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REVIEW PAPER



A literature review of the state of the art of sustainable waste collection and vehicle routing problem

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ABSTRACT

Over the past decades, the amount of waste has dramatically increased worldwide due to rapid population growth and urbanization. Inefficient waste collection and transportation, known as the waste collection vehicle routing problem (WCVRP), negatively impacts economic, environmental, and social dimensions. This issue has drawn considerable attention from local and national governments. There is an urgent need for sustainable practices in waste collection and transportation. This paper conducts an exhaustive literature review on the WCVRP. The review covers various aspects, including waste types, common model characteristics, objective functions, solution methods, datasets and case studies. The analysis indicates a need for further research on underrepresented waste types, such as medical waste (MW). It also stresses the importance of incorporating more model characteristics to better capture the complexities of real-world scenarios. Moreover, there is a lack of multiple objectives optimization models that concurrently address economic, environmental, and social dimensions, in line with sustainable development goals. Additionally, there is insufficient research on hybrid algorithms, especially regarding their application to uncertainty management and advanced techniques. Finally, the use of hybrid testing is restricted, highlighting the need for diverse tests to validate solution methods under various real-world conditions. This study outlines a roadmap for decision-makers in the WCVRP domain, offering opportunities for the evolution of more efficient, adaptable, and sustainable waste collection and transportation systems.

Implications: The discussion of WCVRP is an urgent global concern in waste management that requires immediate attention. Through a multi-dimensional evaluation of the research papers, this review paper provides recommendations for future research and practice in WCVRP. Initially, while urban solid waste has received significant attention, other categories remain insufficiently examined. Future research should focus on efficient collection and transportation strategies for these types. Then, although common characteristics are well-explored, this review emphasizes the need for further investigation into lesser-studied characteristics and vehicle types in WCVRP models. Next, current models predominantly prioritize cost and public health exposure risk minimization. There is a necessity for more holistic approaches that incorporate multiple objectives, particularly those crucial for achieving sustainable development goals. Moreover, hybrid algorithms have emerged as efficient solutions, yet advanced technologies coupled with uncertainty management strategies remain underutilized, presenting significant potential to address the evolving complexities of WCVRP. Finally, the study highlights the importance of datasets and case studies in validating WCVRP models. Hybrid tests enable researchers to comprehensively evaluate WCVRP solutions, providing insight into their performance under various conditions. In conclusion, these implications offer a roadmap for advancing WCVRP research and guiding practical strategies to contribute to the development of more efficient, adaptable, and sustainable waste collection and transportation systems.

PAPER HISTORY

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Introduction

Urbanization and population growth have led to a significant increase in global waste production, creating urgent challenges for effective waste management (Benitez-Bravo et al. 2021; Hemidat et al. 2017). In 2020,

global generation of municipal solid waste (MSW) reached approximately 2.24 billion metric tons, a figure expected to rise by 73% to 3.88 billion metric tons by 2050 (World Bank 2022). Similarly, in Wuhan, China, the daily production of MW surged from 40 metric tons before the COVID-19 pandemic to a peak

of 240 metric tons during the pandemic (Eren and Tuzkaya 2021). These trends highlight the urgent need for efficient waste collection and transportation systems, posing significant challenges for local and national governments (Hong, Yan, and Ge 2023).

Efficient waste collection and transportation are crucial for optimizing waste management and supporting sustainable development (Tirkolaee et al. 2020). Despite the high costs associated with WCVRP in many developing countries, the effectiveness and coverage of these services remain relatively low (Han and Cueto 2015). Furthermore, the global transportation industry emits approximately 7.3 billion metric tons of carbon dioxide annually, significantly impacting the environment by increasing air pollution, greenhouse gas emissions, fuel consumption, thus contributing to global climate change (Erdem 2022a; Ghannadpour, Zandieh, and Esmaili 2021; Rouhi, Shafiepour Motlagh, and Dalir 2023). In addition, improperly collected, managed, and disposed of waste, particularly from small medical centers, can spread of diseases and infections, increasing the risks to healthcare workers and patients (Ghannadpour, Zandieh, and Esmaili 2021). Therefore, developing sustainable waste collection and transportation systems is essential for maximizing cost savings (Hannan et al. 2020; Liang, Minanda, and Gunawan 2022), safeguarding the environment (Atthirawong and Luangpaiboon 2022; Tirkolaee and Aydin 2021), and benefiting health and safety (Das et al. 2019). In response to these challenges, this study addresses the following research questions:

- (1) Which waste categories have become more prominent in WCVRP recently?
- (2) What key model characteristics are most frequently considered in WCVRP models?
- (3) What objective functions used in designing WCVRP models?
- (4) What solution methods are applied in WCVRP?
- (5) What types of tests are conducted in WCVRP?

Several reviews have been published in this field, each focusing on different aspects of WCVRP. Han and Cueto (Han and Cueto 2015) explored the application of the vehicle routing problem (VRP) within MSW management networks. Similarly, Hannan et al. (2020) and Beliën, De Boeck, and Van Ackere (2014) each provided comprehensive reviews on MSW collection and management, but they overlooked sustainable development dimensions. Furthermore, Sar and Ghadimi (2023) systematically evaluated the use of VRP in reverse logistics operations yet lacked detailed descriptions of the specific vehicle involved. Liang, Minanda, and Gunawan (2022)

focused exclusively on solution techniques for WCVRP. While these reviews offer valuable insights, they do not fully address the evolving challenges and complexities of WCVRP. Most existing reviews focus on specific aspects or fail to comprehensively integrate sustainable development goals and emerging trends in WCVRP. This study aims to fill these gaps by providing a holistic and up-to-date synthesis of WCVRP research. It integrates multiple dimensions of WCVRP, including sustainability, and examines how recent advancements address the evolving challenges in this field. Based on these insights, this study makes several key contributions:

- (1) It presents an extensive survey of WCVRP studies published between January 2020 and March 2024, synthesizing recent research trends and identifying gaps in the literature.
- (2) This study offers an in-depth analysis of WCVRP by examining waste classification, model characteristics, objective functions, solution methods, and types of tests. This analysis improves understanding of the critical components of WCVRP, laying a foundation for future research.
- (3) By establishing the connection between WCVRP and sustainable development goals (SDGs), this study highlights how efficient collection and transportation processes contribute to 10 out of 17 SDGs.

The remainder of this review is structured as follows: [Section 2](#) describes the research methodology. [Section 3](#) presents a comprehensive analysis of the content. [Section 4](#) provides a discussion and offers suggestions for future research on WCVRP. Finally, [Section 5](#) presents the conclusion.

Research methodology

This literature review categorized and synthesized existing knowledge on the WCVRP. To ensure a rigorous review of the published works, a comprehensive methodology as suggested by Hannan et al. (2020) has been adopted, whereas the extensive search on the Web of Science and Scopus databases, similar to the work by Lin, Musa, and Yap (2022). The search strategy is outlined in [Figure 1](#).

Initially, terms such as “transportation,” “collection,” “routing,” and “route” were used in place of “vehicle routing problem.” Related terms for “waste” (e.g., “garbage,” “trash,” “refuse”) and “approach” (e.g., “algorithm,” “optimization,” “mathematical”) were also included in the search. The specific search strings applied across various databases is detailed in

Step Four: Search in the Scopus Database.

Repeat the same steps and cross-check, eight papers were selected. The whole process resulted in 130 articles.

Step Three: Scope check.

Two inclusion criteria in this step and 122 articles were chosen.

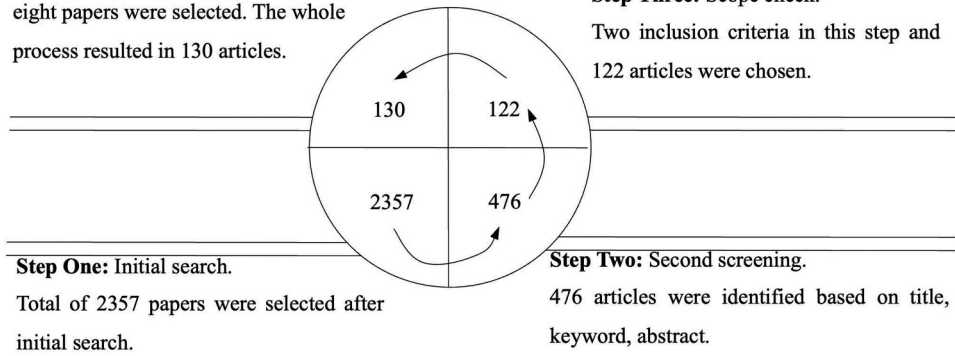


Figure 1. Search methodology.

Table 1. Papers published from January 2020 to March 2024 and written in English were selected. Only full papers were included, excluding conference papers, review papers, book chapters, theses, and technical reports. Papers unrelated to the fields of environmental sciences, green sustainable science technology, engineering environmental, environmental studies, management, operations research management science, multidisciplinary sciences, computer science interdisciplinary applications, business, computer science artificial intelligence, economics, transportation science technology, mathematics interdisciplinary applications, transportation, mathematics applied, mathematics, development studies, and social sciences interdisciplinary were omitted, leaving 2357 papers.

Second, numerous papers were identified, and suitable papers were selected by screening titles, keywords, and abstracts. This process effectively filtered out irrelevant publications, resulting in 476 papers for in-depth analysis.

Next, two inclusion criteria were applied: (1) papers must focus on WCVRP, and (2) the key terms “waste,” “vehicle routing problem,” “approach,” or similar terms must appear in the body text. Exclusion criteria included: (1) papers that did not focus on WCVRP or only used it as an example or a minor part of the content; (2) papers focused on waste management systems, supply chains,

reverse logistics, daily necessities, and vaccines. Consequently, 122 papers were selected.

Finally, the steps were replicated in the Scopus database, which included different categories of papers compared to the Web of Science database, covering environmental, engineering, computer science, social science, mathematics, business, management and accounting, decision sciences, economics, econometrics, and finance and multidisciplinary fields. Cross-checking with the Web of Science database ensured completeness, resulting in eight additional papers from the Scopus database and a total of 130 relevant and high-quality papers selected.

The results were organized into six groups. First, a comprehensive review of waste types was conducted. Second, the most common characteristics of models were presented. Third, the objective functions were discussed. Next, the solution methods were analyzed, followed by an examination of the types of tests. Finally, the study offers recommendations for further research. The research methodology framework is illustrated in [Figure 2](#).

Content analysis

This section reviews the collected papers on various types of waste, model characteristics, objective functions, solution methods, and test types. These topics are further elaborated in the following subsections.

Table 1. The search strings are utilized on the online databases.

