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Optimisation and Policy in Waste Management

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ABSTRACT

Waste management systems must decide where waste is collected, how it is transported, where it is treated and under which rules, and operations research supplies the quantitative tools for these decisions. This study maps the published research at the point where optimization and waste policy meet. A Scopus search for "waste management", "optimization" and "policy", screened in four PRISMA 2020 stages, produced a final sample of 967 journal articles and reviews published from 2016 onwards. The records were examined through performance analysis, title-based thematic counts, keyword co-occurrence mapping, a thematic map and a multiple correspondence analysis, together with a reading of the 167 review papers in the sample. Output grew at a compound annual rate of 25.5% between 2016 and 2025, and almost three in five records were published from 2024 onwards. The literature is dispersed across 425 journals and is highly collaborative. Circular economy, sustainability and artificial intelligence form the dominant motor theme, while optimization of solid waste systems and waste-to-energy form two further well-developed themes. Titles on artificial intelligence and machine learning rose from 1.6% to 15.2% of output between 2016–2019 and 2024–2027. Collection and routing, the classic operations research problem in waste management, appear in only 3.7% of titles, and household, residential, citizen or consumer terms in 1.4%. The paper closes with a six-part agenda for future research.

Keywords: *Waste management; Optimization; Operations research; Policy; Circular economy; Bibliometric analysis; PRISMA.*

1. INTRODUCTION

Cities everywhere are producing more waste than their systems were designed to handle. The World Bank estimates that about 2.56 billion tonnes of municipal solid waste were generated worldwide in 2022 and that, without further action, the figure could reach 3.86 billion tonnes by 2050, an increase of roughly 50 per cent (World Bank, 2026). Collection coverage is uneven. In parts of Sub-Saharan Africa only about 31 per cent of waste is collected, and in South Asia the figure is about 67 per cent (World Bank, 2026). The United Nations Environment Programme (2024) warns that poorly managed waste carries costs for the environment, for public health and for local economies. Waste management is therefore not only an environmental question but also one of how cities organize their operations and spend their budgets.

Every stage of a waste system involves a decision. Planners decide which areas to serve and how often, the order in which trucks visit collection points, where to place transfer stations, recycling plants, waste-to-energy facilities and landfills, which treatment technologies to install and at what capacity, and how waste flows between them. These choices are made under limits on vehicles, crews, land and money. They are also made under rules: landfill taxes, recycling targets, carbon prices, extended producer responsibility schemes and collection mandates all change which option is cheapest or feasible.

Operations research provides the methods for making such decisions systematically. It represents a planning problem as a mathematical model with an objective, such as minimizing cost, distance or emissions, and with constraints, such as vehicle capacity, working hours or a policy target, and then searches for the best feasible solution. Earlier surveys show that waste management has

long been a fertile area for these methods, covering strategic decisions such as facility location and tactical and operational ones such as routing and scheduling (Ghiani et al., 2014; Gdowska, 2021). The best-known example is collection routing, which is usually modelled as a variant of the vehicle routing problem. A basic model can be extended with truck capacities, collection days, time windows and several objectives at once (Beliën et al., 2014; Hess et al., 2024). Small instances can be solved exactly with mixed-integer linear programming, while large ones usually require heuristics such as genetic algorithms or simulated annealing. Applied work shows that these methods matter in practice. In an Indian metropolis, for example, a re-optimized truck-routing plan reduced costs compared with the routes previously in use (Kala & Sodhi, 2023).

Real systems are harder than textbook models. Waste quantities change from day to day, road conditions vary, and a route that is shortest is not necessarily the one with the best service level or the lowest emissions (Hess et al., 2024). Policy adds a further layer, because instruments such as carbon pricing or landfill taxes alter costs and constraints in ways that a purely technical model may not capture. A growing body of work now tries to bring optimization and policy together, for instance by comparing network designs under different carbon-policy regimes (Hallak & Abdul Hafez, 2026).

Despite this activity, there is little systematic evidence on how the research at this intersection has developed, which topics organize it and which areas remain thin. Existing reviews tend to focus on one problem type, such as collection routing (Restrepo-Franco et al., 2025), facility siting (Alhassan et al., 2026) or a single technology (Nsekela et al., 2026). This study addresses that gap with a bibliometric review of journal research that combines waste management, optimization and policy. It asks three questions:

- RQ1. How has research on optimization and policy in waste management developed since 2016, and where is it published?
- RQ2. Which topics and keyword groups structure this literature, and how have they changed over time?
- RQ3. Which areas remain under-researched and offer directions for future operations research studies?

The study contributes a reproducible map of 967 journal records, a set of thematic indicators that can be updated as the field grows, and an evidence-based research agenda. The rest of the paper is organized as follows. Section 2 reviews the literature, Section 3 describes the methodology, Section 4 presents the results, Section 5 discusses them, Section 6 sets out a future research agenda and Section 7 concludes.

2. LITERATURE REVIEW

2.1 Review studies in the sample

The sample contains 167 review papers, or 17.3% of all records. Their number has risen sharply: six were published in 2016–2019, 28 in 2020–2023 and 133 in 2024–2027, and 110 (65.9%) appeared from 2025 onwards. Most are narrative or critical reviews. Only 18 describe themselves in their titles as systematic, PRISMA-based, scoping or meta-analytic reviews, and eight as bibliometric or science mapping studies. Table 1 lists the 23 reviews whose titles refer both to waste and to optimization, decision-making, logistics, digital tools or policy. Together they show the main lines of the field: mathematical optimization of waste systems, decision analysis for siting and technology choice, artificial intelligence, reverse logistics and governance.

Table -1: Reviews in the sample that address waste systems together with optimization, decision-making, logistics, digital tools or policy

Authors (year)	Scope of review (title)	Type of study
Lee (2020)	Restructuring municipal solid waste management and governance in Hong Kong: Options and prospects	Review
Vlachokostas et al. (2021)	Multi-Criteria Decision Analysis towards promoting Waste-to-Energy Management Strategies: A critical review	Critical review
Singh (2022)	Sustainable Waste Management Through Systems Engineering Models and Remote Sensing Approaches	Review
Hoy et al. (2024)	Municipal solid waste management for low-carbon transition: A systematic review of artificial neural network applications for trend prediction	Systematic review
Najar et al. (2024)	From waste management to circular economy: Leveraging thermophiles for sustainable growth and global resource optimization	Review
Olawade et al. (2024)	Smart waste management: A paradigm shift enabled by artificial intelligence	Review
Sandoval-Reyes et al. (2024)	Mathematical optimization of waste management systems: Methodological review and perspectives for application	Methodological review
Al Kaabi et al. (2025)	Bridging the policy-practice divide: global systematic mapping of circular economy implementation in construction waste	Systematic mapping
Almelhem et al. (2025)	Industry 4.0 for sustainable reverse waste collection: A systematic literature review	Systematic review
Belyamani (2025)	Artificial intelligence in waste management systems: Applications, challenges, and prospects	Review
Filho et al. (2025)	Artificial Intelligence and MCDA in Circular Economy: Governance Strategies and Optimization for Reverse Supply Chains of Solid Waste	Review
Kosoe et al. (2025)	Assessing transportation route efficiency in solid waste collection: a mixed-methods study from Wa Municipality, Ghana	Mixed-methods study*

