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Waste and the Urban Economy: A Semantic Network Analysis of Smart, Circular, and Digital Transitions

Dragan Cisic , Saša Drezgić * , Saša Čegar

Posted Date: 15 July 2025

doi: 10.20944/preprints202507.1261.v1

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Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 15 July 2025 doi:10.20944/preprints202507.1261.v1

Review

Waste and the Urban Economy: A Semantic Network Analysis of Smart, Circular, and Digital Transitions

Dragan Čišić [1], Saša Drezgić [2,*] and Saša Čegar [2]

[1] University of Rijeka, Faculty of Economy, Faculty of Informatics and Digital Technologies, European University Cyprus, European Academy of Sciences and Arts

[2] University of Rijeka, Faculty of Economy

* Correspondence: sasa.drezgic@efri.uniri.hr

Abstract

As cities confront rising populations and mounting environmental pressures, waste is rapidly transforming from a logistical liability into a strategic economic resource. In this article, we investigate the evolving nexus between waste and urban economic systems by analysing over 2,000 scientific publications sourced from Web of Science and Scopus. Using advanced semantic embedding and network analysis, we identify seven major research communities at the intersection of digital innovation, circular economy, and smart urban infrastructure. Through PageRank-based influence mapping, we highlight key contributions that shape each thematic cluster—ranging from AI-powered waste classification to blockchain-enabled traceability and IoT-driven logistics. Our results reveal a dynamic and interdisciplinary research landscape where waste valorisation is not only a sustainability imperative but also a driver of urban economic renewal. This study offers both a conceptual map and a methodological framework for understanding how cities can embed intelligence, efficiency, and circularity into waste systems as part of a broader transition to regenerative, data-informed urban economies.

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Introduction

As urban populations increase and cities grow denser and more complicated, the economics of waste are increasingly impossible to ignore. Conventional disposal practices, dumping, and incinerating are both ecologically and economically nonviable. More and more waste is now viewed as a potential resource with untapped economic value. It's part of a larger shift in how cities manage their material flows, transitioning from a linear model of consumption and disposal to a more circular, restorative urban economy. In this perspective, waste is not the end of the life of a product, but the raw material of new economic activities.

Urban waste flows are varied, including organic leftovers, construction debris, electronic waste, and industrial by-products. These materials, often overlooked in conventional economic planning, are now being reconsidered for their potential to fuel local industry, reduce raw material imports, and generate new forms of employment. Cities that successfully integrate waste into their economic planning can reduce costs, create green jobs, and stimulate innovation. For instance, food waste can be transformed into biogas, construction rubble into recycled materials, and e-waste into recoverable rare metals—each representing a node in a broader value chain that links waste to economic renewal.

This transformation is being accelerated by the digitalization of urban infrastructure. Artificial intelligence, the Internet of Things (IoT), blockchain and a variety of other technologies are adding smarts and traceability to city waste systems. Such tools help to monitor the waste in real time, automate sorting and classification, and deliver clear and transparent transactions throughout the recycling system. For city economies, that not only means greater efficiency and cost savings, but also new data-driven input for city planners and industrial policies. Smart waste solutions are becoming part of the future-proofed economies of successful cities.

In this article, we explore the evolving relationship between waste and the urban economy by analysing a curated collection of scientific literature sourced from two leading academic databases: Web of Science and Scopus. Through semantic network analysis and thematic clustering, we examine how emerging technologies, circular economy principles, and industrial cooperation are reshaping the perception and management of waste. By identifying key trends and influential contributions in the literature, in this study, we stress how waste is becoming a central component of economic strategy in cities transitioning toward sustainable, low-carbon futures.

Literature Review

Reforming a city into sustainability and efficiency has always been the core idea of cities for design and planning, and how intelligent technology be incorporated into the urban waste management system is a hot research issue in waste management systems now. The literature on solid waste management in smart cities is highly converged with the application of the Internet of Things (IoT), artificial intelligence (AI), machine learning, and data-driven approaches to solve the myriad of challenges in solid waste collection, supervision, segregation, and disposal. With the continuous increase in waste generation rates in fast-urbanizing areas, conventional systems are no longer sufficient making researchers develop smarter, connected, and predictive approaches that maximize operational performance, minimize the operational cost and are environment-friendly.

This review is based on a corpus of 2,297 distinct articles retrieved from Scopus and Web of Science, filtered for relevance using a semantic similarity threshold (cosine > 0.9) and clustered into thematic communities using the Louvain algorithm to reveal prevailing research trends and interconnections in the field.

A considerable part of recent research emphasizes the deployment of IoT-enabled sensors and smart bins as a foundational infrastructure for real-time waste monitoring. For instance, Qureshi et al. [1] and Ali et al. [2] describe smart solid waste bin systems that use sensor networks and mobile technologies to notify municipal services when bins are full, thus enabling timely collection and reducing overflow incidents. Asha et al. [3] and Shekhawat and Uniyal [4] reinforce the effectiveness of such systems, demonstrating that real-time feedback loops help optimize routing and reduce public health risks. Mehta and Singh [5] show that smart bins increase garbage collection frequency while significantly reducing missed pickups and operational costs.

AI and machine learning are being integrated to further optimize waste-handling processes. Chauhan et al. [6] propose a deep neural network approach for automatic waste categorization, outperforming traditional image classifiers and improving segregation at source. Hasan et al. [7] deploy a CNN-based classification system in conjunction with IoT-enabled smart bins to automate waste sorting and enhance recycling efficiency. Sanjay et al. [8] integrate machine learning with sensor data for predictive route optimization, showing measurable gains in cost reduction and environmental impact.

The architecture and systemic integration of waste management technologies also obtain considerable attention. Ahmed et al. [9] propose a comprehensive AI and IoT architecture for municipal waste automation, including bin-level monitoring and optimized vehicle dispatch. Kasat et al. [10] emphasize the mobility aspect of waste management by incorporating GPS-enabled trucks and dynamic routing into centralized waste tracking systems. Haribabu et al. [11] and Chaudhari and Bhole [12] present early prototypes of mobile-linked smart bins and cloud-based monitoring systems, laying the groundwork for scalable municipal deployment.

Several studies provide holistic reviews and systematizations of current practices and research gaps. Sosunova and Porras [13] and Alaoui et al. [14] conduct systematic literature reviews of IoT-enabled waste management systems, identifying trends such as the use of smart garbage bins (SGBs), route optimization, and predictive maintenance. Silva et al. [15] and Joshi et al. [16] frame smart waste management within broader smart city architecture, noting that while technological components exist, socioeconomic and governance challenges still hinder widespread adoption. Szpilko et al. [17] use bibliometric analysis to map the evolution of waste management research in smart cities and point to emerging priorities such as energy recovery, citizen engagement, and policy standardization. Karger et al. [18] further demonstrate how AI-focused bibliometric studies reveal cross-sector innovations in mobility, energy, and waste within the smart city paradigm.

