. When there are inconsistencies in data standards or some ambiguity in data ownership, optimization models might be hypothetical. In addition, algorithmic decisions must be transparent enough to be understood by public managers and modified by them, rather than a black-box system that is difficult to audit.

The main point is that the optimization of urban solid waste should cease to be a solitary technical advancement and become collective resource management [30]. The separation of sources, logistics of the third type, intelligent sorting, recycling markets, carbon accounting, and population participation should be considered interdependent elements. The most appropriate system is not necessarily the one with the most advanced technology, but the one that has achieved stable classification behavior, a high degree of logistics, a high degree of recycling quality, a high degree of credibility in carbon reduction, and a high degree of economical use of resources.

4. Governance Mechanisms and Resource Utilization Strategies under Low-Carbon Goals

4.1. Policy and Regulatory Mechanisms

Environmental quality governance is a pillar of optimizing urban solid waste classification and recycling systems [35]. Technological amelioration can increase the efficiency of resource sorting and recovery, though not of the institutional fragmentation that can weaken waste classification systems. To achieve low-carbon governance, the waste management policy needs to shift terminal disposal control to a full-chain regulatory framework that encompasses product design, consumption, source classification, collection, recycling, resource utilization, and final disposal. This change is required because the world population generating municipal solid waste is projected to increase significantly by 2050, and the economic, health, pollution, and climate costs of poor waste management are set to rise dramatically unless governance systems improve.

One of the key regulatory tools is the development of clear and enforceable classification principles. In most cities, classification regulations are not effectively integrated with the collection and treatment systems. This creates a disconnect between policy demands and operational reality. For example, if residents separate recyclables, kitchen waste, hazardous waste, and residual waste, but collection vehicles or transfer stations fail to maintain this separation, the policy loses credibility. Thus, household classification obligation should not only be defined, but also the sanitation company, recycling enterprise, property management, community, and treatment facilities must also be defined [36]. The governance chain should be modeled so that all actors have quantifiable responsibilities and consequences.

Another significant mechanism that helps bridge the gap between waste classification and upstream product design is the concept of extended producer responsibility [37]. EPR shifts some of the burden of municipal and consumer post-consumer waste to the producers, thus encouraging businesses to minimize excessive packaging, enhance recyclability, and fund collection and recycling systems. EPR is a policy approach identified by the OECD as shifting responsibility for products from producers to municipalities and consumers, particularly as the volumes and complexity of waste are rising in countries. Nevertheless, EPR cannot be reduced to financing the waste treatment once the products are discarded. It has a greater value in transforming the production and design incentives. When the costs of EPR are associated with product durability, recyclability, recycled content, and carbon footprint, product producers will have more reasons to work on minimizing waste production at the source.

Cross-regional waste transfer and recycling leakage should also be considered in regulatory governance [38]. In cases where cities have performed better at local classification and have exported difficult-to-process trash to other locations, environmental burdens may be displaced. The European Commission has underscored the fact that its waste shipment regulation of 2024 is meant to ensure that the EU does not offload its waste challenges, a broader principle of governance that states that recycling systems need to be environmentally responsible throughout the entire value chain. This observation is quite pertinent to the overall set of urban solid waste systems: low-carbon governance cannot be judged solely by local recycling rates, but also by whether waste flows can be traced, legally processed, and converted into secondary resources.

4.2. Economic Incentive Mechanisms

Economic incentives are needed because the recycling market does not necessarily reflect the value of environmental preservation [14]. Most recyclable materials have low or fluctuating market prices, whereas the costs of collection, sorting, cleaning, and processing are high. Consequently, recycling businesses usually focus on high-value products, metals, and clean paper, and, in the process, ignore low-value plastics, contaminated packaging, textiles, and composite materials. This creates a disjuncture between the ecological requirement for the wholesome recycling of resources and the economic rationality of selective recovery.