Authors (year)	Scope of review (title)	Type of study
Nizar et al. (2025)	Bibliometric analysis of global research on organic waste enzymes for plastic biodegradation: Trends, microbial roles, and process optimization	Bibliometric analysis
Sharma et al. (2025)	A review on digital transformation in healthcare waste management: Applications, research trends and implications	Review
Alhassan et al. (2026)	Spatial optimization methods for waste-to-energy facility siting: a review of GIS-MCDA approaches	Review
Bytyqi et al. (2026)	Innovative Preservation Technologies and Supply Chain Optimization for Reducing Meat Loss and Waste: Current Advances, Challenges, and Future Perspectives	Review
Cirstea et al. (2026)	Sustainable Management of Medical Waste in Surgical Units: Operational Challenges and Policy Perspectives	Review
Feng et al. (2026)	From linear to circular: review and future agenda of waste battery recycling network optimization	Review
Kadri et al. (2026)	A Critical Evaluation of Sustainability Practices, Waste Management Strategies, and Circular Economy Principles in Sago Processing Optimization	Critical review
Loni et al. (2026)	Sewage sludge management in wastewater treatment plants: Integrated treatment, resource recovery, and AI-enabled optimization	Review
Nsekela et al. (2026)	Optimization of biogas production using municipal solid waste in sub Saharan Africa: a systematic review	Systematic review
Rani et al. (2026)	Smart valorization of food waste for sustainable bioenergy production: a review of emerging technologies and policy strategies	Review
Yang et al. (2026)	A comprehensive review of sustainable hazardous waste management: Generation patterns, storage safety, transportation optimization, and treatment technologies	Comprehensive review

Note: Selection rule: review papers in the sample whose titles contain "waste" and at least one of optima, decision, logistic*, collection, siting, artificial intelligence, machine learning, digital, policy*, governance, systems engineering, mathematical or network. Type of study follows the authors' own description in the title. *Classified as a review by Scopus.*

2.2 Optimisation models for waste systems

Mathematical optimization has been applied to almost every stage of the waste chain. Sandoval-Reyes et al. (2024) review optimization models of waste management systems and show how they are used to identify policy levers under different regional conditions. Strategic models decide where facilities go and which technologies they use. Saif and Zoroufchi Benis (2026), for example, locate waste processing facilities, select among three waste-to-energy technologies and plan their capacities with two objectives, profit and greenhouse gas emissions. Earlier, Mavrotas et al. (2015) used multi-objective optimization to include external costs when comparing waste-to-energy solutions, and Kuznetsova et al. (2019) proposed a decision-support method for combined centralized and decentralised waste-to-energy systems. Optimization is also used for specific waste streams, such as recycling networks for used electric-vehicle batteries (Feng et al., 2026) and the management of hazardous waste across generation, storage, transport and treatment (Yang et al., 2026).

2.3 Collection, routing and logistics

Collection is usually the largest operating cost of a municipal waste system, and routing has been the classic operations research problem in the field (Beliën et al., 2014; Hess et al., 2024). Recent reviews classify routing variants applied to residential collection (Restrepo-Franco et al., 2025), medical waste (Li et al., 2025) and similar collection problems such as donations (Gutiérrez-Sánchez & RochaMedina, 2022). Newer models add conditions that make routing more realistic: separate compartments for different waste fractions (Mohammadi et al., 2023), electrified fleets (Bragatto et al., 2025) and damaged road networks after disasters, where multi-agent reinforcement learning is used to coordinate collection vehicles (Şara et al., 2027). Policy can enter routing directly. Huang and Lin (2015) designed routes and schedules around a policy requiring that waste is never left on the ground, and Almelhem et al. (2025) examine how Industry 4.0 technologies support reverse collection under extended producer responsibility. Empirical work in low-income settings finds that road conditions and route markings are significantly associated with collection frequency (Kosoe et al., 2025).

2.4 Facility siting and multi-criteria decision analysis

Where to place facilities is the second main decision area. Alhassan et al. (2026) screened 54 studies on siting waste-to-energy plants with geographic information systems (GIS) and multi-criteria decision analysis and synthesized 35 case studies. The Analytic Hierarchy Process dominated (74%), fuzzy extensions made up 14%, hybrid models combining decision analysis with optimization 6% and AI integrated methods only 3%. Environmental criteria appeared in 97% of studies, logistics in 91% and policy and social criteria in 60%. Vlachokostas et al. (2021) review the wider use of multi-criteria decision analysis for choosing waste-to-energy strategies. Optimization models of the whole network are now appearing, such as the mixed-integer model of Hallak and Abdul Hafez (2026), which weighs cost, carbon emissions, feasibility risk and site risk under three carbon-policy regimes.

2.5 Energy and resource recovery

A large part of the literature concerns what happens to waste after collection. Optimization is used to raise biogas yields, choose treatment technologies and plan recovery networks. Nsekela et al. (2026) synthesized more than 80 studies on biogas from municipal

waste in Sub-Saharan Africa and found that co-digestion can raise methane yield by 25–40% and that temperature and retention-time control can raise gas output by up to 30%, while limited financing, technical capacity and inconsistent policy held back adoption. Zadorozhna et al. (2027) analyzed 287 publications on the techno-economics of biogas and found a shift from cost-based evaluation towards frameworks that combine technical, economic, environmental and uncertainty factors. Bedasa and Habtegebriel (2026) describe how black soldier fly larvae convert organic waste into feed and fertilizer, a value chain with its own collection needs.

2.6 Digital tools and artificial intelligence

Digital tools are the fastest-growing theme in the recent literature. Reviews describe how artificial intelligence supports waste sorting, generation forecasting, route planning and facility monitoring (Olawade et al., 2024; Rao et al., 2025; Belyamani, 2025). Hoy et al. (2024) review artificial neural networks for predicting waste and emissions trends, and Neelemagam et al. (2026) explain per-capita waste generation across 36 Indian states and union territories with machine-learning models (R^2 of 0.952 for CatBoost), identifying urbanization and population density as the main drivers. Filho et al. (2025) show how artificial intelligence is being combined with multi-criteria decision analysis in the governance of reverse supply chains. Kontokosta et al. (2018) earlier used machine learning to predict building-level waste generation in cities, an input that routing and capacity models can use directly.

2.7 Circular economy, costs and policy

The circular economy has become the main framing for waste research. Campitelli and Schebek (2020) reviewed how the performance of waste management systems is assessed worldwide, and Schreck and Wagner (2017) examined how incentives for secondary raw material markets can support sustainable waste management. Policy shapes infrastructure directly: Kůdela et al. (2020) show how legislation drives the planning of waste processing capacity in the Czech Republic, and Lee (2020) traces how weak policy implementation undermined waste governance in Hong Kong. In developing regions, Zhang et al. (2024) identify land, finance and public behavior as the main constraints on implementing waste policy. Households, where municipal waste originates, are usually represented through waste quantities rather than behavior (Zhang et al., 2022; Neelemagam et al., 2026).