The reviewed literature clusters into several overlapping themes: infrastructure-focused research on IoT-enabled monitoring systems, algorithmic approaches integrating AI and machine learning, system-level architectural innovations, and socio-policy frameworks embedded in urban sustainability. This thematic convergence reflects a maturing field where technological and governance models are increasingly interdependent.

Recent advances have also addressed unplanned and seasonal waste, which traditional systems often neglect. Belhiah et al.[19] propose an IoT-based platform to manage sporadic waste types through GIS mapping and dynamic scheduling. Idwan et al. [20] focus on optimization algorithms, developing a multi-truck routing model to improve collection efficiency using agent-based simulation and genetic algorithms. Hussain et al. [21] use multi-agent simulation to compare traditional and IoT-driven models, demonstrating the benefits of sensor-based monitoring in reducing truck mileage and increasing public satisfaction. Giang et al. [22] reveal the extent of plastic waste leakage into lagoon systems in Vietnam, underscoring the need for targeted policy and source reduction strategies. Hannon and Zaman [23] emphasize that the conceptual framing of zero waste catalyses innovation and public engagement, contributing to the rethinking of waste management practices. Bibri and Krogstie [24] illustrate through Swedish eco-city districts how systemic design and behavioural interventions jointly shape sustainable waste outcomes. Ramaiah and Avtar [24] highlight the critical role of local communities and water management in maintaining green spaces and urban sustainability in India. Terama et al. [25] argue that integrating the SDG framework into Nordic urban planning has opened pathways for more inclusive and coordinated sustainability strategies. However, the success and scalability of these technologies are context-dependent; for example, while IoT-based routing has proven efficient in high-density urban areas, rural or resource-constrained settings often lack the infrastructure to support real-time data systems, leading to uneven implementation success.

While the reviewed contributions advance a shared vision of efficiency and adaptability, they also reveal notable tensions. For instance, high deployment costs and fragmented data standards often delay scaling beyond pilot implementations. Moreover, several studies assume technology acceptance without adequately addressing behavioural or institutional inertia in local governance structures.

Moreover, many smart waste systems implicitly support circular economy goals by promoting resource recovery, closed-loop recycling, and material flow optimization, though this connection is often under-theorized in the literature and requires more explicit policy framing.

At the same time, this literature has emphasized the necessity of a holistic data-oriented approach to waste management in smart cities. IoT, AI, and machine learning are coalescing in adaptive systems which do not merely respond to when waste is being piled, but foresee trends even in the way plans are executed. However, issues like high start-up investment costs, data interoperability, and lack of standardization still persist. This requires innovation in all aspects of the waste management system with a focus on policy reform and stakeholder engagement, hybrid rather than purely technical solutions, are those that have the most potential for realising the value proposition of smart waste systems on sustainable urban futures.

Importantly, few studies engage with the role of informal waste workers in transitioning systems, despite their critical contributions in many cities, raising questions about inclusivity, job displacement, and equitable access to new infrastructure.

Methodology

Our methodology integrates AI-driven text analysis with social network analysis (SNA) to examine how scientific articles connect through shared conceptual content as demonstrated in Drezgić et al. [26]. We began by downloading 3,567 articles in total, 2,448 from Scopus and 1,119 from Web of Science. After deduplication, 2,297 unique articles remained for analysis. To identify relationships based on textual content, we employed the BAAI/bge-small-en-v1.5 transformer model to embed the article abstracts into a high-dimensional vector space that captures semantic meaning.

Cosine similarity was computed between all article pairs, yielding a similarity score from 0 to 1, where values closer to 1 indicate greater semantic relatedness. Articles with a cosine similarity score above 0.9 were considered conceptually linked. This threshold resulted in a semantic network comprising 788 connected articles, while 1,509 articles did not exhibit strong enough semantic alignment to be linked. This network of articles, defined by meaningful textual overlap, forms the foundation for further structural analysis.

After generating this semantic map, we applied SNA techniques to interpret the network's topology. Each article became a node in the graph, and edges were created between nodes that surpassed the similarity threshold. This structure reveals the thematic proximity and intellectual flow across the corpus. Using established SNA tools and metrics, such as those by Freeman, we identified prominent subgroups and influential nodes within the network.

Unlike traditional citation or co-authorship networks, our approach uncovers relationships based solely on textual content. This enhances the ability to trace thematic patterns, expose research gaps, and detect emerging clusters. Notably, SNA has been previously applied to analyse citation links, Twitter networks, and author collaborations. However, by starting from AI-derived semantic relationships, our study introduces a novel perspective for mapping the knowledge structure of scientific fields.

We used the Louvain algorithm for community detection. This algorithm clusters nodes into communities by maximizing modularity, a measure of how well-connected nodes are within a group compared to outside it. Initially, each node starts in its own group, and the algorithm iteratively reassigns nodes to neighbouring communities to improve modularity. It aggregates groups and repeats this process until further optimization yields negligible gains.

The resulting network featured clusters of varying sizes. We applied post-processing to exclude trivial communities (i.e., clusters with too few articles), ensuring the analytical focus remained on substantial thematic structures. For overly large clusters, we used recursive sub-clustering to uncover internal structures.

To identify the most influential articles within each cluster, we calculated both Degree Centrality and PageRank. Degree Centrality highlights articles with the most direct links—those that are semantically related to many others—while PageRank considers the quality of connections, favouring articles linked to other central works. Together, these metrics help spotlight key contributions that shape each thematic area.

This combined methodology—embedding articles using transformer-based models, building a semantic similarity network, and analysing it with SNA—provides a robust framework for uncovering the intellectual structure and thematic evolution within complex scientific domains. It also demonstrates the potential of semantic AI and network science to enrich literature reviews and strategic research planning.

Results

The study began with a dataset of 3,567 scientific articles retrieved from Scopus (2,448 articles) and Web of Science (1,119 articles). After removing 1,270 duplicate entries, we retained a total of 2,297 distinct articles for semantic analysis. Using the BAAI/bge-small-en-v1.5 transformer model, each article's abstract was vectorized into a high-dimensional semantic space. Pairwise cosine similarity

 doi:10.20944/preprints202507.1261.v1

was computed across all articles, with a strict threshold of 0.9 applied to define meaningful conceptual connections.

This filtering yielded a connected semantic network of 788 articles, while 1,509 articles remained isolated, lacking strong semantic similarity with others in the corpus. Within this network, each article represents a node, and links (edges) indicate semantic similarity scores above the 0.9 threshold. The resulting graph contains 3,767 edges, reflecting a total of 788 nodes with an average of approximately 4.78 connections per article. The global clustering coefficient of 0.3919 suggests a moderately cohesive structure, with several localized clusters of densely connected research.