Pay-as-you-throw can enhance classification behavior because the cost of waste disposal is correlated with the quantity of unused waste produced. When the cost per kilo to dispose of mixed waste is greater than the cost per kilo to dispose of recyclable waste or to separate organic waste, then waste reduction and classification are economically significant. Such systems, however, need to be designed with care. Illegal dumping can grow when the costs are high or surveillance is inadequate. If the fees are excessively low, behavioral effects might be limited. As such, pay-as-you-throw must be accompanied by easy access to recycling facilities, transparent data monitoring, and effective communication with residents to avoid imposing too much of a burden on them [39].

Low-carbon recycling technologies can also be supported by subsidies and tax incentives, especially in the early stages of infrastructure development [4]. The intelligent sorting, washing, anaerobic digestion, and composting facilities, as well as digital tracking platforms, are often costly for recycling enterprises to invest in. These barriers can be reduced with specific subsidies; however, these subsidies should be performance-based rather than input-based. Governments need to tie financial aid to recycling volume, material quality recovered, carbon reduction, pollution control, and the safe disposal of residues. This will help avoid inefficient investments and improve operational performance in the long term.

Carbon markets and carbon credit schemes can also enhance the economic merits of recycling [12]. When recycling reduces emissions by substituting for the production of virgin material or by preventing landfill methane emissions, these reductions can be measured and converted into an economic benefit. Carbon-crediting systems should not be overestimated, though. The carbon advantage of recycling is conditional on the actual substitution rates, the energy consumed in recycling processes, the distance traveled in transporting recycled products, and the quality of the recycled products. An unverified carbon credit system might provide false gains without an actual reduction in emissions. Consequently, the carbon incentives must be based on life-cycle assessment, clear accounting boundaries, and third-party verification. The main governance mechanisms that support low-carbon waste classification and recycling are compared in **Table 3**, with an emphasis on their policy instruments, system functions, and critical limitations.

Table 3. Governance mechanisms supporting low-carbon waste classification and recycling.

Governance Mechanism	Main Policy Instruments	Function in the Recycling System	Critical Insight
Regulatory governance	Waste classification laws, recycling standards, disposal restrictions, and enforcement measures	Defines responsibilities and ensures minimum compliance	Regulation must cover the full chain, not only household classification
Extended producer responsibility	Producer recycling obligations, packaging reduction requirements, and eco-design incentives	Shifts responsibility upstream to producers	More effective when fees are linked to recyclability and carbon footprint
Economic incentives	Pay-as-you-throw, recycling subsidies, tax benefits, carbon credits	Encourages residents and enterprises to reduce and recycle waste	Incentives must avoid illegal dumping and artificial carbon-credit inflation
Public participation	Environmental education, community supervision, feedback platforms, and reward systems	Builds stable source-separation behavior	Trust increases when residents see visible recycling outcomes

Table 3. *Cont.*

Governance Mechanism	Main Policy Instruments	Function in the Recycling System	Critical Insight
Market governance	Green procurement, recycled-content standards, and recyclable trading platforms	Expands demand for secondary resources	Recycling systems need stable downstream markets to remain viable
Digital governance	Waste tracking, data platforms, smart collection systems, and carbon monitoring	Improves transparency, traceability, and operational efficiency	Data quality and interdepartmental coordination are essential

4.3. Public Participation and Behavioral Governance

The social basis of waste classification is people's participation [40]. Even the most developed recycling facilities cannot operate properly when source separation at the beginning of the recycling cycle is inaccurate or inconsistent. Nevertheless, residents' classification behavior is determined by various factors, such as environmental awareness, convenience, habit, trust, social norms, and perceived fairness. This is why it is not enough to rely on slogans or short-run campaigns. Behavioral governance must establish a social environment in which the classification of waste is convenient, understandable, and socially appreciated.