Taken together, the literature shows that optimization methods are well established for routing, siting and technology choice, that digital tools and the circular economy are reshaping the field, and that policy is increasingly treated as part of the planning problem. What is missing is a quantitative picture of how these strands relate to one another, which the following sections provide.

3. RESEARCH METHODOLOGY

3.1 Research design

The study uses a bibliometric research design, a form of systematic literature review that treats published research as data that can be counted, mapped and compared (Paul & Criado, 2020). Compared with a narrative review, this design makes the selection of studies explicit and repeatable and allows a large body of work to be examined without relying on the reviewer's recollection. Following Donthu et al. (2021), the analysis combines performance analysis, which describes the contribution of years, journals, authors and countries, with science mapping, which examines how topics and keywords relate to one another. The study proceeded in four phases: defining the aim and scope, collecting the data, analyzing the data and interpreting the results. The three research questions in Section 1 move from description (RQ1) to structure (RQ2) and direction (RQ3).

3.2 Data source

The data were drawn from Scopus, which indexes peer-reviewed journals in engineering, mathematics, management, economics and the environmental and social sciences. This breadth suits a topic in which optimization methods meet planning, cost and regulation. Scopus records include the title, authors, affiliations, abstract, author keywords, publication year, document type, language, source and DOI, and they can be exported in BibTeX and RIS formats. Using a single database avoids the duplicate records and inconsistent fields that arise when databases are merged, at the cost of some coverage, as discussed in Section 7.

3.3 Search strategy

The search used three concepts joined by the Boolean operator AND: "waste management", "optimization" and "policy". The first concept defines the domain. The second captures the quantitative methods that operations research brings to it, broadly enough to include routing, location and capacity decisions, mathematical programming, heuristics and learning-based methods. The third reflects the aim of connecting technical solutions to the rules and incentives under which waste systems operate. Joining the three with AND excludes studies that treat waste purely as a chemical or environmental subject without a decision or policy dimension. The cost of this choice is that optimization studies that never mention policy are not retrieved. This affects routing studies in particular and is considered when interpreting the results.

3.4 Screening and selection

The search was run on 10 September 2026 and screening followed the identification, screening, eligibility and inclusion stages of the PRISMA 2020 statement (Page et al., 2021), as shown in Figure 1. The search returned 1,739 records. Restricting publication years to 2016 onwards removed 402 records and left 1,337, focusing the analysis on the decade in which digital tools, artificial intelligence and carbon policy have changed how waste systems are planned. Restricting document types to articles and reviews removed 321 conference papers, book chapters, notes, editorials and errata, leaving 1,016; these document types are less consistently peer reviewed and indexed. Restricting the language to English removed 44 records, leaving 972, so that titles and keywords could be read and coded consistently. Restricting the source type to journals removed five more, leaving a final sample of 967 records (800 articles and 167 reviews). All screening steps were based on indexed metadata rather than personal judgement. The final sample includes one article in press dated 2027.

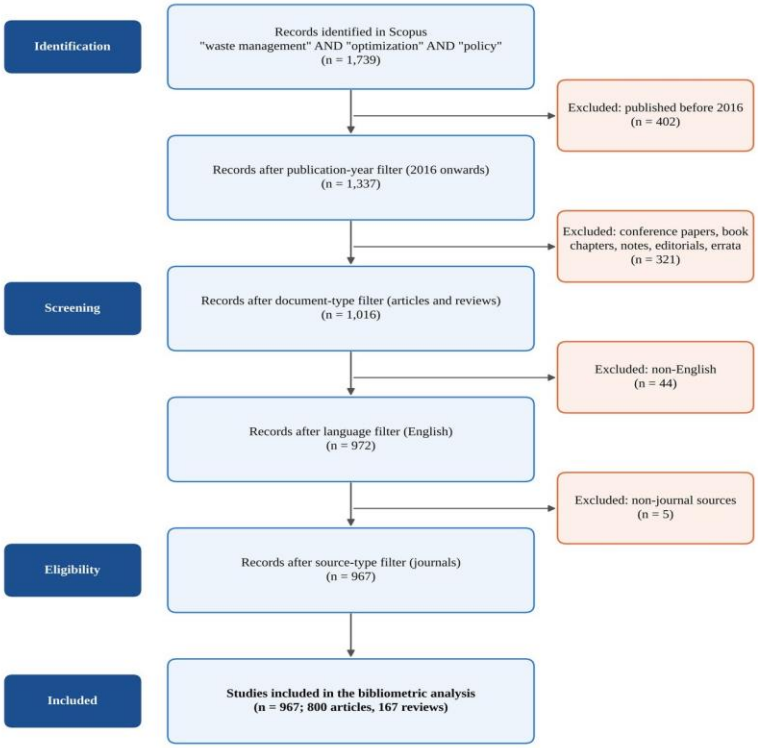

Figure -1: PRISMA flow diagram of the search and screening process

3.5 Data preparation

The full records of the final sample were exported from Scopus in BibTeX format and checked for duplicates and for records outside the stated filters; none were found. Author keywords were harmonized so that variants of the same concept were counted together, including British and American spellings (for example, optimization and optimization), abbreviations (for example, LCA and life cycle assessment) and singular and plural forms. Citation counts are those reported by Scopus on the export date, and countries were taken from the author affiliations. Thirty-three records (3.4%) have no author keywords and are excluded from the keyword analyses only.

3.6 Analytical procedures

Performance analysis reports annual output, the compound annual growth rate over the complete years 2016–2025, the leading journals, authorship and collaboration, countries and the most cited documents. Thematic change was measured by counting groups of related terms in titles (for example, optimization, programming or heuristic; policy, regulation or legislation; artificial intelligence or machine learning) across three periods of four years each: 2016–2019, 2020–2023 and 2024–2027. Because the periods differ in size, counts are reported as shares of each period's output.

Science mapping used author keywords in three complementary ways. A keyword co-occurrence network was built from the 40 most frequent keywords, with links weighted by the number of documents in which two keywords appear together, and clusters were identified with the Louvain algorithm (Blondel et al., 2008). A thematic map was built from the 144 keywords that occur at least four times. Keywords were clustered in the same way, and each cluster was positioned by its centrality (the strength of its links to other clusters) and its density (the strength of its internal links), following the strategic diagram of Callon et al. (1991) as implemented in bibliometric practice (Cobo et al., 2011; Aria & Cuccurullo, 2017). Finally, a multiple correspondence analysis was applied to the 40 most frequent keywords, excluding the three search terms, across the 234 documents that contain at least two of them, and the keywords were grouped with k-means clustering. All analyses were carried out in Python (pandas, NetworkX and scikit-learn), following the procedures of the Bibliometrix package (Aria & Cuccurullo, 2017). The review papers were then read by scope and type to connect the quantitative patterns with substantive findings.

3.7 Reliability and validity

The database, search string, search date, filters and record counts at each stage are reported, so the search can be repeated. Because Scopus is continuously updated, a later search may return slightly different counts. Screening relied on indexed metadata, which reduces subjective judgement. Validity is supported by triangulation: the title-based counts, the three keyword maps and the reading of review papers are compared, and a theme is treated as robust only when several of these sources point to it. All data come from published records, and no personal or confidential data were collected.