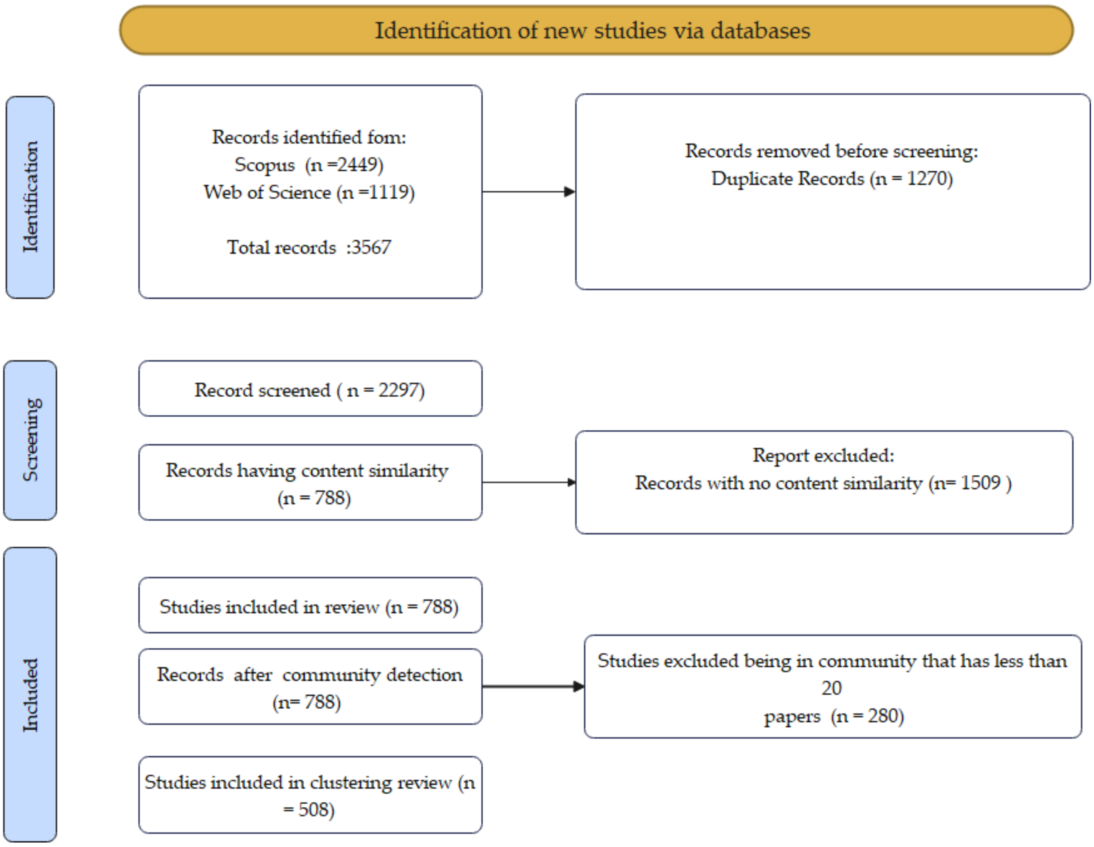

Figure 1. Prisma flowchart.

The network visualization is shown in Figure 2. To uncover the underlying thematic structure, we applied the Louvain algorithm for community detection. This process yielded 126 communities of varying sizes. However, our analysis focused exclusively on communities with more than 20 articles, resulting in seven communities qualifying for in-depth thematic exploration. The remaining communities were relatively small: 98 had two articles, 14 had three articles, 4 had four, and 10 were singular instances of slightly larger but still analytically marginal groups.

Figure 2. Waste management articles similarity graph.

This selective focus on substantial clusters allows for clearer thematic interpretation and centrality assessment in the next phase of the analysis.

The seven largest thematic communities identified through the Louvain clustering algorithm vary significantly in both size and internal connectivity, reflecting the diverse thematic orientations and maturity levels within the research field.

The largest community, titled IoT-Enabled Management Systems in Smart Cities, consists of 124 nodes and 994 edges, yielding an average degree of 8.02. This high average degree indicates a densely interconnected cluster, suggesting that articles in this group share strong semantic alignment around the development and integration of IoT infrastructure for urban services. Closely following is the AI-Powered Waste Classification and IoT-Enabled Infrastructure in Smart Cities cluster, with 98 articles and 733 edges, resulting in an average degree of 7.48. This community demonstrates a similarly dense structure, likely reflecting intensive methodological cross-linking between AI-based classification models and IoT-supported implementation strategies in waste systems.

The third most prominent cluster, IoT-Based Smart Waste Monitoring and Management Systems, contains 106 articles and 649 edges, with an average degree of 6.12. While slightly less dense than the top two, it still reflects substantial cohesion, indicating a mature and interconnected subfield dedicated to sensor-based monitoring, smart bins, and real-time data analytics for waste tracking.

In contrast, Blockchain-Driven Waste Management in Smart Cities and Circular Economy and Smart Waste Management in Sustainable Urban Transitions consist of 38 and 40 articles respectively,

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with average degrees of 3.55 and 2.08. These clusters exhibit more moderate connectivity, suggesting either emerging research topics or more conceptually diverse subfields. The former likely represents the novel integration of blockchain into traceability and transparency of waste flows, while the latter focuses on policy-driven or systems-level frameworks linking waste to circular economy goals.

The two least connected communities are AI and IoT Architectures for Sustainable Smart Cities (76 nodes, average degree of 1.51) and Intelligent Routing and Optimization Models for Smart Waste Logistics (28 nodes, average degree of 1.61). Their low internal connectivity points to thematic fragmentation or the recent emergence of topic overlap, particularly in the case of optimization algorithms being applied across distinct research niches. These findings highlight varied stages of cohesion and thematic development across the seven major clusters and provide a structured foundation for qualitative thematic interpretation in the subsequent discussion.