The cognitive burden caused by the complex classification rules is one of the obstacles. If residents do not know whether a material is recyclable, kitchen waste or hazardous waste, or residual waste, there is a higher likelihood of misclassification. It is particularly widespread with composite packaging, contaminated containers, used tissues, batteries, textiles, and small electronic products. An effective behavioral governance system needs to streamline front-end instructions and enhance downstream sorting capacity. That is, they should not expect the residents to work out all the technical classification issues at home. Rather, the household classification should be based on categories that are easy to comprehend and highly significant for downstream treatment, particularly the separation of organics, hazardous waste, and clean recyclable materials [41].

Another determining factor is trust. By making residents feel their actions have a purpose, they would be more willing to attend the concert as long as it continues. On the other hand, participation decreases when they see that classified waste is mixed during the collection. This implies that even individual environmental morality is not merely a question of individual moral responsibility; institutional moral responsibility is also at issue. Trust can be enhanced by being transparent about recycling results, community response, digital traceability, and visible improvements in collection practices. For example, communities can post information on how much of the kitchen waste was diverted, how much of the recyclable material was collected, or how much of the carbon emissions were avoided. This type of feedback converts classification into an abstract obligation and a measurable contribution [6].

Social differences should also be taken into consideration in behavioral governance. Classification may impose various constraints on elderly residents, tenants, the migrant population, students, and commercial households. Similar rules can thus bring about dissimilar participation. Community-level governance can assist in changing classification systems to fit local conditions through volunteers, property management, neighborhood committees, schools, and local enterprises [42]. This is not intended to substitute regulation with moral persuasion, but to integrate institutional rules with the day-to-day social support.

4.4. Resource Utilization and Low-Carbon Transformation Pathways

The essence of the connection between waste classification and low-carbon governance lies in resource utilization [11]. Until the classified waste is transformed into a useful product or service, energy, or product, classification is merely a symbolic exercise. The shift in solid waste management to resource management necessitates cities to treat solid waste as an element of urban material metabolism. This implies that recyclables, organic waste, bulky waste, textile waste, electronic waste, and construction-related waste need to be linked to industrial chains capable of absorbing secondary resources.

Recycling high-value materials should be emphasized, as it can help eliminate the need to exploit virgin resources and primary production. Metals, paper, glass, and some plastics can offer significant environmental benefits when recycled to a high enough quality [25]. But the impact of recycled materials varies depending on whether or not they actually substitute virgin materials. The European Environment Agency observes that recycling data tend to be used as a proxy for estimating the extent to which recycled materials can meet material demand. This is a significant difference. A high recycling rate may not imply high circularity in case the recycled materials are downcycled, stockpiled, exported without traceability, or used in low-value applications.

The potential of organic waste use is especially significant in low-carbon governance, since organic residues in landfills can be converted to methane. This risk can be mitigated by composting and anaerobic digestion, which also produce soil amendments, biogas, and digestate. However, such routes are extremely contingent on the purity of organic waste. Plastic pieces, heavy metals, and other harmful residues may compromise the quality of compost and digestate, decreasing their commercial value and causing secondary contamination. Thus, the low-carbon value of using organic waste in the kitchen is driven by strict separation of kitchen waste, along with further quality control, product standards, and market development for the recovered product [23].

Industrial symbiosis offers a broader avenue for exploiting resources. In this model, urban waste materials are used as inputs in the manufacturing, construction, agricultural, and energy systems [43]. For example, recycled plastics can be used in packaging or textile manufacturing; compost, as a byproduct, can be used in urban agriculture; biogas, as a byproduct, can supply heat or electricity; and construction waste can be processed into recycled aggregates. The IPCC has identified circular economy solutions as increasingly important for mitigating climate change, as they can reduce waste in the production and consumption of materials by optimizing material use. Nevertheless, industrial symbiosis demands consistency in material quality, reliable supply, product standards, and demand-side policies. In the absence of these, secondary resources can remain economically disadvantaged compared to virgin materials.