Database	Search String
Web of Science	(((TS = (collection)) OR TS = (vehicle routing problem)) OR TS = (route)) OR TS = (routing)) OR TS = (transportation)) AND (((TS = (waste)) OR TS = (garbage)) OR TS = (trash)) OR TS = (refuse)) AND (((TS = (algorithm)) OR TS = (mathematical)) OR TS = (optimization)) OR TS = (approach))
Scopus	((TITLE-ABS-KEY (waste) OR TITLE-ABS-KEY (garbage) OR TITLE-ABS-KEY (trash) OR TITLE-ABS-KEY (refuse))) AND ((TITLE-ABS-KEY (collection) OR TITLE-ABS-KEY (vehicle routing) OR TITLE-ABS-KEY (routing) OR TITLE-ABS-KEY (transportation) OR TITLE-ABS-KEY (route))) AND ((optimization) OR (algorithm) OR (mathematical) OR (approach))

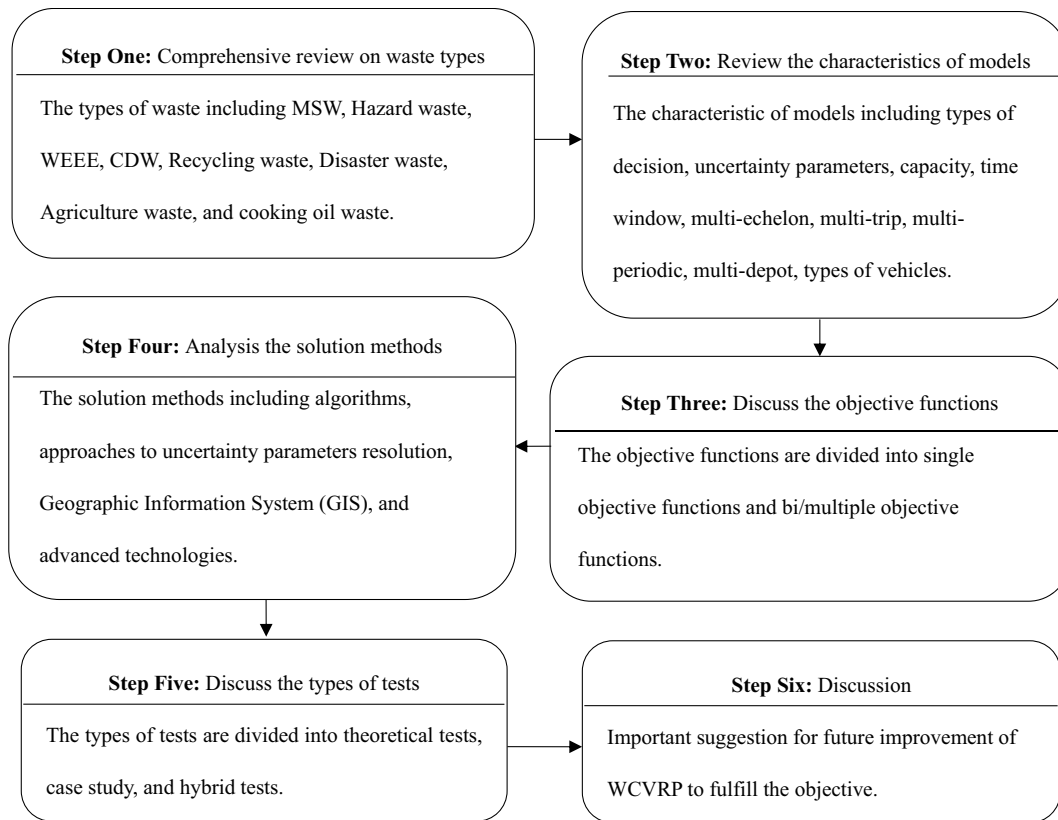


Figure 2. The framework of the research methodology.

Classification of waste

Interest in the WCVRP has grown among scholars and practitioners since the first paper on the topic was published (Beltrami and Bodin 1974). Beliën, De Boeck, and Van Ackere (2014) classified waste into four categories: garbage, skips and containers, hazardous waste, and recyclable waste. Kim, Kim, and Sahoo (2006) systematically defined and categorized waste into three types: residential, commercial, and roll-on-roll-off waste. Based on the work of Kim, Kim, and Sahoo (2006), Han and Cueto (2015) provided a comprehensive overview of waste classification. This paper examines and categorizes waste types based on previously reviewed papers, including MSW, hazardous waste, waste electrical and electronic equipment (WEEE), construction and demolition waste (CDW), recyclable waste, disaster waste, agriculture waste, and cooking oil waste. Table 2 details the classification and quantities of each type of waste.

MSW was the primary focus in more than half of the reviewed papers, with over two-thirds treating MSW as “general waste” without specifying its subtypes. However, some papers classified MSW into categories such as wet and dry waste (Zhou, Zhang, and Wu 2022), bio-waste

(Lavigne, Beliën, and Dewil 2021; Rambandara et al. 2022), commercial waste (Masmoudi, Coelho, and Demir 2022), recyclable and non-recyclable (Valizadeh 2020), and hazardous waste and cooking oil waste (Erdem 2022b; Lu, Pu, and Han 2020). Additionally, other papers further divided MSW into more specific waste types, such as food, plastic, drink cartons, metal, glass (Olishevych and Danchuk 2023; Roy et al. 2022; Shang et al. 2022; Van Engeland and Beliën 2021). The second most common type of waste was hazardous waste, accounting for approximately 27% of the total. Notably, the majority of hazardous waste was MW, which is categorized into infectious and noninfectious types for proper collection and transportation and originates from hospitals, clinics, and laboratories (Aydemir-Karadag 2022; Govindan et al. 2021; Nikzamir and Baradaran 2020). In contrast, Erdem (2022a), Daoud, Kammoun, and Hachicha (2020), Linfati, Gatica, and Escobar (2021), and Suksee and Sindhuchao (2021) primarily focused on infectious waste, whereas Kordi et al. (2023) focused on dental waste. Additionally, industrial hazardous waste has also received attention from academics (Delfani et al. 2021; Ma and Li 2021; Nikzamir, Baradaran, and Panahi 2020; Raeisi and Jafarzadeh Ghouschi 2022). In comparison, recyclable

Table 2. The types of waste in the reviewed papers.

Types of Waste	Accounts	References
MSW	73	Akbarpour et al. (2021), Aliahmadi, Barzinpour, and Pishvaei (2020, 2021), Blazquez and Paredes-Belmar (2020), Bouleft and Elhilali Alaoui (2023), Cao et al. (2021), De Moraes et al. (2023), Dereci and Karabekmez (2022), Erdem (2022b), Fan (2023), Gao et al. (2023), Ghiani et al. (2021), Gläser (2022), Gruler et al. (2020), Hannan et al. (2020), Hashemi-Amiri, Ji, and Tian (2023), Hina et al. (2020), Hong, Yan, and Ge (2023), Hu et al. (2024), Huang et al. (2021), Hurkmans et al. (2021), Janela, Mourão, and Pinto (2022), Jin et al. (2021), Jorge et al. (2022), Kapadia and Mehta (2023), Kaya (2023), Kim et al. (2023), Lan et al. (2022), Lavigne et al. (2023), Lavigne, Beliën, and Dewil (2021), Li et al. (2023, 2023), Liu and Liao (2021), Lu et al. (2023), Luo, Zhao, and Zhang (2024), Lu, Pu, and Han (2020), Ma et al. (2021), Mahéo, Rossit, and Kilby (2022), Masmoudi, Coelho, and Demir (2022), Moazzeni, Tavana, and Darmian (2022), Mohammadi et al. (2023, 2023), Mojtahedi et al. (2021), Molfese Greco et al. (2023), Nurprihatin and Lestari (2020), Olishevych and Danchuk (2023), Qiao et al. (2020), Rabbani, Mokarrari, and N (2021), Rahmanifar et al. (2023), Rambandara et al. (2022), Rossit, Toncovich, and Fermani (2021), Roy et al. (2022), Sallem et al. (2021), Shang et al. (2022), Shang, Ma, and Liu (2023), Shen et al. (2023), Shi et al. (2020), Tirkolaee et al. (2020, 2023), Valizadeh (2020), Van Engeland and Beliën (2021), Wan et al. (2023), Wei, Liang, and Tang (2022), Wu et al. (2020), Wu, Tao, and Yang (2020), Xin et al. (2021), Yang, Tao, and Zhong (2022), Yu et al. (2022), Yu, Zhou, and Liu (2020), Zhang et al. (2022, 2023), Zhang, Mu, and Wang (2020), Zhou, Zhang, and Wu (2022)
Hazardous	35	Araee, Manavizadeh, and Aghamohammadi Bosjin (2020), Aydemir-Karadag (2022), Ben-Romdhane et al. (2023), Cao et al. (2021), Daoud, Kammoun, and Hachicha (2020), Delfani et al. (2020, 2021), Erdem (2022a), Eren and Tuzkaya (2021), Gao et al. (2021), Ghannadpour, Zandieh, and Esmaeili (2021), Govindan et al. (2021), Hassanpour et al. (2023), Kordi et al. (2023), Li et al. (2021), Linfati, Gatica, and Escobar (2021), Ma and Li (2021), Nikzamir and Baradaran (2020), Nikzamir, Baradaran, and Panahi (2020), Niranjani and Umamaheswari (2022), Ouertani et al. (2023), Rabbani, Nikoubin, and Farrokhi-Asl (2021), Raeisi and Jafarzadeh Ghouschi (2022), Saeidi, Aghamohammadi-Bosjin, and Rabbani (2021), Suksee and Sindhuchao (2021), Taslimi, Batta, and Kwon (2020), Tirkolaee and Aydin (2021), Tirkolaee, Abbasian, and Weber (2021), Torkayesh, Vandchali, and Tirkolaee (2021), Wang et al. (2023), Xin et al. (2023), Yu et al. (2020), Zhang et al. (2022), Zhao et al. (2023), Zhao, Wu, and Ke (2021)
WEEE	5	Arias-Osorio, Ríos-Mercado, and Tamayo-Morantes (2020), Pourhejazy et al. (2021), Sari, Masruroh, and Asih (2021), Swarc, Nowakowski, and Boryczka (2021), Zheng, Sun, and Liu (2021)
CDW	5	Chen and Liao (2022), Elshaboury and Marzouk (2021), Wang, Yi, and Liu (2022), Wöhlk and Laporte (2022), Yazdani et al. (2021)
Recyclable	7	Cao, Liao, and Huang (2021), Ghobadi et al. (2022), Herrera-Cobo, Escobar, and Álvarez-Martínez (2023), Kızıltaş, Alakaş, and Eren (2020), Książek, Gdowska, and Korcyl (2021), Silva et al. (2023), Yu et al. (2024)
Disaster	1	Cheng et al. (2022)
Agriculture	2	Tran et al. (2024), Wang et al. (2022)
Cooking oil	2	Olmez et al. (2022), Quintana et al. (2020)
Total	130	

waste, WEEE, and CDW constitute approximately 5%, 4%, and 4% of the total waste, respectively. For instance, Książek, Gdowska, and Korcyl (2021) categorized waste into types such as paper, glass, and plastic. Meanwhile, the volume of WEEE has surged due to the increased use of electrical and electronic equipment in recent years, making its recycling a pressing issue (Zheng, Sun, and Liu 2021). In response to this challenge, Chen and Liao (2022) proposed an integrated collection scheme for WEEE recycling that handles both on-call and door-to-door requests simultaneously. Similarly, the volume of CDW has significantly increased over recent decades, drawing scholarly attention. Concerned about the environmental and resource impacts of CDW, Chen and Liao (2022) developed an optimization model for CDW transportation that incorporates sustainable considerations. Agricultural waste, cooking oil waste, and disaster waste have received less consideration, with only two, two, and one studies on each, respectively.