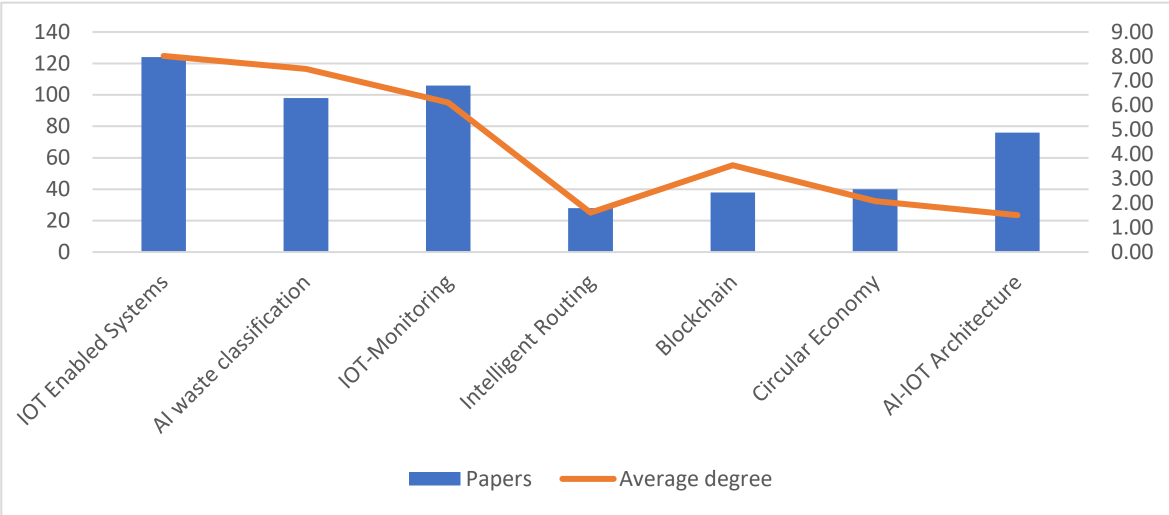

Figure 3. Thematic clusters and Connectivity.

In the sections that follow, we present the results of this analysis for each of the major communities identified through our network modelling. These communities represent distinct but interrelated dimensions of how waste is conceptualized within the urban economy, including smart waste logistics, digital infrastructure, AI-enabled classification systems, and circular economy practices.

Circular Economy and Smart Waste Management in Sustainable Urban Transitions

This community brings together research at the intersection of circular economy principles and smart city strategies, particularly focusing on waste management as a core urban sustainability challenge. The papers collectively examine how integrating circularity into urban planning, through technology, policy, and citizen engagement, enhances the efficiency and resilience of waste systems. These studies use bibliometric, case-based, and empirical approaches to map current practices, assess challenges, and propose frameworks for sustainable waste governance in cities globally. Together, they underscore that waste is not merely a by-product but a resource stream whose intelligent handling can shape the next generation of sustainable cities.

Several studies conduct bibliometric reviews on the convergence of circular economy and smart city paradigms. Santibanez Gonzalez et al. [27] identify major research themes linking circular economy and smart city development, emphasizing waste management and sustainability as central intersections. Manjushree et al. [28] map the evolving interdisciplinary field combining smart cities and circular economy, proposing integrative research directions. Brglez et al. [29] deepen this mapping by identifying interconnected themes like urban metabolism, value chains, and adaptive reuse as emerging anchors for circular city thinking. Fernando et al. [30] analyse circular supply chains in smart cities using machine learning and bibliometrics, advocating for reverse logistics and remanufacturing as key enablers of resource efficiency.

Additional works explore circular economy in urban policy and planning. Möslinger et al. [31] examine 362 European cities' pathways toward climate neutrality, revealing best practices and governance challenges in adopting circular approaches to waste. Paoli and Pirlone [32] propose a cross-sectoral planning framework to include interlinked circular actions in urban policy, using Genoa as a pilot case. Formisano et al. [33] quantify the relationship between circular economy and smart sustainable cities in the EU, highlighting that waste management is the most impactful contributor to urban smartness. Lakatos et al. [34] synthesize key characteristics of circular cities and propose a framework to guide their transition, emphasizing recirculation, innovation, and citizen support. Pegorin et al. [35]contrast circular cities with other sustainable urban typologies, showing that circular strategies intersect with all major models, including green and resilient cities.

In terms of empirical case studies, Hamdan et al. [36]) assess municipal solid waste practices (SWM) in ten Indian smart cities, focusing on the feasibility of waste-to-energy transitions. Ganesh et al. [37] analyse SWM in Tamil Nadu's smart cities, proposing an integrated framework centred on source segregation and public-private partnerships aligned with circular principles. Kumari et al. [38] conduct a household-level assessment in Pune, identifying opportunities for improving door-to-door collection and segregation under smart city programs. Ghosh et al. [39] present a comparative evaluation of waste systems in three Indian cities, showing that decentralization, source segregation, and energy conversion facilities have enabled scientific disposal. Menghani et al. [40]use a case study from Vadodara to compare traditional waste management and a more sustainable, incentive-based model, underscoring gaps in citizen satisfaction and awareness.

Several papers review the broader smart city waste agenda. Szpilko et al. [17] perform a systematic literature review of smart city waste management, identifying technological innovation, citizen engagement, and energy recovery as future priorities. Their findings, alongside newer contributions, suggest a notable shift from technology-centric pilot studies toward more integrated, governance-oriented approaches in recent years, indicating a maturing research agenda. Venes et al. [41] focus on global trends in waste collection and transport technologies, noting that while economic and environmental aspects are well covered, social dynamics—especially the role of informal workers—remain underexplored. Cheela et al. [42] highlight policy pathways and stakeholder roles in Indian smart cities, emphasizing funding, data use, and service benchmarking. Mokale [43]contrasts smart waste management implementation in small towns and metropolitan cities across India, identifying infrastructural and behavioural gaps. Batar and Chandra [44]assess the SWM system in Jaipur, proposing improvements rooted in best practices to align with smart city objectives. Mingaleva et al. [45] explore Russia's transition to green and smart cities, concluding that localized waste sorting at inter-municipal landfills and civic engagement are critical for success.

IoT-Enabled Waste Management Systems in Smart Cities

This community centres on the design, implementation, and evaluation of Internet of Things-based waste management systems tailored for smart cities. As a group, these studies reflect an evolution from conventional waste collection toward real-time, data-driven, and automated systems. The core innovations include smart bins equipped with sensors, route optimization algorithms, real-time data dashboards, and integration with low-power communication protocols. The research emphasizes improvements in efficiency, cost reduction, environmental impact, and service reliability, while also addressing common limitations such as scalability, interoperability, and the need for standardized frameworks.

Several studies propose novel system architectures or holistic frameworks. Henaien et al. [46] introduce a smart waste system integrating IoT, LPWAN, and ITS technologies, validated through usability tests that show increased monitoring accuracy and reduced operational costs. Aleyadeh and Taha [47] present a two-tier architecture combining real-time bin monitoring and dynamic routing while incorporating environmental awareness and illegal dumping detection. Ahmed et al. [48]

 doi:10.20944/preprints202507.1261.v1

review AI and IoT-based municipal waste systems, emphasizing automated data collection and route optimization to reduce costs and emissions.