4. RESULTS

4.1 Overview of the sample

Table 2 summarizes the sample. The 967 records were published in 425 journals by 4,076 distinct authors. Only 39 documents (4.0%) are single-authored, and the average document has 4.48 authors, which indicates a highly collaborative field. Some 354 documents (36.6%) list affiliations in more than one country. The records had received 23,354 citations by the export date, a mean

of 24.2 and a median of 8 per document, and 163 documents (16.9%) were still uncited. The average document age is 2.8 years, which confirms that most of this literature is recent.

Table -2: Main information about the sample

Indicator	Value
Timespan	2016–2027 (search date 10 September 2026)
Documents	967 (800 articles, 167 reviews)
Sources (journals)	425
Annual growth rate, 2016–2025	25.5%
Average document age	2.8 years
Distinct authors	4,076
Authors per document	4.48
Single-authored documents	39 (4.0%)
Documents with authors in more than one country	354 (36.6%)
Total citations (Scopus, at export)	23,354
Mean / median citations per document	24.2 / 8
Documents with author keywords	934
Distinct author keywords (after harmonization)	3,403

4.2 Annual scientific production

Figure 2 shows annual output. Production rose from 26 documents in 2016 to 201 in 2025, a compound annual growth rate of 25.5%. Growth was gradual until 2023 and then accelerated: output rose from 77 documents in 2023 to 135 in 2024 and 201 in 2025, and 237 documents had already appeared in 2026 by the search date in September. In total, 573 documents (59.3%) were published in 2024–2026. Part of this growth reflects the general expansion of journal publishing, but the pace suggests that the combination of optimization, waste and policy has become a distinct and fast-growing research area.

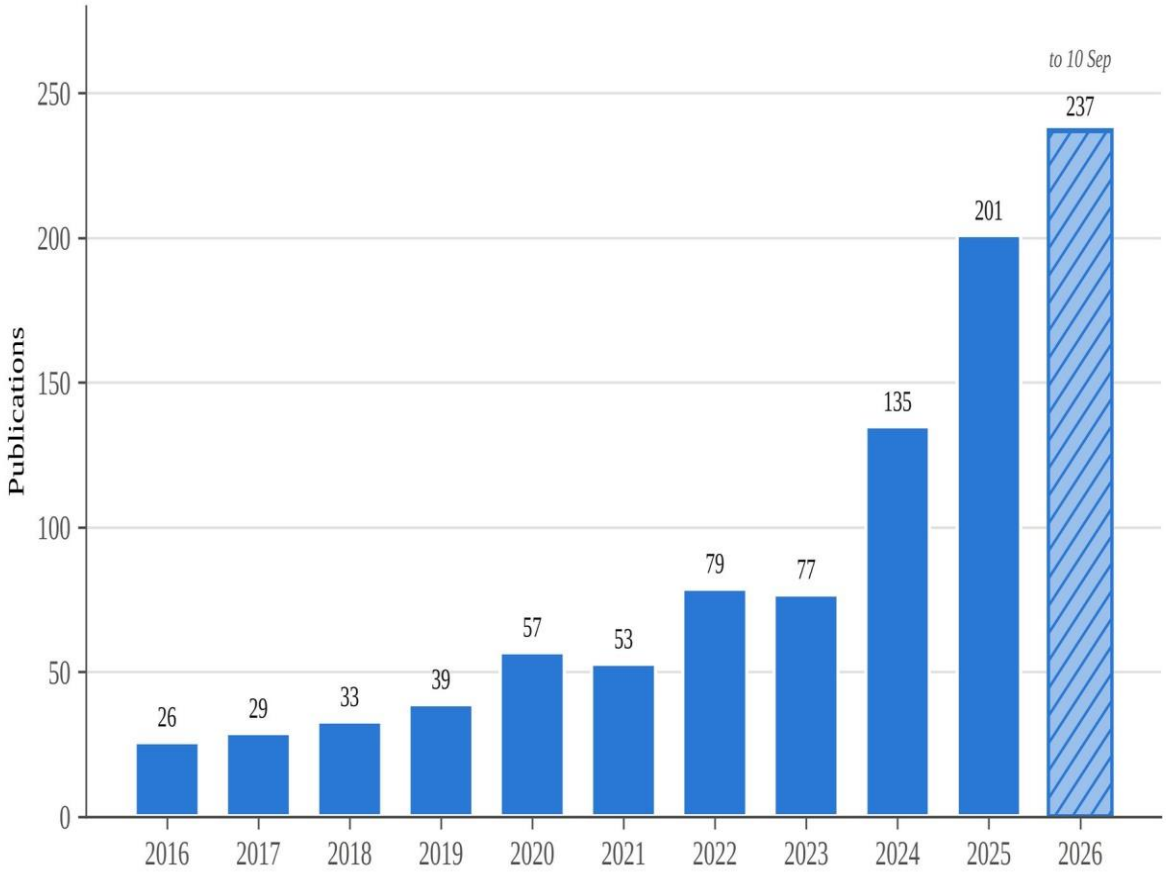

Figure -2: Annual scientific production, 2016–2026 (2026 counts up to the search date of 10 September 2026; one 2027 article in press not shown)

4.3 Sources

The literature is widely dispersed. The 25 most productive journals account for 404 documents (41.8%), and the remaining 400 journals publish only a few documents each. Table 3 lists the ten leading sources. Sustainability and the Journal of Cleaner Production lead with 52 documents each, followed by Waste Management (39), the Journal of Environmental Management (38) and Resources, Conservation and Recycling (29). The leading outlets are sustainability and environmental journals rather than operations research journals, and only one industrial engineering journal (Computers & Industrial Engineering) appears among the top 15. Research at this intersection is therefore communicated mainly to environmental audiences.

Table -3: Ten most productive sources

Rank	Source	Documents	Share (%)
1	Sustainability	52	5.4
2	Journal of Cleaner Production	52	5.4
3	Waste Management	39	4.0
4	Journal of Environmental Management	38	3.9
5	Resources, Conservation and Recycling	29	3.0
6	Science of the Total Environment	22	2.3
7	Energies	17	1.8
8	Energy	16	1.7
9	Waste Management and Research	14	1.4
10	Environmental Science and Technology	13	1.3

Table 4 traces the cumulative output of the five leading journals. In 2019 the Journal of Cleaner Production and Waste Management together held 25 of the 36 documents in these five journals. By 2026, Sustainability and the Journal of Environmental Management had caught up, contributing 52 and 38 documents respectively, most of them after 2022. The field has therefore broadened from specialist waste and cleaner-production outlets into general sustainability journals.