4.5. Challenges and Future Research Directions

Although there is an increasing policy focus, the urban solid waste classification and recycling system continues to face several governance challenges. The first one is coordination failure. The stakeholders in waste governance include environmental departments, sanitation authorities, urban management agencies, market governors, recycling companies, communities, and residents. The system is fragmented when different aims govern these actors. The future of governance must thus focus on integrated planning, data-sharing platforms, and the distribution of responsibility [37].

The second issue is the poor link between recycling and carbon accounting [13]. Most cities measure waste management performance by rates of classification participation, recycling, or disposal reduction, but these measures do not fully capture climate benefits. Future studies are needed to develop more precise models for life-cycle carbon accounting across diverse waste streams, treatment routes, and regional energy systems. This is particularly significant when comparing material recycling, organic waste treatment, incineration, landfill diversion, and reuse.

The third obstacle is unstable markets. The price of recyclable materials is subject to change, and recycled materials tend to compete with low-priced virgin materials. Recycling enterprises might not have long-term economic stability without green procurement, recycled-content standards, EPR fee modulation, and carbon-based incentives [37]. This policy should be supported in the future on both the supply and demand sides of the secondary resource markets.

Lastly, in future studies, more attention should be given to how technology, institutions, and behavior interact [44]. To explain how future research priorities will replace current constraints, and to outline the practical implications for low-carbon urban waste systems, **Table 4** summarizes the main challenges, causes, and effects of these challenges, research directions, and practical implications. Smart bins, AI sorting, digital traceability, and carbon accounting platforms may enhance system performance, but their effectiveness depends on governance design and public acceptance. The following phase of urban solid waste governance must not merely aim to enhance the recycling rate, but rather to establish a low-carbon resource circulation system that is technically sound, economically feasible, socially trusted, and environmentally verifiable.

The overall transition pathway from traditional disposal-oriented waste management to integrated, resource-oriented, and low-carbon governance is presented in **Figure 2**.

Table 4. The challenges and future research directions for low-carbon urban waste systems.

Current Challenge	Underlying Cause	Potential Research Direction	Practical Implication
Unstable classification behavior	Low convenience, weak awareness, and limited trust in recycling systems	Behavioral modeling and community-based governance studies	Improves long-term public participation
Low recycling quality	Contamination, mixed collection, poor sorting precision	AI-assisted sorting, sensor fusion, and quality-control technologies	Increases high-value material recovery
Fragmented governance	Multiple actors with unclear responsibilities	Integrated governance frameworks and cross-departmental coordination models	Strengthens full-chain accountability
Weak carbon accounting	Lack of standardized boundaries and reliable data	Life-cycle carbon assessment for different waste pathways	Supports climate-oriented policy decisions
Market instability for recyclables	Fluctuating prices and low demand for secondary materials	Green procurement, recycled-content standards, and circular supply-chain studies	Improves the economic viability of recycling
Limited organic waste utilization	Contamination and poor product standards	Anaerobic digestion optimization, compost safety assessment, bio-based product development	Reduces methane emissions and increases resource recovery
Technology–society mismatch	Advanced systems may not fit local conditions	Socio-technical evaluation of smart waste systems	Prevents ineffective or unequal technology deployment