In the context of system enhancement, Zoumpoulis et al. [49] propose a novel smart bin based on Industry 5.0 principles, addressing limitations in current commercial solutions through enhanced sensing, automation, and data analytics. Similarly, Joshi et al. [16] developed a smart framework that integrates Sweden's best practices with IoT, colour-coded waste segregation, cloud data storage, and route optimization via vehicle tracking systems. Sanjay et al. [8] combine IoT with machine learning for real-time optimization and show performance improvements via simulation and real-world deployments.

Numerous contributions provide simulation-based validations. Idwan et al. [20] developed and simulated the MITRA algorithm to manage truck routing with smart dumpsters, reducing service time and congestion. Sankar and Fathima [50] propose the IoTBinCap algorithm, which outperforms traditional scheduling models by improving resource use and reducing overflow events. Anagnostopoulos et al. [51] present dynamic waste collection algorithms focused on high-priority urban areas such as schools and hospitals.

Systematic reviews also feature prominently. Sosunova and Porras [13] conducted a large-scale literature review identifying key sensor types, data-sharing patterns, and stakeholder roles in smart waste systems. Alaoui et al. [52] expand this by offering implementation recommendations and calling for hybrid IoT-AI systems, highlighting gaps in data privacy and standardization.

Several studies highlight real-world deployments and case studies. Kasat et al. [10] deploy IoT in urban India, integrating sensor-equipped bins, vehicle telemetry, and analytics to optimize route planning and collection schedules. Vishnu et al. [53] validate a dual-tier monitoring system across public and household bins using LoRaWAN and Wi-Fi networks, emphasizing battery performance and GUI integration. Belhiah et al. [19] focus on unplanned waste types like construction debris in Tangier, Morocco, employing a modified routing algorithm for responsive collection.

Others investigate comparative evaluations or performance analytics. Hussain et al. [54] simulate multi-agent IoT environments, contrasting predictive routing with traditional methods and showing measurable improvements in fuel use, cost, and public satisfaction. Mehta and Singh [5] analyse six months of real-time bin deployment, reporting significant reductions in overflow, missed collections, and operational costs. Shukla and Hait [55] explore cyber-physical integration for full lifecycle waste tracking, promoting AI and RFID for segregation and recycling.

Early works such as Chaudhari and Bhole [12] lay foundational principles for cloud-based bin monitoring and dynamic collection using mobile apps, while Anagnostopoulos et al. [56]) survey ICT-enabled waste models, setting the stage for future smart waste research by identifying key architectural strengths and limitations.

This community illustrates a rapidly maturing field where IoT-enabled smart waste systems are not only technologically viable but critical for the operational and environmental sustainability of urban ecosystems.

IoT-Based Smart Waste Monitoring and Management Systems

This community focuses on the integration of Internet of Things (IoT) technologies into waste collection and monitoring systems within the context of smart cities. This community is about building and testing smart bins, practical, close-to-user, and hardware-oriented. Previous community addresses how entire cities can manage waste intelligently, considering system optimization, integration, and policy planning The research in this community collectively addresses the challenges of overflowing bins, inefficient collection routes, and lack of real-time data by proposing sensor-enabled smart bins, wireless communication networks, and mobile applications for municipal coordination. These studies underscore the importance of timely waste disposal, hygiene enhancement, and environmental protection, while also examining cost efficiency, user engagement, and scalability. The widespread application of IoT across diverse urban contexts highlights the technology's potential to automate and optimize solid waste management in developing and developed city infrastructures.

Several studies propose full smart bin systems integrated with IoT sensors and remote communication tools. Roshan and Rishi [57] design a dynamic, stakeholder-integrated waste management system using smart bins and route optimization tailored for India's urban settings. Mittal et al. [58] present an intelligent bin with odour, weight, flame, and fill-level sensors to ensure scalable and hygienic waste disposal in smart cities. Haribabu et al. [11] propose a mobile-app-enabled smart bin system to replace traditional bins and reduce roadside littering in developing cities. Gupta et al. [59] introduce a smart bin that classifies waste into biodegradable and non-biodegradable, providing a flexible, scalable solution for smart city integration.

Other studies emphasize the importance of efficient communication and bin status alerts. Sathishkumar et al. [60] propose a dustbin monitoring system with dumpster alert functions using odour and toxicity detection to prevent overflow and environmental degradation. Qureshi et al. [1] suggest a cost-effective, fast-response system integrating sensors, cellular networks, and social media to notify authorities about bin status. Keerthika et al. [61] implement low-cost embedded devices that detect bin fill levels and automatically alert waste collection drivers. Kumar et al. [62] propose an IoT-based smart bin network that communicates with trash collection vehicles and optimizes their routes in real time.

Several studies have enhanced smart bins with more advanced sensors and user interfaces. Shekhawat and Uniyal (2021) designed a real-time garbage monitoring system that uses ultrasonic and gas sensors to track ammonia emissions and air quality. Shanthini et al. [4] developed a smart bin with waterproof sensors and mobile app integration for user-level interaction and garbage status updates. Ravi et al. [63] propose an IoT-enabled garbage system for route planning, real-time bin monitoring, and municipal coordination via mobile applications. Nirde et al. [64] present a GSM-based alert system to notify municipal teams when bins reach capacity, aiming to optimize collection time and cost.

Additional contributions focus on system-level analysis and overviews. Chaudhari et al. [65] provide a comprehensive review of hardware integration in smart bins using ultrasonic and weight sensors, describing GSM alert triggers and threshold-based notifications. Asha et al. [3] offer a structured review of IoT-based waste management, highlighting architectural components and real-world case studies. Ali et al. [2] designed a smart waste monitoring system that also forecasts waste generation and includes fire detection capabilities. Gattim et al. [66]) include hazardous gas monitoring and community notification before garbage truck arrival, integrating public awareness with technological monitoring.

Finally, several papers present unique functional or regional innovations. Bali and Mathur [67] focus on reducing fuel and work hours by finding optimal collection paths using IoT-enabled smart dustbins. Sathyamoorthy et al. [68] propose a smart city waste system that includes gas, temperature, and motion sensors for contactless interaction and bacterial hazard reduction. Rajeshvaran et al. [69] introduce smart dustbins with AI segregation and odour detection, linked to a mobile app for public and worker coordination. Durga Devi et al. [70] implement an Arduino-based alert system that transmits garbage levels to authorities, supporting cleaner and more efficient public waste services.