Table -4: Cumulative production of the five leading sources, 2016–2026

Year	Sustainability	J. Cleaner Production	Waste Management	J. Environmental Management	Resources, Conservation & Recycling
2016	1	3	3	0	0
2017	1	4	6	0	0
2018	1	10	9	2	2
2019	1	15	10	4	6
2020	3	23	14	6	10
2021	7	30	17	9	14
2022	10	34	20	17	17
2023	17	37	24	17	19
2024	25	44	26	24	22
2025	41	47	34	33	24
2026	52	52	39	38	29

4.4 Countries and most cited documents

Research is concentrated in a few countries. Authors based in China contributed to 288 documents (29.8%) and authors in India to 129 (13.3%), followed by the United States (98), the United Kingdom (70), Italy (53), Iran (44), Australia (43) and Canada (42). Table 5 lists the ten most cited documents. The most cited document, a review of thermoelectric generators with 1,344 citations (Champier, 2017), shows how broadly the search terms reach. The others range from biogas and the circular economy, life cycle assessment and municipal waste in developing regions to data centers, food systems and aviation fuel, and most are reviews. No routing or facility-location model appears among them.

Table -5: Ten most cited documents in the sample (Scopus citations at export)

Rank	Document	Title	Source	Citations
1	Champier (2017)	Thermoelectric generators: A review of applications	Energy Conversion and Management	1,344
2	Kapoor et al. (2020)	Valorization of agricultural waste for biogas based circular economy in India: A research outlook	Bioresource Technology	394
3	Corominas et al. (2020)	The application of life cycle assessment (LCA) to wastewater treatment: A best practice guide and critical review	Water Research	393
4	Huang et al. (2020)	A review of data centers as prosumers in district energy systems: Renewable energy integration and waste heat reuse for district heating	Applied Energy	386
5	Zhang et al. (2024)	Municipal solid waste management challenges in developing regions: A comprehensive review and future perspectives for Asia and Africa	Science of the Total Environment	353
6	Devaux et al. (2021)	The Potato of the Future: Opportunities and Challenges in Sustainable Agri-food Systems	Potato Research	348
7	Zhang et al. (2019)	Food-energy-water (FEW) nexus for urban sustainability: A comprehensive review	Resources, Conservation and Recycling	318
8	Olawade et al. (2024)	Smart waste management: A paradigm shift enabled by artificial intelligence	Waste Management Bulletin	285
9	Doliente et al. (2020)	Bio-aviation Fuel: A Comprehensive Review and Analysis of the Supply Chain Components	Frontiers in Energy Research	270
10	Sarkar et al. (2019)	Optimal design and implementation of solar PVwind-biogas-VRFB storage integrated smart hybrid microgrid for ensuring zero loss of power supply probability	Energy Conversion and Management	223

4.5 Thematic change in titles

Figure 3 shows the share of titles that mention ten groups of terms in the three periods. Optimization, programming or heuristic terms appear in 262 titles (27.1%), a share that stays almost constant across the periods. Policy, regulation or legislation terms appear in 107 titles (11.1%). The clearest change is the rise of artificial intelligence and machine learning, from 1.6% of titles in 2016–2019 to 4.1% in 2020–2023 and 15.2% in 2024–2027. Circular economy and life cycle assessment also grew, from 6.3% to 11.3%. In contrast, cost and techno-economic terms fell from 7.1% to 3.7%, and collection and routing terms fell from 5.5% to 3.3%. In total, only 36 titles (3.7%) mention collection, routing or routes, and seven mention the vehicle routing problem. Energy recovery appears in 40 titles (4.1%), biogas and anaerobic digestion in 23 (2.4%), waste generation and forecasting in 26 (2.7%), and household, residential, citizen or consumer terms in only 14 (1.4%).

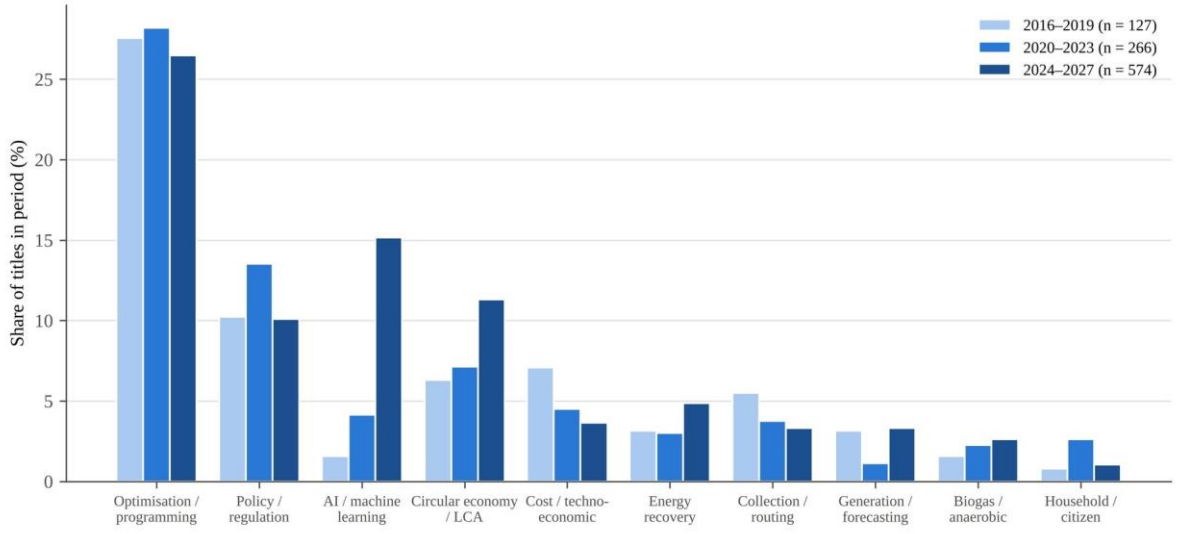

Figure -3: Share of titles mentioning selected groups of terms, by period

4.6 Conceptual structure

Figure 4 shows the multiple correspondence analysis of the 40 most frequent keywords. The first two dimensions explain 4.9% and 4.6% of the inertia, a level typical of keyword data, which is sparse. Four groups emerge. The largest (Group 1) combines the circular economy, sustainability, recycling, reverse logistics, supply chain management, the internet of things and artificial intelligence, and represents systems-level and digital approaches to the circular economy. Group 2 brings together life cycle

assessment, environmental impact, multi-objective optimization, machine learning, system dynamics and municipal solid waste management, and represents assessment and modelling. Group 3 combines energy efficiency, renewable energy, greenhouse gas emissions, the carbon footprint, uncertainty, genetic algorithms and reinforcement learning, and represents energy and carbon optimization. Group 4 contains municipal solid waste, waste-to-energy, anaerobic digestion, biogas and bioenergy, and sits apart from the other three on both dimensions. Waste-to-energy research is therefore a distinct strand that rarely shares keywords with circular-economy or digital research. No routing or collection keyword is frequent enough to enter the analysis.