Characteristics of model

This section outlines the model characteristics based on Delfani et al. (2021). The inclusion of more characteristics makes the models more realistic; however,

presenting all characteristics is challenging due to various factors (Goli and Tirkolaee 2023). Therefore, this section discusses only the most common characteristics.

Type of decision

The primary decision-making categories include VRP and LRP. The classical VRP had the largest proportion, with over 80% of the papers devoted to this category. The LRP was the second most common decision type, receiving approximately 18% of the attention. For instance, Hong, Yan, and Ge (2023) and Li et al. (2023) integrated location problems into VRP models for waste collection and transportation. Scheduling has also received some attention from researchers. For example, Linfati, Gatica, and Escobar (2021) proposed a mathematical model for scheduling and assigning of MW collection routes to customers, while Hashemi-Amiri, Ji, and Tian (2023) established a framework integrating scheduling and routing for MSW management. Notably, some papers used electric vehicles (EVs) for MSW collection, involving charging decisions. For instance, Erdem (2022a) and Erdem (2022b) introduced an electric medical WCVRP model to optimize routes and schedules. They considered various charging types with different durations and selected the appropriate

technology based on constraints to avoid time violations, allowing for both linear and partial charging. Research on inventory IRP (Taslimi, Batta, and Kwon 2020), allocation routing (Książek, Gdowska, and Korcyl 2021; Roy et al. 2022; Sallem et al. 2021), location-allocation routing (Arias-Osorio, Ríos-Mercado, and Tamayo-Morantes 2020; Blazquez and Paredes-Belmar 2020; Govindan et al. 2021; Mahéo, Rossit, and Kilby 2022; Olmez et al. 2022; Wei, Liang, and Tang 2022; Yu et al. 2020), and location-allocation inventory routing (Aydemir-Karadag 2022; Mojtahedi et al. 2021; Rabbani, Mokarrari, and Akbarian-saravi 2021; Torkayesh, Vandchali, and Tirkolaee 2021) received less attention.

Uncertainty parameter

The survey demonstrated that 27 studies employed uncertainty parameters, indicating a growing focus on these aspects in recent research. Uncertainty refers to the inability to precisely determine or predict variables or outcomes during the decision-making process. This uncertainty can arise from various factors such as incomplete information, system complexity, and environmental changes (Goli 2023). In VRP, uncertainty parameters primarily refer to stochastic and fuzzy parameters.

Stochastic parameters represent uncertainty arising from natural random processes or environmental changes. These parameters are quantified using probability distributions that describe the frequently and likelihood of events (Nikzamir and Baradaran 2020). The volume of waste generated was the most frequency considered stochastic parameter. For instance, Saeidi, Aghamohamadi-Bosjin, and Rabbani (2021) developed a mathematical model for municipal and industrial hazardous waste, assuming that the waste volume produced at each network node was uncertain. Additionally, uncertain time is another parameter. Gruler et al. (2020) addressed a time-dependent WCVRP with unpredictable journey times, whereas Nikzamir and Baradaran (2020) considered the uncertainty of transfer times between healthcare facilities and treatment centers. Moreover, some authors considered multiple stochastic parameters simultaneously. For instance, Cao, Liao, and Huang (2021) presented a mathematical model that incorporates stochastic customer demand, uncertain recycling quantity volumes, required service times, and various recyclable waste types.

Fuzzy parameters are challenging to define or measure precisely and often involve subjective judgments or vague concepts. These parameters are represented by fuzzy sets and membership functions, rather than

precise values or probability distributions (Aliahmadi, Barzinpour, and Pishvae 2020). Waste generation is one of the most frequently examined aspects in this context (Aliahmadi, Barzinpour, and Pishvae 2020, 2021; Kordi et al. 2023; Tirkolaee et al. 2020; Tirkolaee, Abbasian, and Weber 2021). Some studies considered waste generation a stochastic parameter, while others treated it as a fuzzy parameter due to insufficient historical data for statistical analysis (Goli, Ala, and Mirjalili 2023). Additionally, some studies considered multiple fuzzy parameters simultaneously. For instance, Raeisi and Ghouschi (2022) proposed a robust multi-objective LRP model for hazardous waste, incorporating fuzzy transportation cost and waste volumes.

Capacity

Capacity is a fundamental aspect of WCVRP, often considered in intermediate centers (Aliahmadi, Barzinpour, and Pishvae 2020), bins (Hina et al. 2020), temporary transfer centers (Cao et al. 2022), vehicles (Niranjani and Umamaheswari 2022), and collection centers (Olmez et al. 2022). Additionally, some studies focused on multiple capacity considerations simultaneously. For instance, Liu and Liao (2021) examined the capacities of vehicles and temporary transfer stations, while Lavigne et al. (2023) investigated the capacities of vehicles and intermediate facilities. Akbarpour et al. (2021) and Ma et al. (2021) examined the capacities of both vehicles and specific centers such as separation and recycling centers. Additionally, Araee, Manavizadeh, and Aghamohammadi Bosjin (2020) considered the capacities of vehicles, storage centers, depot centers, and other related facilities. Raeisi and Ghouschi (2022) took this a step further by considering both the maximum and minimum capacities of various centers for hazardous waste recycling, incineration, and disposal. Saeidi, Aghamohamadi-Bosjin, and Rabbani (2021) considered the capacities of vehicles, treatment, disposal sites, and recycling facilities in WCVRP. Their work underscores the critical role of detailed and adaptive capacity management strategies in avoiding operational inefficiencies and enhancing the overall efficiency and resilience of WCVRP.

Time window

Time windows are critical for ensuring the timely and efficient operation of WCVRP. The term “time window” typically refers to the service period, which is divided into hard and soft time windows. In a hard time window, if a vehicle arrives early, it must wait to start service; if it arrives late, the vehicle must return with the undelivered goods (Chen and Liao 2022). In a soft time window, if

a vehicle arrives earlier or later than scheduled, compensation may be required, but delivery can still be completed (Chen and Liao 2022). For instance, Govindan et al. (2021) considered a hard time window, requiring vehicles to return to distribution centers within a specific period, ensuring that waste collection aligns with predetermined schedules to optimize operations. Similarly, Quintana et al. (2020) ensured that the travel time for each vehicle did not exceed the total working hours and adhered to the time window constraints. Niranjani and Umamaheswari (2022) proposed a sustainable WCVRP model that explicitly defined the start time, end time, and service time within a time window. Their work highlights the crucial role of time window in WCVRP and underscores their importance in maintaining operational efficiency and reliability.

Multiple echelons

The term “multi-echelon” refers to a problem divided into multiple stages to enhance the efficiency of waste collection and transportation. Some papers divided transportation process into two stages. For instance, Ghobadi et al. (2022) established a two-echelon VRP: the first stage involved collecting waste from customers and transporting it to primary stations or separation facilities; in the second stage, it was moved to landfills or recycling centers. Some papers integrated location decisions into multiple stage processes. For example, in the location stage, Arias-Osorio, Ríos-Mercado, and Tamayo-Morantes (2020) identified potential locations for WEEE and allocated different waste types to specific sites; in the routing phase, the collection routes were planned to minimize associated costs. Yu et al. (2020) designed the first stage of the network by strategically selecting facility locations and installed technologies, while the second stage involved allocation and route planning. Additionally, one study concentrated on three stages: The first echelon combined depots and destinations into a single network node; the second stage allowed a single node to function as both depot and customer; and in the final stage, individual roles were assigned to each node (Mojtahedi et al. 2021). These studies demonstrate how strategic planning at multiple echelons can optimize the waste collection and transportation process.

Multiple trips

The term “multi-trip” refers to vehicles being able to start new trips to collect waste from additional storage locations after unloading waste at the treatment facilities, often making several trips before all sites are emptied (Nurprihatin and Lestari 2020). For instance, Aliahmadi, Barzinpour, and Pishvae (2020) developed

a system that enables vehicles to undertake multiple waste collection trips, setting a maximum limit on the number of trips per vehicle. Additionally, Zhang, Mu, and Wang (2020) showed that vehicles conducted multiple tours daily between the waste facility and other processing sites; Aliahmadi, Barzinpour, and Pishvae (2021) allowed all vehicles to make more than one trip per time window in a given day. These studies show that multi-trip can significantly improve operational efficiency by maximizing vehicle utilization, reducing travel times, and enhancing the flexibility and responsiveness of WCVRP.

Multiple periodic

Recent research trends indicate a growing interest in multi-period scheduling, which allows waste collection activities to be distributed over multiple time periods, providing greater flexibility in WCVRP. This approach is particularly useful for addressing fluctuations in waste generation and optimizing resource allocation over time. For instance, Taslimi, Batta, and Kwon (2020) integrated a periodic collection schedule into their models for MW. Gläser (2022) developed an extended periodic LRP model for waste collection, which includes a service type option. Additionally, Ma and Li (2021) allowed for partial collection at each source during the current period and delayed the collection of uncollected hazardous waste to subsequent periods. Furthermore, Cao et al. (2022) developed a multi-period VRP model for disaster MW and demonstrated that the multi-period model outperformed the single-period model. These studies demonstrate the benefits of multi-period models in enhancing WCVRP efficiency, particularly in complex environments, and highlights the role of periodic scheduling in managing fluctuating waste volumes and ensuring consistent collection services.

Multiple depots

In the context of WCVRP, depots can be classified as single and multiple, with the latter receiving greater attention recently. The use of multiple depots in WCVRP has been shown to improve the efficiency of waste collection and transportation. For instance, Aliahmadi, Barzinpour, and Pishvae (2020) considered multiple trips among various depots and intermediary facilities. Similarly, Chen and Liao (2022) formulated a multi-depot VRP model with time windows to enhance the efficiency of CDW transportation. Lan et al. (2022) formulated VRP models incorporating multi-depot, multi-disposal facilities, and multi-trip. Additionally, Niranjani and Umamaheswari (2022) focused on optimizing transportation routes for MW

to various disposal sites. Xin et al. (2021) designed a WCVRP model incorporating time windows and multiple transfer stations. These studies explore the importance of multi-depot strategies, highlighting how they can enhance the flexibility and efficiency of WCVRP. They suggest that incorporating multiple depots into WCVRP can significantly improve both operational efficiency and service quality.

Types of vehicles

Vehicles serve as resources for collecting and transporting waste from various depots (Beliën, De Boeck, and Van Ackere 2014). Table 3 categorizes vehicles into four types: homogeneous and heterogeneous vehicles; EVs, ICVs, and plug-in hybrid electric vehicles (PHEVs);

single- and multi-compartment vehicles; and owned and rental vehicles.