Intelligent Routing and Optimization Models for Smart Waste Logistics

This community focuses on advanced computational strategies and intelligent decision-support systems aimed at optimizing urban waste collection in smart city contexts. It consolidates research on dynamic vehicle routing, heuristic algorithms, and mathematical models that enhance efficiency, reduce environmental impacts, and accommodate real-time urban complexities. These works highlight the growing importance of integrating optimization techniques with IoT data, cloud computing, and AI algorithms to support scalable and adaptive waste management infrastructure. The cluster serves as a critical foundation for cities seeking to operationalize sustainability through high-performance logistics and intelligent waste handling.

doi:10.20944/preprints202507.1261.v1

Several studies address dynamic route optimization using nature-inspired algorithms. Sharmin and Al-Amin [71] proposed a cloud-based dynamic waste collection system using ant colony optimization to define shortest routes based on real-time sensor data and adaptable to urban disruptions. Reji et al. [72] developed an IoT-based system combining a Swin Transformer for waste classification and ACO for optimizing collection paths, demonstrating very high accuracy in classification and routing. Alwabli et al. [73] introduced a dynamic vehicle routing solution for bin collection based on ACO to reduce unnecessary truck operations. Wang et al. [74] integrated the Internet of Vehicles with an enhanced ACO algorithm, modelling asynchronous vehicle coordination to reduce congestion and cut collection and transportation costs. Thangarasu and Alla [75]used a hybrid approach merging ACO with Harmony Search to optimize bin routes and resource use while improving sustainability metrics.

Several papers apply genetic algorithms or compare heuristic routing techniques. Ozmen et al. [76] introduced a GA-based route planner for waste trucks tested in a simplified urban scenario to optimize efficiency using real-world data. Melo et al. [77] proposed a genetic algorithm for garbage truck routing to reduce fuel consumption, considering traffic and bin positions. Ahmad et al. [78] implemented a multi-objective optimization system using evolutionary methods to generate cost- and distance-efficient waste carrier routes, validated on real waste data from Jeju Island. Begum et al. [79] performed a comparative study of shortest-path algorithms—including ACO and Dijkstra—to optimize waste truck routes across ten stations in Bengaluru to minimize fuel and emissions.

Another group explores mathematical programming and stochastic models. Noreña-Zapata et al. [80] introduced a mixed-integer linear programming model and a metaheuristic to solve the periodic location-routing problem for waste separation and logistics, showing significant efficiency gains over exact solvers. Akbarpour et al. [81] developed a stochastic vehicle routing model for smart cities that accounts for waste separation uncertainty and recovery value, solved using metaheuristic optimization and chance-constrained programming.

Petri net-based modeling forms another sub-theme. Dolinina et al. [82] used Petri nets with priorities to simulate and optimize solid waste disposal processes, allowing the incorporation of probabilistic transitions for dynamic adaptability. In follow-up studies, Dolinina et al. [83]explored the same modelling apparatus to simulate truck behaviour under empirical data and optimize container filling rates, idle time, and job assignments. Dolinina et al. [84] also proposed a hybrid Petri net and expert system model for municipal waste transport management, evaluating system decisions based on probabilistic thresholds.

Further research contributes to route planning and vehicle coordination enhancements. Bouleft and Alaoui [85] presented a hybrid GA-based solution to the dynamic multi-compartment vehicle routing problem, minimizing transport and overflow penalties in selective waste collection. Kim et al. [86] tackled uncertainty in bin fill levels with a clustered VRP approach using a hybrid ACO and K-means algorithm, integrated with IoT data and operational constraints. Alaliyat et al. [87] addressed on-demand waste collection in Alesund, Norway, proposing a data-driven model comparing routing algorithms under multiple real-world constraints. Hurtado-Olivares et al. [88] proposed a hybrid simulated annealing algorithm combined with greedy initialization for optimizing time-windowed waste collection from tourism sector facilities, modelled in an industrial district context.

Blockchain-Driven Waste Management in Smart Cities

This community focuses on the application of blockchain technology, often combined with IoT, in enhancing transparency, traceability, and efficiency in waste management systems. The research spans general frameworks for solid waste and e-waste management, smart contract implementations, traceability solutions, and the role of blockchain in circular economy models. The overarching contribution of this community lies in its effort to replace manual, opaque, and inefficient systems with decentralized, auditable, and secure digital infrastructures suited to smart city contexts.

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Blockchain is shown not only to improve operational logistics and regulatory compliance but also to incentivize sustainable behaviours among stakeholders.

Several papers deal specifically with electronic waste (e-waste) using blockchain and smart contracts to ensure safe disposal and full lifecycle traceability. Santhuja and Anbarasu [89] propose a blockchain-enabled IoT solution that monitors e-waste bins and automates collection processes through smart contracts. Kumar and Al-Sharif [90] focus on consistent tracking of e-waste disposal from origin to final point using a decentralized ledger, supported by machine learning analytics to detect incomplete disposal. Rafiee et al. [91] simulate the entire e-waste lifecycle using coloured Petri nets on a blockchain platform with smart contracts to ensure service reliability and transparency. Shyamala Devi et al. [92] introduce a permissioned blockchain framework with cryptographic security for multi-stakeholder visibility into e-waste flows. Chithra et al. [93] address blockchain's ability to handle lifecycle traceability and secure data standards, including encryption, in India's largely unregulated e-waste sector.

Further studies address general solid waste management and its integration with blockchain infrastructures. Sen Gupta et al. [94] developed a proof-of-concept system using Ethereum smart contracts to compare blockchain-based waste logistics with traditional models. Gopalakrishnan et al. [95] designed a blockchain-based traceability system that enables stakeholders to access reliable waste data and optimize service selection. Castiglione et al. [96] propose a blockchain system tied to citizen reward mechanisms and cost optimization in a circular economy framework. Ahmad et al. [97] survey use cases of blockchain in solid waste operations, including compliance, auditing, fleet tracking, and smart contracts, identifying research gaps and future challenges. Baralla and Pinna [98] provide a critical analysis of blockchain's transformational role in solid waste tracking and compliance within smart cities. Makani et al. [99] and Chugh et al. [100] offer broader reviews on blockchain in urban sustainability, emphasizing its application in waste as one of several smart city domains.

Some papers emphasize the convergence of blockchain and IoT infrastructures for real-time monitoring and data-driven optimization. Filho et al. [101] and Chandra Sekhar et al. [102]implement systems combining LoRaWAN and blockchain to remotely monitor fill levels in waste bins, addressing overflow and collection inefficiencies. De Almeida et al. [103] simulate the viability of LoRaWAN for differentiated waste collection on university campuses, suggesting broader smart campus applications. Fedchenkov et al. [104] describe early implementations of LoRaWAN and IoT protocols in pilot smart waste management systems, contributing architectural lessons for future deployments. Jeyabharathi et al. [105]explore how blockchain-linked IoT sensors can provide real-time waste tracking and dynamic penalties or incentives. Finally, Paturi et al. [106]combine blockchain, smart contracts, and IoT to create a reward-based waste bin system tested across different blockchain networks for performance comparison.