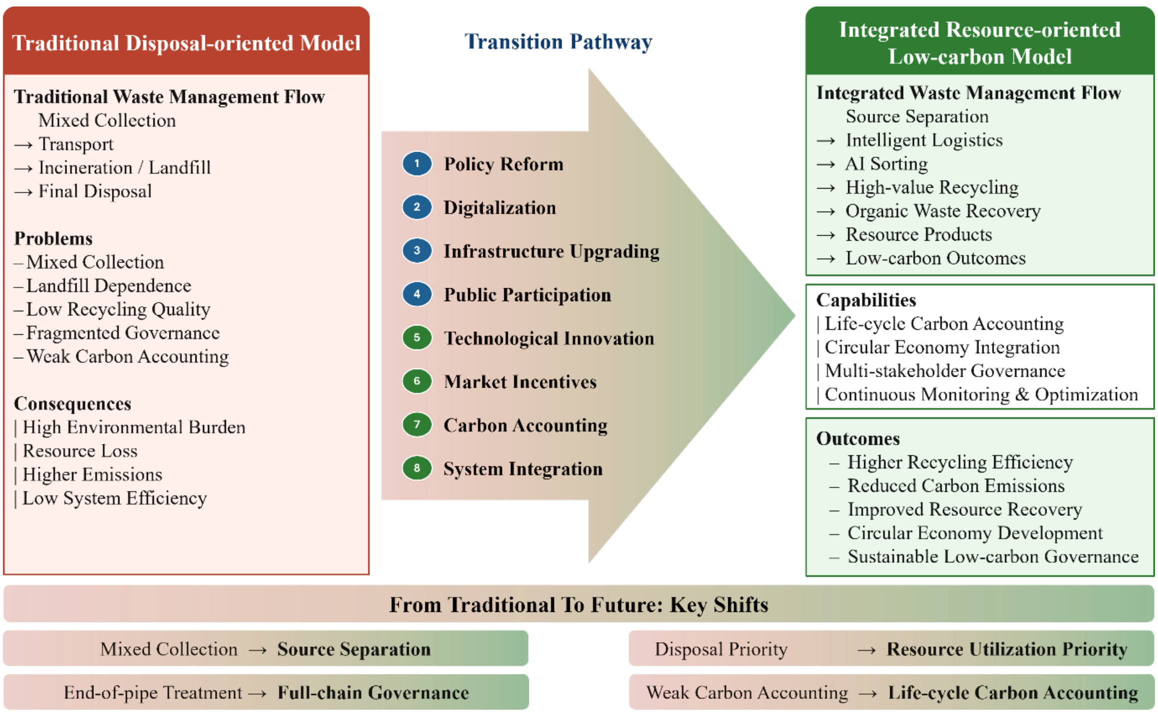

Figure 2. Transition pathway from traditional disposal-oriented waste management to integrated, resource-oriented, and low-carbon urban environmental governance.

5. Conclusion

The classification and recycling system of solid waste in cities is a key element of low-carbon environmental governance, as it links waste reduction, pollution control, and carbon emissions with resource circulation within a single urban management system. This review demonstrates that classification functionality cannot be assessed solely by the number of waste categories and the rate of residents' participation. Rather, it is based on the coordination of the overall chain, including source separation, classified collection, transportation, intelligent sorting, recycling technology, resource utilization, market demand, and policy supervision.

The ongoing transformation of urban waste systems is constrained by several structural limitations, including instability in public participation, irregularity in classification criteria, inadequacy of recycling facilities, inefficiency in carbon accounting, and inefficiency in the high-value exploitation of secondary resources. These issues demonstrate that waste classification is not only a behavioral problem at the household level but also a complex socio-technical governance process. As such, system optimization ought to involve technological innovation coupled with the institutional structure, economic motivation, and societal trust. Recycling and emissions-reduction performance can be enhanced together through digital monitoring, route optimization, AI-based sorting, life-cycle assessment, extended producer responsibility, carbon-credit mechanisms, and green procurement.

With low-carbon development objectives, solid waste management in urban areas must transition to resource-focused governance rather than disposal-oriented treatment. Future studies should enhance full-chain carbon accounting, advance multi-objective optimization models, test the real substitution effect of recycled materials, and explore governance mechanisms applicable across various urban settings. A recycling system and a scientifically developed classification system can turn urban waste into a resource that can be used to develop the circular economy, reduce carbon emissions, and transform urban areas in a sustainable manner.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data is all presented in the article.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this work, the authors used AI tools for grammar checking. The authors subsequently reviewed and edited the content as necessary and take full responsibility for the final content of the published article.

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