The term “homogeneous vehicle” refers to one or more vehicles with the same capacity, which can simplify the problem (Beliën, De Boeck, and Van Ackere 2014). However, using heterogeneous vehicles is more realistic because diverse capabilities typically correspond to different vehicle sizes (Beliën, De Boeck, and Van Ackere 2014). For instance, Nikzamir and Baradaran (2020) explored using a heterogeneous fleet of vehicles to manage the segregation and collection of infectious and non-infectious waste. Rabbani, Mokarrari, and Akbarian-Saravi (2021) utilized heterogeneous vehicles with varying capacities, compatibilities, or environmental emissions, for different waste collection and transportation

Table 3. Types of vehicles in the review papers.

References	Characteristics of vehicles								
	Vehicle type		Engine type		compartment	ownership			
	HO	HE	ICV	EV	PHEV	S	M	O	R
Arias-Osorio, Ríos-Mercado, and Tamayo-Morantes (2020), Blazquez and Paredes-Belmar (2020), Cao et al. (2021, 2022), Chen and Liao (2022), Daoud, Kammoun, and Hachicha (2020), De Moraes et al. (2023), Delfani et al. (2020), Dereci and Karabekmez (2022), Eren and Tuzkaya (2021), Fan (2023), Ghannadpour, Zandieh, and Esmaeili (2021), Gruler et al. (2020), Hannan et al. (2020), Hassanpour et al. (2023), Hina et al. (2020), Hu et al. (2024), Huang et al. (2021), Hurkmans et al. (2021), Janela, Mourão, and Pinto (2022), Jin et al. (2021), Jorge et al. (2022), Kapadia and Mehta (2023), Kim et al. (2023), Lan et al. (2022), Lavigne et al. (2023), Lavigne, Beliën, and Dewil (2021), Li et al. (2021, 2023, 2023), Linfati, Gatica, and Escobar (2021), Liu and Liao (2021), Luo, Zhao, and Zhang (2024), Lu, Pu, and Han (2020), Ma and Li (2021), Ma et al. (2021), Mahéo, Rossit, and Kilby (2022), Mohammadi et al. (2023), Molfese Greco et al. (2023), Olmez et al. (2022), Pourhejazy et al. (2021), Qiao et al. (2020), Raeisi and Jafarzadeh Ghouschi (2022), Rambandara et al. (2022), Rossit, Toncovich, and Fermani (2021), Sallem et al. (2021), Sari, Masruroh, and Asih (2021), Shen et al. (2023), Shi et al. (2020), Silva et al. (2023), Suksee and Sindhuchao (2021), Szwarc, Nowakowski, and Boryczka (2021), Taslimi, Batta, and Kwon (2020), Tirkolaee et al. (2023), Tran et al. (2024), Valizadeh (2020), Van Engeland and Beliën (2021), Wang et al. (2022, 2023), Wei, Liang, and Tang (2022), Wöhlk and Laporte (2022), Wu et al. (2020), Wu, Tao, and Yang (2020), Xin et al. (2021, 2023), Yazdani et al. (2021), Yu et al. (2020, 2022, 2024), Zhang et al. (2022, 2022, 2023), Zhang, Mu, and Wang (2020), Zhao et al. (2023), Zhao, Wu, and Ke (2021)	✓		✓			✓		✓	
Akbarpour et al. (2021), Aliahmadi, Barzinpour, and Pishvaei (2020, 2021), Araee, Manavizadeh, and Aghamohammadi Bosjin (2020), Aydemir-Karadag (2022), Cheng et al. (2022), Delfani et al. (2021), Elshaboury and Marzouk (2021), Gao et al. (2021, 2023), Ghiani et al. (2021), Gläser (2022), Kaya (2023), Kızıltaş, Alakaş, and Eren (2020), Kordi et al. (2023), Mojtahedi et al. (2021), Nikzamir and Baradaran (2020), Nikzamir, Baradaran, and Panahi (2020), Niranjani and Umamaheswari (2022), Nurprihatin and Lestari (2020), Oliskevych and Danchuk (2023), Quintana et al. (2020), Rabbani, Mokarrari, and N (2021), Rabbani, Nikoubin, and Farrokhi-Asl (2021), Rahmanifar et al. (2023), Roy et al. (2022), Saeidi, Aghamohammadi-Bosjin, and Rabbani (2021), Shang et al. (2022), Tirkolaee and Aydın (2021), Tirkolaee et al. (2020), Tirkolaee, Abbasian, and Weber (2021), Torkayesh, Vandchali, and Tirkolaee (2021), Wan et al. (2023), Wang, Yi, and Liu (2022), Yu, Zhou, and Liu (2020), Zhou, Zhang, and Wu (2022)		✓	✓			✓			✓
Hashemi-Amiri, Ji, and Tian (2023), Hong, Yan, and Ge (2023), Lu et al. (2023), Mohammadi et al. (2023)		✓	✓				✓		✓
Ben-Romdhane et al. (2023), Bouleft and Elhilali Alaoui (2023), Herrera-Cobo, Escobar, and Álvarez-Martínez (2023), Ouertani et al. (2023), Shang, Ma, and Liu (2023)	✓		✓				✓		✓
Erdem (2022a, 2022b), Książek, Gdowska, and Korcyl (2021)		✓		✓		✓			✓
Govindan et al. (2021), Zheng, Sun, and Liu (2021)		✓	✓			✓		✓	✓
Masmoudi, Coelho, and Demir (2022)	✓				✓	✓		✓	
Moazzeni, Tavana, and Darmian (2022)	✓			✓		✓		✓	
Yang, Tao, and Zhong (2022)	✓			✓			✓	✓	
Cao, Liao, and Huang (2021)	✓	✓	✓	✓			✓	✓	
Ghobadi et al. (2022)		✓	✓	✓		✓		✓	
Total	84	47	124	7	1	119	11	130	2

Notes. HO: homogeneous; HE: heterogeneous; ICV: internal combustion vehicle; EV: electric vehicle; PHEV: plug-in hybrid electric vehicle; S: single compartment; M: multi-compartment; O: owned; R: rental.

tasks. 124 publications used ICVs, indicating that fuel-powered vehicles are the primary type used in this domain. It is widely acknowledged that these vehicles consume gasoline and emit harmful gases. Eight papers explored the use of EVs in their research. For example, Książek, Gdowska, and Korcyl (2021) used various EVs to collect recyclable waste, aiming to reduce carbon emissions and energy consumption. Erdem (2022b) deployed a heterogeneous fleet of EVs for multi-trip MSW container collection. Additionally, two papers employed EVs and ICVs simultaneously: in the first echelon, EVs collected recyclable waste, while in the second echelon, ICVs transported it to recycling centers (Cao, Liao, and Huang 2021; Ghobadi et al. 2022). Finally, one paper utilized PHEVs to collect MSW (Masmoudi, Coelho, and Demir 2022). Regarding vehicle compartments, over 100 papers used single-compartment vehicles, while only 11 papers used multi-compartment vehicles. For example, Yang, Tao, and Zhong (2022) aimed to sort, collect, and transport MSW using EVs with multiple separate compartments. Shang, Ma, and Liu (2023) considered carbon emissions and flexible multi-compartment sizes; and Herrera-Cobo, Escobar, and Álvarez-Martínez (2023) used vehicles with adjustable compartments. Moreover, in the context of the sharing economy, two papers used rental vehicles. Govindan et al. (2021) considered rental vehicles as a resource, while Zheng, Sun, and Liu (2021) incorporated social vehicles with rental costs into the classical VRP for a WEEE recycling network.

Objective functions

The objective functions in this section are categorized into two groups: single-objective functions and bi/multi-objective functions. Among the reviewed papers, 78 focused on single-objective functions, while 52 addressed bi/multi-objective functions. Tables 4 and 5 present the various objective functions discussed in this literature review.

Single objective function types

Table 4 shows that over 65% of the reviewed papers focused on cost minimization, which was the primary objective in 78 single-objective models. Additionally, cost performance varied across different papers as they addressed distinct issues. For instance, Olmez et al. (2022) minimized total costs, including vehicle costs, weekly fixed costs, and bin-related costs. Travel distance minimization was the second most popular objective, comprising about 22% of the review papers in single-objective functions, while approximately 5% of papers focused on minimizing time. Three papers explored profit-maximization strategies (De Moraes et al. 2023;

Jorge et al. 2022; Pourhejazy et al. 2021). Minimizing the number of vehicles used (Ghani et al. 2021) and maximizing the daily truck loads (Linfati, Gatica, and Escobar 2021) were less frequently addressed, each addressed in only one paper. Only one paper focused on the social dimension (Li et al. 2021).

Bi/multi-objective function types

Table 5 shows that cost minimization was the most prevalent objective function in this section, with 41 publications focusing on it. Minimization of public health infection risk, including population, transportation, treatment, and disposal risk minimization, was the second most common objective function, featured in 26 publications. This was followed by 20 papers focusing on carbon emissions minimization and 12 publications on distance minimization. Nine papers addressed time minimization, profit maximization, workload balance, fuel consumption, and visual pollution, with six, six five, and two publications, respectively. Other objectives, such as the minimization of overlap, maximization of the average usage rate of waste collection sites, job creation, the number of hired laborers, and safety scores, were each the focus of a single publication. This section presents four categories: economic dimension, economic and social dimension, economic and environmental dimension, and the integration of economic, environmental, and social dimensions.

Economic dimension. Although there were various objective functions, only five papers exclusively focused on the economic dimension. Blazquez and Paredes-Belmar (2020) and Sari, Masrurroh, and Asih (2021) each established a WCVRP model aimed at minimizing the total cost and distance of waste collection and disposal. Akbarpour et al. (2021) focused on minimized travel distance and maximized revenue from waste collection. Aliahmadi, Barzinpour, and Pishvaei (2021) primarily focused on the minimization of overall costs and time in WCVRP, while Hina et al. (2020) included travel distance as an additional objective.

Economic and social dimensions. Approximately 46% of the studies concurrently investigated the economic and social dimensions. For instance, Eren and Tuzkaya (2021) aimed to minimize travel distance and maximize safety scores. Zhou, Zhang, and Wu (2022) aimed to minimize travel distance, transportation risk, and achieve a balanced workload. Additionally, 15 papers mainly focused on minimizing cost and infection risk in public health. For example, Hassanpour et al. (2023) proposed a VRP model for MW to minimize total cost and

Table 4. Objective function types in single objective models.