AI and IoT Architectures for Sustainable Smart Cities

This community brings together a comprehensive body of literature exploring the integration of artificial intelligence (AI), the Internet of Things and machine learning (ML) as foundational technologies in designing smart cities that are sustainable, adaptive, and citizen-centric. The studies address both theoretical architectures and practical implementations, demonstrating how data-driven models, intelligent infrastructure, and sensor networks improve urban planning, mobility, environmental management, and quality of life. A recurring theme is the convergence of technological innovation with sustainability imperatives, alongside the pressing need for inclusiveness, ethical governance, and scalable deployment models. These contributions as a group offer insight into the current technological landscape, practical case studies, and future research directions essential for evolving smart urban ecosystems.

Several studies focus on the foundational role of AI and IoT in shaping smart city architectures. Bittencourt et al. [107] provide a broad survey on adaptive smart urban systems, emphasizing responsiveness to real-time conditions in domains like mobility, safety, and waste management.

Gourisaria et al. [108] propose a conceptual self-sustained smart city model enabled by AI, IoT, and complex sensor networks, aiming at automation with minimal human intervention. Vishwakarma and Vishwakarma [109] analyze AI and IoT integration in urban planning and service delivery, showing how these technologies enhance functions such as smart traffic, parking, and healthcare. Vivek et al. [110] present a review of IoT applications across various urban domains and address open challenges related to data security and scalability. Ullah et al. [111] highlight how the fusion of IoT and ML enables a data-centric smart environment, demonstrating successful international implementations while addressing privacy and ethical challenges. Soni [112] explores IoT as a front-end for AI in smart city infrastructure, emphasizing its role in generating actionable insights through predictive analytics and real-time feedback loops.

A second group of papers provides bibliometric and model-based overviews of technological trends. Karger et al. [18] conduct a bibliometric analysis of AI in urbanization, identifying major research streams and outlining a future research agenda for mobility, waste, and energy optimization. Hassebo and Tealab [113] review eight global smart city models, mapping IoT applications across sectors and proposing evaluation frameworks. Mrabet and Sliti [114]focus on ML's role in achieving SDG 11, with case studies showing how AI improves resource management and urban sustainability. Sharifi and Khavarian-Garmsir [115] examine climate adaptation in smart cities using bibliometric text mining, identifying technological contributions and potential rebound effects. Gavade [116] discusses how AI, IoT, and big data are transforming urban planning toward low-emission, livable cities, while Nyokum and Tamut [117]propose a stakeholder-based framework for integrating smart technologies into infrastructure planning.

Another subgroup deals with green and sustainable aspects of IoT implementation. Almalki et al. [118] review green IoT strategies that reduce pollution, energy use, and electronic waste in smart city applications. Ramadass et al. [119] focus on the intersection of sustainability and ICT, analyzing how green IoT supports smart governance and public well-being. Sharma et al. [120]examine the role of IoT in environmental monitoring, addressing AI-IoT convergence and its potential for biodiversity and climate data integration.

Some studies concentrate on policy models and comparative urban strategies. Oyadeyi and Oyadeyi [121] present a comparative analysis of Zurich, Oslo, and Copenhagen, identifying strengths in waste-to-energy systems, e-mobility, and urban resilience, while emphasizing the need for public participation and policy innovation. Atanasova and Naydenov [122] analyze successful case studies of smart city transitions in cities like Barcelona, emphasizing the role of participatory governance and tailored technology adoption.

Finally, studies by Silva et al. [15]and Kravchenko [123]outline the technical and architectural foundations of smart cities. Silva et al. provide a structured overview of components, architectures, and adoption barriers, while Kravchenko highlights unresolved IoT challenges including interoperability, security, and government inertia in implementation. These contributions offer practical grounding for technology adoption and point to persistent gaps requiring cross-sector collaboration.

AI-Powered Waste Classification and IoT-Enabled Infrastructure in Smart Cities

This community focuses on AI-based solid waste classification systems and their integration with IoT infrastructures to enable real-time monitoring, segregation, and management within smart urban environments. A core theme across the papers is the deployment of deep learning architectures, particularly CNNs, hybrid CNN-LSTM models, and transformers, for accurately classifying waste into multiple categories such as biodegradable, recyclable, electronic, and biomedical. Additionally, IoT integration enables sensor-driven data collection and automation, improving operational efficiency and enabling predictive analytics for optimized waste logistics. The literature also emphasizes practical deployment frameworks, challenges such as sensor limitations and data security, and the alignment of these technologies with SDG targets and smart city policies.

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Several papers propose enhanced classification models using deep learning. Lilhore et al. [124]introduce a hybrid CNN-LSTM model with transfer learning and adaptive moment estimation, achieving high precision in classifying recyclable and organic waste. Kashaf et al. [125] apply a vision transformer model integrated with IoT for automated categorization of urban waste, highlighting scalability and the use of advanced deep learning methods. Singh et al. [126]) compare CNN and VGG16 models in automated waste segregation, reporting better performance for CNN due to its simpler architecture and better generalization. Gondal et al. [127] develop a real-time waste classification model using a combination of multilayer CNN and perceptron, with a novel camera-based conveyor system achieving 99% accuracy.

A second group of studies integrates CNN models with IoT or embedded systems. Selvi et al. [128]use CNN (DenseNet121) alongside Arduino-based hardware and ultrasonic sensors for real-time bin monitoring and waste classification. William et al. [129] propose a smart waste collection system using IoT sensors and DL for classification, showing significant efficiency in garbage collection. Mohammed Aarif et al. [130] present a smart bin that combines CNN-based classification with IoT sensors for segregating bio and non-bio waste, achieving 97.49% accuracy. Hasan et al. [7] deploy a CNN-based waste classification module integrated into an IoT-enabled microchip bin, providing end-to-end management from collection to sorting. Bonala et al. [131] design an autonomous system with IoT-connected smart bins using DL algorithms for real-time classification and route optimization, though they note challenges with sensor limitations and data privacy.

Several studies focus on hybrid or specialized CNN architectures. Ramya et al. [132] propose a hybrid ResNet152 and MobileNetV2 CNN model using transfer learning for high-accuracy solid waste classification. Kabilan et al. [133] develop a robust CNN architecture with data augmentation and real-time edge deployment for sorting waste into four categories, aimed at smart city and healthcare applications. Zhang et al. [134] use an AlexNet-based CNN for feature extraction and DBN for classification, supported by Optuna for hyperparameter tuning, achieving an R^2 score of 0.94. Cai et al. [135] introduce a novel CT-Net combining CNN and transformers for high-performance sorting on the Huawei cloud dataset, showing improved robustness and processing speed.