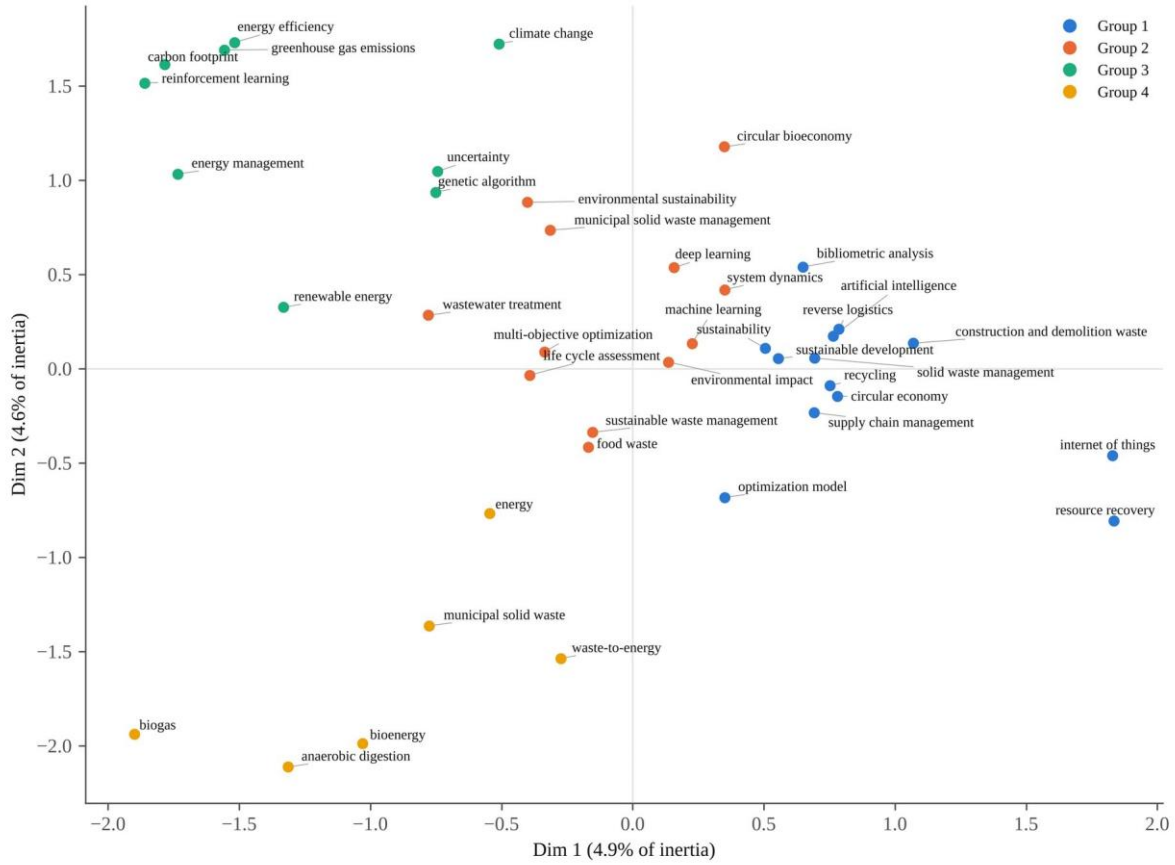

Figure -4: Conceptual structure map: multiple correspondence analysis of the 40 most frequent author keywords

4.7 Thematic map

Figure 5 positions the six keyword themes by centrality and density. Three themes lie in the motor quadrant, which contains themes that are both well developed and central to the field. The largest, built around the circular economy, waste management, sustainability, artificial intelligence, machine learning and multi-objective optimization, dominates on both dimensions. The second, built around optimization, solid waste management, uncertainty, system dynamics and supply chain management, lies close to the boundary with the basic quadrant. It is central but only moderately developed, which suggests that optimization acts as a shared method across the field rather than as a self-contained topic. The third motor theme covers municipal solid waste, waste-to-energy, anaerobic digestion and biogas. Three themes fall in the emerging or declining quadrant: energy efficiency, renewable energy, reinforcement learning and greenhouse gas emissions; life cycle assessment, environmental impact and carbon neutrality; and sustainable development, the circular bioeconomy and smart cities. The rapid growth of reinforcement learning and carbon-related terms in titles suggests that the first of these is emerging rather than declining.

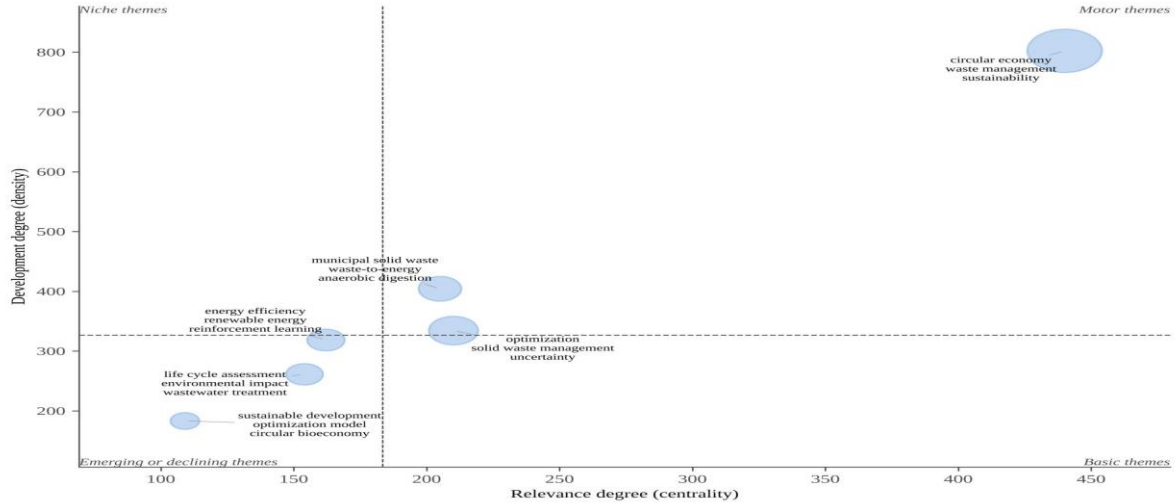

Figure -5: Thematic map of author-keyword themes (bubble size proportional to keyword occurrences)

4.8 Keyword co-occurrence network

Figure 6 shows the co-occurrence network of the 40 most frequent keywords. The circular economy (123 occurrences), waste management (85), sustainability (84) and optimization (71) are the largest nodes, followed by life cycle assessment (45), artificial intelligence (42) and machine learning (37). The Louvain algorithm identifies four clusters. Cluster 1 (blue) links the circular economy and sustainability with artificial intelligence, recycling, reverse logistics, system dynamics, the internet of things and policy. Cluster 2 (orange) is organized around optimization and links it with energy efficiency, renewable energy, uncertainty, reinforcement learning and energy management. Cluster 3 (green) joins waste management, machine learning, municipal solid waste, waste-to-energy and multi-objective optimization. Cluster 4 (yellow) covers life cycle assessment, anaerobic digestion, biogas, bioenergy, wastewater treatment and food waste. Policy appears as a mid-sized node in the circular-economy cluster rather than as a hub, and routing does not appear at all. The most specific routing keywords, such as route optimization (five occurrences) and waste collection (four), fall below the threshold, and only 61 documents (6.3%) mention collection or routing in their titles or keywords.