Objective function	Sustainability	Accounts	References
A1	Ec	51	Aliahmadi, Barzinpour, and Pishvaei (2020); Arias-Osorio, Ríos-Mercado, and Tamayo-Morantes (2020); Bouleff and Elhilali Alaoui (2023); Cao, Liao, and Huang (2021); Chen and Liao (2022); Cheng et al. (2022); Erdem (2022b); Ghobadi et al. (2022); Gläser (2022); Herrera-Cobo, Escobar, and Álvarez-Martínez (2023); Hong, Yan, and Ge (2023); Huang et al. (2021); Jin et al. (2021); Kapadia and Mehta (2023); Kim et al. (2023); Kızıltaş, Alakaş, and Eren (2020); Lavigne et al. (2023); Lavigne, Beliën, and Dewil (2021); Li et al. (2023); Luo, Zhao, and Zhang (2024); Mahéo, Rossit, and Kilby (2022); Masmoudi, Coelho, and Demir (2022); Moazzeni, Tavana, and Darmian (2022); Mohammadi et al. (2023); Niranjani and Umamaheswari (2022); Nurprihatin and Lestari (2020); Olmez et al. (2022); Qiao et al. (2020); Roy et al. (2022); Shang et al. (2022); Shang, Ma, and Liu (2023); Shen et al. (2023); Suksee and Sindhuchao (2021); Szwarc, Nowakowski, and Boryczka (2021); Tirkolaee et al. (2020); Tran et al. (2024); Van Engeland and Beliën (2021); Wan et al. (2023); Wang et al. (2022); Wang, Yi, and Liu (2022); Wöhlk and Laporte (2022); Wu et al. (2020); Yang, Tao, and Zhong (2022); Yu et al. (2022, 2024); Yu, Zhou, and Liu (2020); Zhang et al. (2022, 2022, 2023); Zhang, Mu, and Wang (2020); Zheng, Sun, and Liu (2021)
A2	Ec	3	De Morais et al. (2023); Jorge et al. (2022); Pourhejazy et al. (2021)
A3	Ec	4	Gruler et al. (2020); Janela, Mourão, and Pinto (2022); Książek, Gdowska, and Korcyl (2021); Yazdani et al. (2021)
A4	Ec	17	Ben-Romdhane et al. (2023); Daoud, Kammoun, and Hachicha (2020); Dereci and Karabekmez (2022); Fan (2023); Gao et al. (2021); Hannan et al. (2020); Hu et al. (2024); Lan et al. (2022); Molfese Greco et al. (2023); Oliskevych and Danchuk (2023); Ouertani et al. (2023); Quintana et al. (2020); Rambandara et al. (2022); Rossit, Toncovich, and Fermani (2021); Shi et al. (2020); Silva et al. (2023); Wei, Liang, and Tang (2022)
A5	Ec	1	Linfat, Gatica, and Escobar (2021)
A6	Ec	1	Ghani et al. (2021)
C5	S	1	Li et al. (2021)
Total			78

Notes. A1: minimizing cost; A2: maximizing profit; A3: minimizing time; A4: minimizing distance; A5: minimizing daily truck loads; A6: minimizing vehicle number; C5: minimizing infection risk of public health minimization; Ec: economic, S: social.

population exposure risk. Besides cost and risk, Torkayesh, Vandchali, and Tirkolaee (2021) aimed to maximize job creation as an additional objective.

Economic and environmental dimensions. 14 papers simultaneously focused on economic and environmental dimensions. For instance, Xin et al. (2021) aimed to minimize travel distance and fuel consumption for MSW. In addition to costs, Liu and Liao (2021) and Rahmanifar et al. (2023) also focused on minimizing carbon emissions as a key objective. Additionally, different studies focused on minimizing total travel distance (Kaya 2023; Wu, Tao, and Yang 2020), travel and collection time (Rabbani, Mokarrari, and N 2021), as well as maximizing the average usage rate of waste collection sites (Cao et al. 2021) and profit (Valizadeh 2020).

Economic, environmental, and social dimensions. Nine papers simultaneously considered the economic, environmental, and social dimensions. For instance, Mojtahedi et al. (2021) introduced a model that considers the triple bottom line of sustainability to minimize total cost, carbon emissions, and workload deviations, while Tirkolaee et al. (2023) included maximizing the number of hired labor as an objective. Li et al. (2023) considered cost,

carbon emissions, and population risk as objectives, while Delfani et al. (2020) included transportation risk as an additional objective. In addition to costs, carbon emissions, and transportation risk, Raeisi and Ghoushchi (2022) also included distance minimization as an objective. Additionally, Ghannadpour, Zandieh, and Esmaeili (2021), Hashemi-Amiri, Ji, and Tian (2023), Mohammadi et al. (2023), and Saeidi, Aghamohamadi-Bosjin, and Rabbani (2021) also considered triple bottom-line objectives in their studies on WCVRP.

Solution methods

Algorithms in WCVRP

This section discusses the solution approaches, which are presented in Tables 6 and 7. These tables list the algorithms applied in single-objective and bi/multi-objective functions, respectively. The solution techniques include exact methods, approximate algorithms, and hybrid algorithms. This classification follows the frameworks provided by Sar and Ghadimi (2023), Lin, Musa, and Yap (2022), and Laporte (2009). Exact methods are defined as approaches that solve problems using commercial solvers and exact algorithms. Approximate algorithms are described as solutions utilizing heuristics and metaheuristics. Hybrid

Table 5. Objective function types in Bi/Multiple objective models.

References	Objective function																Sustainability		
	A1	A2	A3	A4	A7	A8	B1	B2	C1	C2	C3	C4	C5	C6	Ec	En	S		
Aydemir-Karadag (2022), Delfani et al. (2021), Erdem (2022a), Govindan et al. (2021), Hassanpour et al. (2023), Ma and Li (2021), Ma et al. (2021), Nikzamir, Baradaran, and Panahi (2020), Taslimi, Batta, and Kwon (2020), Tirkolaee and Aydin (2021), Wang et al. (2023), Xin et al. (2023), Yu et al. (2020), Zhao et al. (2023), Zhao, Wu, and Ke (2021)	✓												✓		✓		✓		
Liu and Liao (2021), Nikzamir and Baradaran (2020), Rahmanifar et al. (2023)	✓						✓								✓	✓			
Tirkolaee, Abbasian, and Weber (2021)			✓										✓		✓	✓	✓		
Ghannadpour, Zandieh, and Esmaeili (2021)	✓							✓					✓		✓	✓	✓		
Kordi et al. (2023)	✓		✓										✓		✓	✓	✓		
Cao et al. (2022)		✓					✓								✓	✓	✓		
Delfani et al. (2020), Li et al. (2023)	✓						✓						✓		✓	✓	✓		
Li et al. (2023)	✓			✓									✓		✓	✓	✓		
Raeisi and Jafarzadeh Ghouschi (2022)	✓	✓					✓						✓		✓	✓	✓		
Elshaboury and Marzouk (2021), Gao et al. (2023)	✓		✓				✓	✓							✓	✓	✓		
Kaya (2023), Wu, Tao, and Yang (2020)	✓			✓			✓								✓	✓			
Valizadeh (2020)	✓	✓					✓								✓	✓			
Xin et al. (2021)				✓				✓							✓	✓			
Rabbani, Mokarrari, and N (2021)	✓		✓				✓								✓	✓			
Cao et al. (2021)	✓					✓	✓								✓	✓			
Sallem et al. (2021)			✓	✓				✓							✓	✓			
Lu et al. (2023)				✓			✓								✓	✓			
Mohammadi et al. (2023)	✓						✓								✓	✓	✓		
Saeidi, Aghamohamadi-Bosjin, and Rabbani (2021)		✓					✓							✓	✓	✓	✓		
Blazquez and Paredes-Belmar (2020), Sari, Masruroh, and Asih (2021)	✓			✓											✓				
Akbarpour et al. (2021)		✓		✓											✓				
Aliahmadi, Barzinpour, and Pishvaei (2021)	✓		✓												✓				
Hina et al. (2020)	✓		✓	✓											✓				
Eren and Tuzkaya (2021)				✓								✓			✓		✓		
Lu, Pu, and Han (2020)	✓								✓						✓		✓		
Hurkmans et al. (2021)			✓		✓				✓						✓		✓		
Tirkolaee et al. (2023)	✓						✓		✓		✓				✓	✓	✓		
Torkayesh, Vandchali, and Tirkolaee (2021)	✓								✓		✓		✓		✓		✓		
Rabbani, Nikoubin, and Farrokhi-Asl (2021)	✓								✓		✓		✓		✓		✓		
Zhou, Zhang, and Wu (2022)				✓					✓				✓		✓	✓	✓		
Hashemi-Amiri, Ji, and Tian (2023)		✓					✓		✓				✓		✓	✓	✓		
Mojtahedi et al. (2021)	✓						✓		✓				✓		✓	✓	✓		
Total	41	6	9	12	1	1	20	5	6	1	1	1	26	2					

Notes. A1: minimizing cost; A2: maximizing profit; A3: minimizing time; A4: minimizing distance; A7: minimizing overlap; A8: maximizing the average utilization rate of waste collection points; B1: minimizing carbon emission; B2: minimizing fuel consumption; C1: workload balance; C2: maximizing job creation; C3: maximizing the number of hired labor; C4: maximizing safety scores; C5: minimizing infection risk of public health; C6: minimizing visual pollution; Ec: economic, En: environmental, S: social.

algorithms combine two or more techniques, such as exact methods, approximate algorithms, simulation, and machine learning (Montazerolghaem et al. 2022).

Exact methods. Among the papers listed in Tables 6 and 7, 12 employed commercial solvers, while 18 utilized exact algorithms. Cplex was the most commonly used commercial solver (Cao et al. 2022; Kızıltaş, Alakaş, and Eren 2020; Lavigne, Beliën, and Dewil 2021; Ma and Li 2021; Molfese Greco et al. 2023; Zhang et al. 2022). Additionally, ArcGIS (Hina et al. 2020; Sallem et al. 2021) was predominantly used in bi/multi-objective studies, while Gurobi (Książek, Gdowska, and Korcyl 2021) was used in single-objective studies. Furthermore, exact algorithms were applied in 12 bi/multi-objective and six single-objective studies. These exact algorithms included the goal programming-based expansion algorithm (Govindan et al. 2021; Hashemi-Amiri, Ji, and Tian 2023; Tirkolaee and Aydin 2021; Torkayesh, Vandchali,

and Tirkolaee 2021), branch-and-bound (Linfati, Gatica, and Escobar 2021), branch-and-price (Hassanpour et al. 2023), branch-and-price-and-cut (Huang et al. 2021; Zhang et al. 2023), benders decomposition (Mahéo, Rossit, and Kilby 2022; Nikzamir, Baradaran, and Panahi 2020), the modified lexical search algorithm (Olishevych and Danchuk 2023), and the sequence-generating algorithm (Wang, Yi, and Liu 2022). Additionally, some papers compared various exact methods within the same study (Delfani et al. 2020, 2021; Zhao, Wu, and Ke 2021). However, due to the complexity of the problems, most papers used exact methods only for smaller instances (Lavigne, Beliën, and Dewil 2021).

Approximate algorithms. Tables 6 and 7 indicate that approximately 32% of the studies employed approximate algorithms. Specifically, 15 bi/multi-objective and 21 single-objective studies used metaheuristics to optimize the proposed models. In contrast, heuristics were

Table 6. Algorithms applied in bi/multi-objective function studies.