A broader system-level perspective is presented in papers addressing end-to-end infrastructure and strategic challenges. Chauhan et al. [6] present a CNN-based waste classification framework, outperforming existing models like AlexNet and VGG16. Malik et al. [136] develop a CNN model for multi-category litter detection in urban areas using transfer learning, optimized for large-scale deployment. Das et al. [137] describe a real-time waste monitoring framework combining CNN and YOLOv3, with six-object class training and real-time adaptability. Cheema et al. [138] implement a decentralized waste grid segmentation model using VGG16 and edge computing to minimize latency. Belsare et al. [139] propose a fog-layer intelligent classification system integrating ResNet101 with IoT and wireless sensor networks, using SVM and AdaBoost for robust object classification. Namoun et al. [140] provide a survey of ML applications in waste generation and disposal prediction, outlining critical barriers like dataset scarcity and model benchmarking.

This community illustrates a rich and maturing field of AI- and IoT-driven waste management innovation, with the convergence of deep learning models and real-time infrastructure yielding scalable, efficient, and sustainable solutions aligned with smart city goals.

Discussion and Next Steps

This study examines a paradigm shift in urban governance: the reimagining of waste not as a terminal burden, but as a dynamic catalyst for economic renewal. Through semantic network analysis of 2,297 scholarly articles, we identify seven interconnected thematic clusters demonstrating how digital technologies, circular economy principles, and systemic innovation are transforming urban material flows. These findings collectively reveal a field undergoing a profound transformation—where waste management evolves from disposal logistics toward becoming a strategic foundation for sustainable urban development.

 doi:10.20944/preprints202507.1261.v1

Our analysis uncovers a diverse intellectual landscape. Certain clusters—particularly those addressing IoT infrastructure and AI integration—exhibit strong internal coherence and advanced technical maturity. Others, such as blockchain applications and circular economy policy frameworks, appear more fragmented, suggesting emergent or transitional stages of development. This thematic breadth signals an expanding conceptualization of waste's role in urban systems.

Using PageRank centrality, we identified pivotal studies anchoring each thematic community. These influential works illuminate critical innovations including AI-optimized collection routes, blockchain-enabled governance models, and IoT-driven operational control systems—demonstrating how technical advances bridge to policy implementation.

Two clusters stand out for their scale and maturity: IoT-Enabled Management Systems (124 articles) and AI-Powered Waste Classification (98 articles). These domains underscore technology's transformative capacity, where real-time monitoring slashes collection costs by 20–30%, AI classifiers achieve over 95% material recovery accuracy, and blockchain traceability enables new markets for secondary materials. Such innovations are actively replacing linear disposal models with intelligent, circular networks.

Nevertheless, significant challenges persist. The AI and IoT Architectures cluster (76 articles) reveals critical gaps in system interoperability, financing mechanisms, and data security frameworks—highlighting that technological potential requires integrated, scalable solutions to achieve impact.

Concurrently, the Circular Economy cluster (40 articles) illustrates how cities from India to the European Union are embedding circularity principles into policy and practice through localized infrastructure solutions like community-level waste-to-energy systems and inclusive partnerships with informal sectors. Despite progress, fragmented governance approaches and underdeveloped recycling ecosystems continue to hinder broader adoption.

Crucially, our analysis identifies urgent research priorities: routing optimization models largely neglect reverse logistics for reuse and repair; digital systems may inadvertently marginalize informal waste workers; and contextually tailored solutions remain underdeveloped, as approaches successful in technologically advanced cities often prove unsuitable for resource-constrained municipalities.

Moving forward, three pathways merit priority attention: deeper investigation into the socioeconomic implications of digital waste systems, integration of practice-based evidence beyond academic literature, and stronger conceptual bridges between technical innovations and policy-equity frameworks. Through such integrative approaches, cities can fundamentally reconfigure waste from an operational liability to a cornerstone of resilient urban economies.

Our future research should aim to deepen the socio-technical and policy relevance of the findings presented in this study. First, a more in-depth socioeconomic analysis is needed to examine how digital waste systems affect vulnerable populations, such as informal waste workers or low-income communities. The transition to automation may unintentionally marginalize these groups unless accompanied by retraining programs, inclusive platform designs, and equitable access policies.

Next, a focused analysis of cross-cluster interactions can uncover valuable synergies—for instance, how AI-powered waste classification (Cluster 7) might supply high-fidelity data to blockchain-based traceability systems (Cluster 5), creating a transparent and responsive recycling value chain. Furthermore, while the dataset spans global sources, future work should develop comparative regional analyses, identifying how smart waste priorities and implementation barriers differ between low-income contexts (e.g., India or Vietnam) and high-income smart cities (e.g., Sweden or South Korea).

In addition, there is a need to integrate environmental impact quantification through the inclusion of case studies and performance metrics such as carbon emissions reductions, fuel savings from optimized logistics, or increased recycling purity achieved via AI classification. Future work should examine stakeholder engagement strategies in depth, identifying effective models for involving citizens, private sector actors, and informal labour. Strategies such as gamification, reward-based recycling, or citizen science initiatives—as seen in Japan's waste sorting campaigns—may enhance public participation and data quality. Also, the appraisal of technological limitations is essential. The high energy demands of blockchain, the scalability challenges of IoT in underfunded cities, and privacy concerns surrounding AI image recognition should be critically assessed alongside their benefits. Finally, our next research should explore future scenarios for waste management by 2035. These may include the rise of robotic sorters, quantum-optimized logistics, or decentralized AI agents that independently manage neighbourhood-scale waste systems, helping to position waste not only as a resource but as a core component of resilient and adaptive smart cities.

Conclusions

In this article, we explored the evolving relationship between waste and the urban economy through a systematic and data-driven review of the scientific literature. By leveraging semantic network analysis and community detection on a curated dataset from Web of Science and Scopus, we identified major thematic clusters that reflect the changing role of waste in urban systems—from logistical burden to economic catalyst. Our analysis not only maps the knowledge structure of this field but also points to a broader transformation underway: cities are embedding intelligence, transparency, and circularity into waste systems as part of a new economic model.

As researchers and practitioners, we believe this shift represents more than a technological trend—it is a redefinition of urban value creation. Waste, once externalized from economic planning, is now being reintegrated as a source of data, innovation, and resource regeneration. The challenge moving forward is to align these technological potentials with inclusive, just, and scalable policy frameworks that can support the transition toward economically vibrant and ecologically sound urban futures.

Funding: Funded by the European Union, under the GA101136834 - CROSS-REIS. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

Acknowledgments: During the preparation of this manuscript/study, the author(s) used sentence transformer BAAI/bge-small-en-v1.5 for the vectorization of Abstracts in semantic similarity calculation. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

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