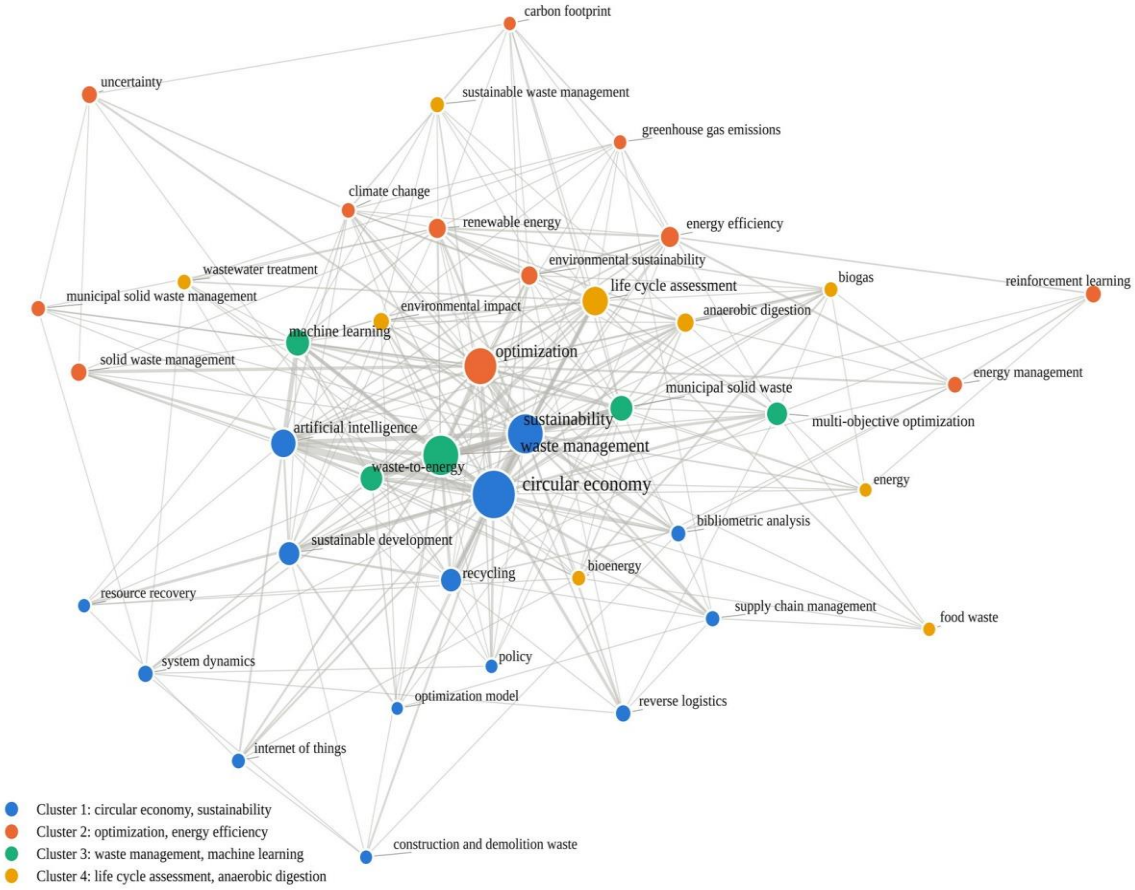

Figure -6: Keyword co-occurrence network of the 40 most frequent author keywords (node size proportional to occurrences; colors show Louvain clusters)

5. DISCUSSION

The results answer the three research questions and qualify some common assumptions about the field. On RQ1, research at the intersection of waste management, optimization and policy has grown quickly, at 25.5% a year between 2016 and 2025, and most of it is very recent. It is collaborative, international and published mainly in sustainability and environmental journals. Methodological advances from operations research therefore reach waste researchers and practitioners largely through outlets oriented towards environmental outcomes, which is consistent with the prominence of emissions, life cycle and circularity keywords in the maps.

On RQ2, the literature is organized less around classical operational problems than around broad frameworks. The circular economy, sustainability and artificial intelligence form the dominant motor theme, and optimization acts as a shared method that connects several themes rather than as a field of its own. Waste-to-energy and biogas form a distinct and well-developed strand that is only loosely connected to the circular-economy and digital research. The clearest change over time is the rise of artificial intelligence, which grew almost tenfold as a share of titles between 2016–2019 and 2024–2027. The literature is therefore shifting from single treatment processes and cost studies towards data-driven, system-level planning.

On RQ3, three areas stand out as thin. Collection and routing, the problem most associated with operations research in waste management (Beliën et al., 2014; Hess et al., 2024), make up a small and shrinking share of this policy-oriented literature. Part of this reflects the search design, because routing studies that do not mention policy are not retrieved. Even so, it shows that routing research and policy research rarely meet, although collection mandates, service standards and fleet electrification policies directly shape routes. Households and citizens are almost absent from titles (1.4%), despite being the source of municipal waste and the

subject of many policy instruments. Finally, although policy is present in 11.1% of titles, only 40 of these 107 titles also refer to an optimization, programming or modelling method, so policy is more often discussed than modelled.

These findings are consistent with the review literature. Alhassan et al. (2026) find that policy and social criteria are the least used in siting studies and that hybrid optimization is rare, and Sandoval-Reyes et al. (2024) find that optimization models are only beginning to be used to identify policy levers. The bibliometric evidence adds that this pattern holds across the field as a whole and that the fastest-growing methods, especially artificial intelligence, are developing mainly within circular-economy research rather than within classical waste logistics.

6. FUTURE RESEARCH AGENDA

The results point to six priorities for future research. Table 6 summarizes them, and each is described below in terms of the evidence behind it, the open questions and the methods that could answer them.

Table -6: Summary of the future research agenda

Priority	Key evidence from this study	Example open question
6.1 Linking routing and collection to policy	Collection/routing in 3.7% of titles, falling from 5.5% to 3.3%; no routing keyword in the maps	How do collection mandates and fleet rules change optimal routes?
6.2 Integrated planning of routes, sites and technologies	Waste-to-energy forms a separate cluster; hybrid siting-optimization models in 6% of siting studies	How much is lost by siting first and routing later?
6.3 Policy as a modelled variable	Policy in 11.1% of titles, but only 40 of 107 also name a modelling method	How do policy instruments compare on one optimization platform?
6.4 AI within operations research models	AI/ML titles rose from 1.6% to 15.2%; reinforcement learning is emerging	Can forecasts feed routing and capacity models directly?
6.5 Households, equity and workload	Households in 1.4% of titles; social criteria least used in siting	What does equitable service cost?
6.6 Comparable evidence and other waste streams	18 of 167 reviews systematic, 8 bibliometric; results rarely comparable	How large are reported savings, relative to what baseline?

6.1 Linking routing and collection to policy

Evidence: Collection and routing appear in only 3.7% of titles, their share fell from 5.5% to 3.3% across the three periods, and no routing keyword enters the keyword maps. Recent routing studies add realistic conditions such as compartments, electric fleets and damaged roads (Mohammadi et al., 2023; Bragatto et al., 2025; Şara et al., 2027), but few connect routes to the policies that shape them.