Solution Approach	Accounts	References
Exact methods	17	
Commercial solver	5	Cao et al. (2022), Eren and Tuzkaya (2021), Hina et al. (2020), Ma and Li (2021), Sallem et al. (2021)
Exact algorithm	12	Delfani et al. (2020, 2021), Govindan et al. (2021), Hashemi-Amiri, Ji, and Tian (2023), Hassanpour et al. (2023), Kordi et al. (2023), Nikzamir, Baradaran, and Panahi (2020), Rabbani, Mokarrari, and N (2021), Tirkolaee and Aydin (2021), Tirkolaee, Abbasian, and Weber (2021), Torkayesh, Vandchali, and Tirkolaee (2021), Zhao, Wu, and Ke (2021)
Approximate algorithms	16	
Heuristics	1	Taslimi, Batta, and Kwon (2020)
Metaheuristics	15	Aydemir-Karadag (2022), Blazquez and Paredes-Belmar (2020), Cao et al. (2021), Elshaboury and Marzouk (2021), Ghannadpour, Zandieh, and Esmaeili (2021), Li et al. (2023, 2023), Lu et al. (2023), Mojtahedi et al. (2021), Nikzamir and Baradaran (2020), Rabbani, Nikoubin, and Farrokhi-Asl (2021), Raeisi and Jafarzadeh Ghouschi (2022), Saeidi, Aghamohamadi-Bosjin, and Rabbani (2021), Valizadeh (2020), Xin et al. (2021)
Hybrid algorithms	19	
Metaheuristics + metaheuristics	5	Akbarpour et al. (2021), Lu, Pu, and Han (2020), Tirkolaee et al. (2023), Zhao et al. (2023), Zhou, Zhang, and Wu (2022)
Metaheuristics + heuristics	9	Erdem (2022a), Gao et al. (2023), Hurkmans et al. (2021), Kaya (2023), Liu and Liao (2021), Ma et al. (2021), Rahmanifar et al. (2023), Sari, Masrurah, and Asih (2021), Wu, Tao, and Yang (2020)
Exact method + metaheuristics	2	Aliahmadi, Barzinpour, and Pishvaei (2021), Mohammadi et al. (2023)
Exact method + simulation	1	Yu et al. (2020)
Exact method + heuristics	1	Wang et al. (2023)
Uncertainly	1	Xin et al. (2023)
Total	52	

Table 7. Algorithms applied in single-objective function studies.

Solution Approach	Accounts	References
Exact methods	13	
Commercial solver	7	Hannan et al. (2020), Kızıltas, Alakas, and Eren (2020), Książek, Gdowska, and Korcyl (2021), Lavigne, Beliën, and Dewil (2021), Molfese Greco et al. (2023), Rambandara et al. (2022), Zhang et al. (2022)
Exact algorithm	6	Huang et al. (2021), Linfati, Gatica, and Escobar (2021), Mahéo, Rossit, and Kilby (2022), Oliskevych and Danchuk (2023), Wang, Yi, and Liu (2022), Zhang et al. (2023)
Approximate algorithms	25	
Heuristics	4	Jin et al. (2021), Kapadia and Mehta (2023), Nurprihatin and Lestari (2020), Van Engeland and Beliën (2021)
Metaheuristics	21	Aliahmadi, Barzinpour, and Pishvaei (2020), Araee, Manavizadeh, and Aghamohammadi Bosjin (2020), Ben-Romdhane et al. (2023), Bouleft and Elhilali Alaoui (2023), Cheng et al. (2022), Dereci and Karabekmez (2022), Gao et al. (2021), Gläser (2022), Lan et al. (2022), Lavigne et al. (2023), Li et al. (2021), Moazzeni, Tavana, and Darmian (2022), Ouertani et al. (2023), Quintana et al. (2020), Rossit, Toncovich, and Fermani (2021), Shen et al. (2023), Silva et al. (2023), Tran et al. (2024), Wang et al. (2022), Yu et al. (2024), Zhang, Mu, and Wang (2020)
Hybrid algorithms	40	
Metaheuristics + metaheuristics	13	Cao, Liao, and Huang (2021), Chen and Liao (2022), Ghobadi et al. (2022), Herrera-Cobo, Escobar, and Álvarez-Martínez (2023), Hu et al. (2024), Masmoudi, Coelho, and Demir (2022), Mohammadi et al. (2023), Qiao et al. (2020), Roy et al. (2022), Suksee and Sindhuchao (2021), Szwarc, Nowakowski, and Boryczka (2021), Wu et al. (2020), Yu et al. (2022)
Metaheuristics + heuristics	17	De Moraes et al. (2023), Erdem (2022b), Fan (2023), Ghiani et al. (2021), Janela, Mourão, and Pinto (2022), Jorge et al. (2022), Kim et al. (2023), Luo, Zhao, and Zhang (2024), Niranjani and Umamaheswari (2022), Olmez et al. (2022), Shang et al. (2022), Tirkolaee et al. (2020), Wöhlk and Laporte (2022), Yang, Tao, and Zhong (2022), Yu, Zhou, and Liu (2020), Zhang et al. (2022), Zheng, Sun, and Liu (2021)
Metaheuristics + simulation	2	Gruher et al. (2020), Yazdani et al. (2021)
Exact method + metaheuristics	2	Arias-Osorio, Ríos-Mercado, and Tamayo-Morantes (2020), Pourhejazy et al. (2021)
Exact method + heuristics	2	Hong, Yan, and Ge (2023), Wan et al. (2023)
Heuristics + machine learning	1	Shang, Ma, and Liu (2023)
Heuristics + heuristics	2	Shi et al. (2020), Wei, Liang, and Tang (2022)
Heuristics + simulation	1	Daoud, Kammoun, and Hachicha (2020)
Total	78	

employed in only one bi/multi-objective and six single-objective studies. For instance, Engeland and Beliën (Van Engeland and Beliën 2021) proposed two distinct heuristics to minimize vehicle depreciation and routing costs. The heuristics included the intelligent heuristic search algorithm (Jin et al. 2021), the near-neighbor

algorithm (Nurprihatin and Lestari 2020), the weighted multiple heuristics-based Optimum A* algorithm (Kapadia and Mehta 2023), and the decomposition-based heuristic approach (Taslimi, Batta, and Kwon 2020). Significant efforts have been focused on developing metaheuristics. Popular metaheuristics included the

adaptive large neighborhood search algorithm (Aydemir-Karadag 2022; Gläser 2022), particle swarm optimization (Gao et al. 2021; Li et al. 2021; Shen et al. 2023), genetic algorithm (Aliahmadi, Barzinpour, and Pishvae 2020; Ben-Romdhane et al. 2023; Bouleft and Elhilali Alaoui 2023; Cheng et al. 2022; Elshaboury and Marzouk 2021; Ouertani et al. 2023; Wang et al. 2022; Xin et al. 2021), simulated annealing algorithm (Quintana et al. 2020; Rossit, Toncovich, and Fermani 2021; Yu et al. 2024; Zhang, Mu, and Wang 2020), and memetic algorithm (Lan et al. 2022; Lavigne et al. 2023). Other applied algorithms included the non-dominated sorting genetic algorithm III (Saeidi, Aghamohammadi-Bosjin, and Rabbani 2021), modified ant colony optimization algorithm (Cao et al. 2021; Li et al. 2023), adaptive memory social engineering optimizer (Mojtahedi et al. 2021), parallel water flow algorithm (Tran et al. 2024), brainstorming algorithm (Lu et al. 2023), multi-objective self-adaptive evolutionary algorithm (Ghannadpour, Zandieh, and Esmaeili 2021), large neighborhood search (Blazquez and Paredes-Belmar 2020), and the multi-objective water-flow-like algorithm (Nikzamir and Baradaran 2020). Additionally, other papers contrasted multiple metaheuristics within the same data set (Araee, Manavizadeh, and Aghamohammadi Bosjin 2020; Li et al. 2023; Moazzeni, Tavana, and Darmian 2022; Rabbani, Nikoubin, and Farrokhi-Asl 2021; Raeisi and Jafarzadeh Ghouschi 2022; Silva et al. 2023; Valizadeh 2020). In addition, comparisons were made between heuristics and metaheuristics (Dereci and Karabekmez 2022), and between exact methods and metaheuristics (Aliahmadi, Barzinpour, and Pishvae 2021).

Hybrid algorithms. Tables 6 and 7 show that hybrid algorithms were used in 19 bi/multi-objective and 40 single-objective studies. In bi/multi-objective studies, nine studies combined metaheuristics with heuristics, while five combined at least two metaheuristics. In single-objective studies, these numbers were 17 and 13, respectively. These two combinations are the most popular among all categories of hybrid algorithms. Other hybrid algorithms received less attention, such as combinations of simulation and metaheuristics (Gruler et al. 2020; Yazdani et al. 2021), exact methods and metaheuristics (Aliahmadi, Barzinpour, and Pishvae 2021; Arias-Osorio, Ríos-Mercado, and Tamayo-Morantes 2020; Mohammadi et al. 2023; Pourhejazy et al. 2021), dual heuristics (Shi et al. 2020; Wei, Liang, and Tang 2022), heuristics and simulation (Daoud, Kammoun, and Hachicha 2020), exact methods and simulation (Yu et al. 2020), exact methods and heuristics (Hong, Yan, and Ge 2023;

Wan et al. 2023; Wang et al. 2023), and heuristics with machine learning (Shang, Ma, and Liu 2023). One study was excluded from hybrid algorithm categorizations due to its complex approach (Xin et al. 2023).

Approaches to uncertainty parameters resolution

Addressing the challenges posed by uncertainty parameters in decision-making requires methods tailored to specific types of uncertainty. Stochastic and fuzzy parameters, each characterized by unique data qualities, necessitate distinct approaches. The following discussion explores approaches for effectively managing these parameters.

Numerous studies have proposed various methods to address the challenges posed by stochastic parameters, reflecting a growing interest in managing data variability and randomness effectively. For instance, chance-constrained programming (Wu et al. 2020; Yang, Tao, and Zhong 2022), the Bertsimas robust optimization method (Zhang et al. 2022), and Monte Carlo simulation (Daoud, Kammoun, and Hachicha 2020) were primarily applied to address stochastic waste generation. Additionally, Monte Carlo simulation (Gruler et al. 2020), normal distribution (Nikzamir and Baradaran 2020), and stochastic simulation (Yazdani et al. 2021) were proposed to address stochastic travel times. To address stochastic budgeting in a green hazardous waste LRP problem, a stochastic budget constraint was applied (Delfani et al. 2020). In addition, chance-constrained programming (Hassanpour et al. 2023) and a sample average approximation-based goal programming approach (Yu et al. 2020) were used to handle multiple stochastic parameters.

Similarly, various approaches have been developed to tackle issues associated with fuzzy parameters, as researchers continue to explore techniques for handling imprecision and ambiguity in data (Goli, Ala, and Hajiaghahi-Keshteli 2023). For instance, fuzzy credibility theory (Tirkolaee et al. 2020), credibility-based chance-constrained programming (Aliahmadi, Barzinpour, and Pishvae 2020), and fuzzy chance-constrained programming (Kordi et al. 2023; Tirkolaee, Abbasian, and Weber 2021) were applied to address the fuzziness in waste generation quantities. Moreover, possibilistic chance-constrained programming (Delfani et al. 2021; Raeisi and Jafarzadeh Ghouschi 2022) and triangular fuzzy numbers (Ghobadi et al. 2022; Zhao et al. 2023) were used to handle multiple fuzzy parameters. These approaches offer flexible decision support without precise data, addressing fuzzy demand and enhancing the model's robustness and adaptability to real-world conditions.

GIS

GIS has received extensive attention as a valuable tool for optimizing WCVRP. For instance, Zhao, Wu, and Ke (2021) retrieved population data from a GIS database, which is critical for understanding waste generation patterns. Similarly, Hina et al. (2020) and Janela, Mourão, and Pinto (2022) used GIS to manage data acquisition, ensuring accurate integration of demographic and geographic information into WCVRP models. In addition to gathering demographic information, GIS has also been extensively used for spatial analysis and distance calculation. Książek, Gdowska, and Korcyl (2021) and Lavigne et al. (Lavigne et al. 2023) used GIS to calculate distances between nodes within a specific district. Similarly, Rambandara et al. (2022) used online GIS tools to estimate the number of residences along each arc, which helps calculate the required waste collection volume. Furthermore, ArcGIS has played an instrumental role in optimizing WCVRP operations. For instance, Sallem et al. (2021) enhanced waste collection efficiency by using ArcGIS to optimize vehicle routes and reallocate collection bins. Similarly, Pourhejazy et al. (2021) employed ArcGIS to calculate the population between connected nodes to assess exposure risk. Additionally, QGIS has also been employed in WCVRP (Gruler et al. 2020; Mahéo, Rossit, and Kilby 2022; Molfese Greco et al. 2023). These papers illustrate the adaptability and accessibility of GIS technology in addressing both logistical and environmental concerns in WCVRP.

Advanced technology in WCVRP

The rapid advancement of information technologies has generated numerous opportunities for developing waste management models, particularly through integrating cutting-edge technologies such as the Internet of Things (IoT) and Information and Communication Technology (ICT) (Saeidi, Aghamohamadi-Bosjin, and Rabbani 2021). These technologies have been recognized as highly impactful in WCVRP (Alhilali and Montazerolghaem 2023). For example, Mohammadi et al. (2023) incorporated IoT-enabled smart bins equipped with various sensors to ensure that the most up-to-date data is used in route planning. These bins were designed to monitor waste fill levels and send this data to waste management systems or relevant departments before route planning. Roy et al. (2022) introduced an IoT-based system utilizing an Arduino Uno microcontroller with ultrasonic sensors. This system was designed to monitor waste levels in bins at various places. Bouleft and Alaoui (2023) introduced smart bins with real-time monitoring that trigger wireless alerts at specific fill levels, optimizing collection schedules through timely interventions.

Additionally, Saeidi, Aghamohamadi-Bosjin, and Rabbani (2021) proposed a solution for waste transportation and bin management based on ICT and IoT infrastructure, demonstrating the potential of these technologies to transform waste logistics by delivering real-time data and enhancing operational efficiency. Beyond IoT and ICT, big data has also been integrated into WCVRP models. Xin et al. (2021) used big data to gather real-time urban traffic conditions, which were subsequently used to dynamically optimize WCVRP models. This application of big data represents a significant advancement in making WCVRP more responsive to real-time conditions, improving overall efficiency and reducing costs.

Dataset and case study

To determine the optimal route for WCVRP, numerous papers have employed various types of tests to validate their solution methods. These tests often include theoretical tests using benchmark datasets and case studies based on real-world applications. However, the effectiveness and applicability of these tests can vary significantly depending on environmental factors, such as geographical regions, climate, and traffic conditions. Consequently, the tests in these studies often reflect the specific environmental characteristics of the locations where they were conducted. Based on Beliën, De Boeck, and Van Ackere (2014), Table 8 summarizes the test types used in the reviewed papers, categorizing them into theoretical test, case study, and hybrid test.

Table 8 further breaks down theoretical tests into two subcategories: randomly generated datasets, with 18 instances, and benchmark datasets, with 20 instances, accounting for a total of 38 theoretical tests. Randomly generated datasets are often used to simulate various scenarios that a WCVRP solution might encounter. By generating parameters based on predefined distributions, these tests allow researchers to assess proposed algorithms under varying conditions. Benchmark datasets offer a standardized set of data, enabling comparison of different algorithms under consistent conditions. The most popular benchmark datasets include the Solomon dataset (Cao, Liao, and Huang 2021; Huang et al. 2021; Wan et al. 2023; Wang et al. 2023), the Gehring and Homberger dataset (Niranjani and Umamaheswari 2022), and the Cordeau dataset (Chen and Liao 2022; Liu and Liao 2021). While these theoretical tests provide a solid foundation for validating algorithms, they may be limited by certain environmental factors when applied to real-world scenarios.

Case studies, on the other hand, are categorized based on the countries where the studies were

Table 8. Summary of test types in reviewed papers.

Type of test	Subcategory	References	Accounts
Theoretical test	Randomly generated dataset	Araee, Manavizadeh, and Aghamohammadi Bosjin (2020), Delfani et al. (2020), Gao et al. (2021), Ghiani et al. (2021), Ghobadi et al. (2022), Hannan et al. (2020), Książek, Gdowska, and Korcyl (2021), Li et al. (2021), Ma and Li (2021), Mojtahedi et al. (2021), Rabbani, Nikoubin, and Farrokhi-Asl (2021), Raeisi and Jafarzadeh Ghouschi (2022), Rahmaniifar et al. (2023), Szwarc, Nowakowski, and Boryczka (2021), Tirkolaee and Aydın (2021), Wang et al. (2022), Yu, Zhou, and Liu (2020), Zheng, Sun, and Liu (2021)	38
	Benchmark dataset	Aydemir-Karadag (2022), Cao, Liao, and Huang (2021), Chen and Liao (2022), Gläser (2022), Herrera-Cobo, Escobar, and Álvarez-Martínez (2023), Huang et al. (2021), Kim et al. (2023), Li et al. (2023), Liu and Liao (2021), Luo, Zhao, and Zhang (2024), Masmoudi, Coelho, and Demir (2022), Niranjani and Umamaheswari (2022), Qiao et al. (2020), Shi et al. (2020), Tirkolaee et al. (2023), Torkayesh, Vandchali, and Tirkolaee (2021), Wan et al. (2023), Wang et al. (2023), Wu et al. (2020), Yang, Tao, and Zhong (2022)	18
Case study	China	Cao et al. (2021, 2022), Fan (2023), Gao et al. (2023), Hu et al. (2024), Lan et al. (2022), Li et al. (2023), Pourhejazy et al. (2021), Wang, Yi, and Liu (2022), Wei, Liang, and Tang (2022), Xin et al. (2021, 2023), Zhao et al. (2023)	52
	Iran	Aliahmadi, Barzinpour, and Pishvae (2020), Govindan et al. (2021), Kordi et al. (2023), Mohammadi et al. (2023), Rabbani, Mokarrari, and N (2021), Tirkolaee, Abbasian, and Weber (2021), Valizadeh (2020)	13
	Turkey	Dereci and Karabekmez (2022), Erdem (2022a, 2022b), Eren and Tuzkaya (2021), Kaya (2023), Kızıltaş, Alakaş, and Eren (2020)	7
	Portugal	De Morais et al. (2023), Janela, Mourão, and Pinto (2022), Silva et al. (2023)	6
	Argentina	Mahéo, Rossit, and Kilby (2022), Molfese Greco et al. (2023)	3
	Chile	Blazquez and Paredes-Belmar (2020), Linfati, Gatica, and Escobar (2021)	2
	Tunisia	Daoud, Kammoun, and Hachicha (2020), Sallem et al. (2021)	2
	Indonesia	Sari, Masrurroh, and Asih (2021), Yu et al. (2022)	2
	Netherlands	Van Engeland and Beliën (2021)	2
	Denmark	Wøhlk and Laporte (2022)	1
	Columbia	Arias-Osorio, Rios-Mercado, and Tamayo-Morantes (2020)	1
	Belgium	Lavigne, Beliën, and Dewil (2021)	1
	Sri Lanka	Rambandara et al. (2022)	1
	Egypt	Elshaboury and Marzouk (2021)	1
	Thailand	Suksee and Sindhuchao (2021)	1
	Pakistan	Hina et al. (2020)	1
	South Korea	Roy et al. (2022)	1
	Australia	Yazdani et al. (2021)	1
	Mexico	Quintana et al. (2020)	1
	Ukraine	Olishevych and Danchuk (2023)	1
	India	Kapadia and Mehta (2023)	1
Hybrid test	Uncertainty	Akbarpour et al. (2021), Hashemi-Amiri, Ji, and Tian (2023)	2
	—	Aliahmadi, Barzinpour, and Pishvae (2021), Ben-Romdhane et al. (2023), Bouleft and Elhilali Alaoui (2023), Cheng et al. (2022), Delfani et al. (2021), Ghannadpour, Zandieh, and Esmaeili (2021), Gruler et al. (2020), Hassanpour et al. (2023), Hong, Yan, and Ge (2023), Hurkmans et al. (2021), Jin et al. (2021), Jorge et al. (2022), Lavigne et al. (2023), Lu et al. (2023), Lu, Pu, and Han (2020), Ma et al. (2021), Moazzeni, Tavana, and Darmian (2022), Mohammadi et al. (2023), Nikzami and Baradaran (2020), Nikzami, Baradaran, and Panahi (2020), Nurprihatin and Lestari (2020), Olmez et al. (2022), Ouertani et al. (2023), Rossit, Toncovich, and Fermani (2021), Saeidi, Aghamohammadi-Bosjin, and Rabbani (2021), Shang et al. (2022), Shang, Ma, and Liu (2023), Shen et al. (2023), Taslimi, Batta, and Kwon (2020), Tirkolaee et al. (2020), Tran et al. (2024), Wu, Tao, and Yang (2020), Yu et al. (2020, 2024), Zhang et al. (2022, 2022, 2023), Zhang, Mu, and Wang (2020), Zhao, Wu, and Ke (2021), Zhou, Zhang, and Wu (2022)	40
Total			130

conducted. China leads with 13 case studies, followed by Iran with seven and Turkey with six, making them the most frequently examined regions. Portugal is represented with three case studies, while Argentina, Chile, Tunisia, and Indonesia each have two case studies. Other countries are represented by one case study each. Additionally, two studies mentioned a country without specifying which one. These studies emphasize the diverse challenges faced in different geographical contexts, underscoring the need for adaptable, region-specific WCVRP solutions.