Open questions: How do collection mandates, service-frequency standards, separate-collection targets and fleet electrification rules change optimal routes and their costs? Do dynamic, sensor-triggered routes outperform well-designed fixed schedules once sensor errors and communication failures are included?

Methods: Routing models with policy parameters as explicit inputs; comparison of fixed, rolling horizon and learning-based policies on the same instances; and field pilots that alternate policies by day or shift, a switchback design (Bojinov et al., 2023).

6.2 Integrated planning of routes, sites and technologies

Evidence: Waste-to-energy and biogas form a separate cluster in all three keyword maps, and siting studies still rely mostly on scoring methods, with hybrid optimization in only 6% of cases (Alhassan et al., 2026). Integrated models that combine location, technology and capacity decisions are appearing but remain few (Saif & Zoroufchi Benis, 2026; Hallak & Abdul Hafez, 2026).

Open questions: How much cost and how many emissions are lost when sites are chosen first and routes planned afterwards? Does the best-scoring site remain the best once transfer stations, collection routes and variations in feedstock are taken into account?

Methods: Two-stage and integrated location-routing models solved on the same case data, with GIS and multi-criteria results used as candidate sites rather than final answers, robust or stochastic optimization for feedstock uncertainty, and results reported as Pareto fronts.

6.3 Policy as a modelled variable

Evidence: Policy terms appear in 11.1% of titles, but only 40 of those 107 titles also name an optimization or modelling method, and policy appears in the co-occurrence network as a mid-sized node rather than a hub. Where policy is modelled explicitly, the results are concrete and comparable (Hallak & Abdul Hafez, 2026; Kůdela et al., 2020).

Open questions: How do carbon prices, landfill taxes, gate fees, extended producer responsibility and collection mandates compare when they are evaluated on the same optimization platform? How sensitive are optimal designs to policy uncertainty and to limited enforcement capacity?

Methods: Scenario-based and bilevel models in which a regulator sets instruments and operators respond, sensitivity analysis over policy parameters, and comparative case studies across regulatory settings in which legislation is coded into model parameters.

6.4 Artificial intelligence within operations research models

Evidence: Artificial intelligence and machine learning rose from 1.6% to 15.2% of titles and now sit within the dominant motor theme, while reinforcement learning appears in an emerging theme. Most of this work concerns prediction and sorting (Olawade et al., 2024; Rao et al., 2025), and its integration with optimization is at an early stage (Filho et al., 2025).

Open questions: Can generation forecasts feed directly into routing and capacity models instead of being produced separately? How robust are learned policies when demand forecasts or road data are inaccurate?

Methods: Predict-then-optimize and end-to-end learning frameworks, benchmarking learned policies against exact and heuristic solutions, and stress tests with deliberately corrupted input data.

6.5 Households, equity and workload

Evidence: Household, residential, citizen and consumer terms appear in only 1.4% of titles. Households enter most models as sources of waste quantities (Neelemagam et al., 2026), and social criteria are the least used in siting (Alhassan et al., 2026). The crews who carry out collection are rarely represented, and decision-support tools can lead dispatchers to rely too heavily on automated recommendations (Parasuraman & Manzey, 2010).

Open questions: How much more do routes cost if they equalize service frequency across neighborhoods or balance crew workload? How do sorting behavior and participation affect collected volumes?

Methods: Multi-objective routing with explicit equity and workload objectives, agent-based simulation of household behavior linked to collection models, and choice experiments on service levels and fees.

6.6 Comparable evidence and other waste streams

Evidence: Of 167 reviews, only 18 are systematic, PRISMA-based, scoping or meta-analytic and eight are bibliometric. Studies use different instances, cost definitions and emission factors and rarely report whether solutions were implemented. Recent work extends optimization to medical, hazardous, construction and battery waste (Li et al., 2025; Yang et al., 2026; Feng et al., 2026; Praveenkumar, 2026), but these streams remain small strands of the literature.

Open questions: How large are the reported savings, and relative to which baseline? Which routing constraints are specific to each waste stream, and which are shared?

Methods: A reporting standard covering instance data, baselines, cost and emission definitions and run times; open benchmark instances based on anonymized municipal data; a living review with a registered protocol updated in line with PRISMA 2020 (Page et al., 2021); and meta-analysis of reported savings by evaluation design.

The six priorities are connected. Common benchmarks and reporting standards (Section 6.6) would make the models in Sections 6.1, 6.2 and 6.4 comparable, policy parameters (Section 6.3) can enter all of them as scenario inputs, and field pilots and behavioral studies (Sections 6.1 and 6.5) can test whether the models work outside the laboratory.

7. CONCLUSION

This study mapped 967 journal articles and reviews published since 2016 at the intersection of waste management, optimization and policy. The field has grown rapidly, at 25.5% a year between 2016 and 2025, and most of it has appeared since 2024. It is collaborative, international and dispersed across 425 journals, most of which are sustainability and environmental outlets rather than operations research journals. The circular economy, sustainability and artificial intelligence form its dominant theme, optimization acts as a shared method across themes, and waste-to-energy forms a distinct, well-developed strand. Artificial intelligence is the fastest-growing topic, while collection and routing and the role of households occupy small and, in the case of routing, shrinking shares of the literature. Policy is frequently discussed but less often modelled as part of the optimization problem.

The study contributes a transparent and repeatable map of this literature, a set of title and keyword indicators that can be updated as the field grows, and an agenda of six research priorities derived from the evidence. For researchers, the results identify where additional studies would add most to the existing body of work: in linking routing to policy, in integrating siting, technology and routing decisions, in modelling policy instruments explicitly, in embedding artificial intelligence within optimization models, in representing households and crews, and in making results comparable across studies. For practitioners and policymakers, the results indicate that most of the evidence on optimized waste systems comes from single case studies and reviews, and that the transferability of reported savings to other cities is not yet established.

7.1 Limitations

The findings rest on several design choices. Only Scopus was searched, so journals indexed elsewhere are not represented. The sample is limited to English-language journal articles and reviews, which excludes conference papers, where new methods often appear first, and research published in other languages. The search required the term policy, so optimization studies that do not mention policy, including many routing studies, were not retrieved; the small share of routing in this sample should be read with this in mind. The year 2026 is incomplete because the search was run in September, and recent documents have had little time to be cited. Finally, bibliometric indicators measure how much attention a topic receives, not the quality or practical value of the studies, which is why they were combined with a reading of the review literature.

8. DECLARATIONS

Funding: The authors received no specific funding for this work.

Conflict of interest: The authors declare no conflict of interest.

Data availability: The bibliographic records analyzed in this study were exported from the Scopus database on 10 September 2026 using the search strategy described in Section 3 and are available from the corresponding author on reasonable request, subject to Scopus terms of use.

Author contributions (CRediT): Richa Saxena: Supervision and guidance. Subhaan Merchant: Methodology, Data curation, Writing – original draft (methodology and future research agenda). Sumeir Singh Ahluwalia: Investigation, Writing – original draft

(literature review). Tathya Patel: Formal analysis, Visualisation, Writing – original draft (data analysis). Tisha Gherani: Writing – original draft (introduction and conclusion). All authors reviewed and approved the final manuscript.

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