Hybrid tests combine elements from both theoretical tests and case studies, offering a comprehensive assessment of WCVRP solutions. These tests often involve complex scenarios where theoretical datasets are modified or integrated with real-world data. Hybrid tests address variability in factors such as waste generation and traffic conditions that can impact route planning. These tests are increasingly recognized as crucial for developing robust and resilient WCVRP solutions that can adapt to changing conditions.

Discussion and results

This section critically evaluated the results from the literature review, emphasizing the novelty and significance of the findings. These findings form a foundation for recommendations on future research directions in this field.

Initially, the analysis revealed that MSW has been the predominant focus in the literature. However, this review identifies a significant research gap in the treatment of other waste types, such as CDW, WEEE, agricultural waste, and disaster waste. While existing literature has largely focused on MSW due to its widespread and consistent generation, the complexity and environmental impacts of other waste types have been underexplored. Additionally, a key finding is the significant increase in the volume of MW. This surge in waste necessitates urgent management strategies, ideally within 48 hours of generation, to mitigate health risks (Nikzamir and Baradaran 2020). Moreover, the collection and transportation methods for waste vary depending on the specific type of waste and geographical area. Notably, there are distinct differences in these methods between urban and rural settings, as well as between residential and commercial regions (Cubillos and Wöhlk 2021). This study highlights the urgent need for optimized strategies tailored to these specific waste streams, particularly considering the increasing necessity to address the unique challenges posed by less-studied waste types, offering novel insights into WCVRP practices that are currently underrepresented in the literature.

This review identifies several underexplored model characteristics that reflect the complexity of WCVRP, highlighting the need for sophisticated modeling approaches. Common characteristics such as VRP, LRP, scheduling, uncertainty parameters, multi-depot, multi-echelon, multi-trip, multi-periodic, time windows, and capacity, have been well-studied. Since the introduction of these common characteristics, other characteristics have received less attention. However, the exploration of other characteristics such as dynamic (Bouleft and Elhilali Alaoui 2023), split demand (Zhang et al. 2023), pickup and delivery (Quintana et al. 2020), workload concern (De Moraes et al. 2023), and waste filling levels (Kim et al. 2023) remains limited. Furthermore, there is still limited exploration of EVs (Moazzeni, Tavana, and Darmian 2022), PHEVs (Masmoudi, Coelho, and Demir 2022), as well as the practical benefits of multi-compartment (Shang, Ma, and Liu 2023), heterogeneous (Gao et al. 2023), and rental vehicles (Govindan et al. 2021), despite their potential to improve operational efficiency and

environmental sustainability. The integration of these less-explored characteristics and vehicle types into WCVRP represents a significant opportunity for innovation. By incorporating more diverse and realistic variables, future research can develop more robust models that better reflect the complexities of real-world waste management systems.

Cost and public health exposure risk minimization have taken precedence over other objectives in existing WCVRP models. While critical, this focus suggests an oversimplification of the problem spaces. Single-objective functions dominated WCVRP models, accounting for 60% of the studies and exceeding bi/multi-objective functions by 20%. This imbalance indicates a need for more holistic approaches that also consider other objectives, and a tendency in modeling toward simplification, potentially at the expense of capturing the complexity of real-world scenarios. Remarkably, only nine papers simultaneously considered economic, environmental, and social dimensions. Additionally, optimizing multiple conflicting objective functions concurrently without worsening any of them is a challenging task. Therefore, this study proposes a shift toward multi-objective optimization that balances economic, environmental, and social goals, a perspective that is not sufficiently addressed in current research (Rabbani, Nikoubin, and Farrokhi-Asl 2021). The novelty of this approach lies in its potential to achieve more sustainable outcomes. Existing literature often isolates these objectives, resulting in suboptimal solutions in complex, real-world scenarios. By integrating multiple objectives into a single framework, this study challenges the traditional focus and offers a more holistic approach to WCVRP, which is critical for addressing the multifaceted nature of waste management in diverse environments.

It was found that hybrid algorithms have become the preferred choice, combining the strengths of different solution approaches to tackle the complexities of WCVRP. This preference arises from the limitations of exact methods, which are often inadequate for large-scale, real-world applications within a reasonable computation time (Ghannadpour, Zandieh, and Esmaeili 2021). While these algorithms have incorporated methods to handle uncertainty parameters, such as stochastic and fuzzy variables, the integration of advanced technologies such as GIS, IoT, big data, and ICT into WCVRP models remains underexplored, especially regarding their full potential to enhance algorithm robustness and adaptability. These characteristics offer new ways to enhance model accuracy and efficiency by providing real-time data and enabling more responsive WCVRP solutions. This review suggests that the future of WCVRP lies in the continued

Table 9. WCVRP toward achieving sustainable development goals.

Domain	SDG	WCVRP objective function	Explanation of how the WCVRP objective function achieving SDGs
1-Environment protection	SDG 6: Clean water and sanitation.	A1, A4, C5	Reducing costs allocates more resources for water sanitation, shortening transport distances lowers pollution risk, and minimizing infection risk safeguards water sources.
	SDG 12: Responsible consumption and production.	A2, A6, A7, C1	Enhancing profitability supports sustainability, reducing vehicle number and overlap conserves resources, and balancing workload optimizes efficiency.
	SDG15: Life on land.	C1, B6	Lower visual pollution and carbon emissions preserves terrestrial ecosystems.
	SDG 7: Affordable and clean energy.	B2	Reducing fuel consumption supports clean energy initiatives.
	SDG 13: Climate action.	B1	Lower carbon emissions mitigate climate change impacts.
1 + 2	SDG 14: Life below water.	A4	Shortening transport distances minimizes marine pollution risks.
	SDG 11: Sustainable cities.	A3, A8, C2, C3	Shortening time frames enhances operational efficiency, creating jobs supports urban sustainability, and maximizing utilization rates improves waste collection efficiency.
			Lower infection risk enhances community health and well-being.
2-Public health protection	SDG 3: Well-being and good health.	C5	
	SDG 11: Sustainable cities.	A1, A4	Reducing costs and minimizing distances support sustainable urban development.
3-Poverty reduction	SDG 8: Decent work and economic development.	A2, C2	Enhancing profitability and creating jobs stimulate economic growth.
3 + 4	SDG 1: No poverty.	C3	Increasing employment opportunities alleviates poverty.
4-Resource value	SDG 12: Accountable production and responsible consumption	A1, A5	Reducing costs and trucks loads improves resource efficiency and supports sustainable consumption.

Notes. A1: minimizing cost; A2: maximizing profit; A3: minimizing time; A4: minimizing distance; A5: minimizing daily truck loads; A6: minimizing vehicle number; A7: minimizing overlap; A8: maximizing the average utilization rate of waste collection points; B1: minimizing carbon emission; B2: minimizing fuel consumption; C1: workload balance; C2: maximizing job creation; C3: maximizing the number of hired labor; C4: maximizing safety scores; C5: minimizing infection risk of public health; C6: minimizing visual pollution.

development of hybrid algorithms that can leverage uncertainty management and advanced technologies to solve increasingly complex WCVRP challenges. The potential applications are vast, ranging from real-time route optimization to predictive maintenance of waste collection vehicles, potentially leading to significant cost savings and environmental benefits.

Integrating diverse datasets and case studies into WCVRP research is crucial for validating the practical applicability of theoretical models. Although theoretical tests provide a controlled environment for testing algorithms, they often fail to capture the full complexity of real-world WCVRP scenarios. To address these limitations, this study highlights the importance of using case studies to understand the regional and contextual factors that influence WCVRP, such as local regulations, waste generation rates, and geographical challenges. Additionally, the approach is innovative in its use of a hybrid testing method, combining theoretical datasets with real-world data to provide a more comprehensive evaluation of WCVRP models. This hybrid method addresses the variability and unpredictability inherent in WCVRP, making the models more robust and adaptable to different contexts. By advocating for a greater emphasis on hybrid testing, this study offers a new direction for future research that could lead to more effective and scalable WCVRP solutions.

The 2030 SDGs, proposed in 2015, offer a unified vision for global prosperity and peace for both the planet and its inhabitants (Vinuesa et al. 2020). Optimizing WCVRP has significant implications for

10 out of 17 SDGs. Particularly in areas such as clean water, public health, terrestrial and marine ecosystems, clean energy, sustainable cities, economic development, and green jobs (Hannan et al. 2020). Based on the work of Hannan et al. (Hannan et al. 2020), Table 9 explicitly links WCVRP optimization with the SDGs, demonstrating how efficient waste collection and transportation can contribute to global sustainability efforts. This approach stands out for its comprehensive perspective, encompassing the economic, environmental, and social impacts of WCVRP practices. For instance, optimized WCVRP enhances SDG 3 by lowering infection risks. Similarly, it supports SDG 8 by creating green jobs and improving economic efficiency. Furthermore, WCVRP optimization aligns with SDG 11 by enhancing urban sustainability. The potential applications of these findings extend beyond WCVRP to broader sustainability initiatives, making this study a significant contribution to the field.

Conclusion

This study provides a comprehensive analysis of the current state of WCVRP, identifying key trends and critical gaps that present opportunities for future advancements. The paper further highlights that WCVRP is a primary and urgent concern in urban environments. It emphasizes the need for advanced strategies in WCVRP, with a particular focus on optimizing waste collection and transportation procedures.

The waste category analysis underscores the predominant focus on MSW in the literature, while revealing a pressing need to address underexplored waste types such as CDW, WEEE, and agricultural waste. Bridging these gaps is crucial for developing comprehensive and sustainable WCVRP strategies. This review emphasizes the importance of integrating underexplored model characteristics and vehicle types into WCVRP models. Such integration can enhance the robustness and adaptability of future models, ensuring they more accurately reflect the operational realities of WCVRP. A key contribution of this study is its call for a shift toward multi-objective optimization in WCVRP, expanding the focus beyond economic considerations to incorporate environmental and social dimensions. This broader approach not only reflects the complexity of real-world scenarios but also aligns with global sustainability goals, offering a holistic framework for future research and practical applications. Additionally, the growing use of hybrid algorithms in WCVRP, particularly when combined with advanced technologies such as GIS, IoT, ICT, smart bins, and big data, represents a promising direction for future research. These technologies, along with uncertainty management, hold significant potential for addressing the evolving challenges of WCVRP. The study also emphasizes the critical role of datasets and case studies in validating WCVRP models. Researchers can use hybrid tests to gain a nuanced understanding of WCVRP solutions, providing a comprehensive evaluation of their performance under varying conditions. This approach is crucial for developing resilient WCVRP solutions that can adapt to changing environments and challenges. From a managerial perspective, the findings provide actionable insights for enhancing the efficiency and sustainability of WCVRP practices. The adoption of advanced technologies and multi-objective frameworks supports informed decision-making, leading to improvements in both operational efficiency and alignment with the SDGs.

In conclusion, this study contributes to the academic understanding of WCVRP while offering practical recommendations for enhancing waste collection and transportation systems. As the field continues to evolve, these insights will be critical in guiding future research and the development of more effective, adaptable, and sustainable waste collection and transportation systems.

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Data availability statement

Data sharing is not applicable to this paper as no new dataset were generated or analyzed in this study.

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