

Vehicle Routing Problem (VRP) Approaches for Waste Collection Optimization: A Systematic Literature Review

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Abstrak

An effective route is necessary because waste transport is an important part of the urban waste management system. The most popular technique is the Vehicle Routing Problem (VRP) to maximize fleet movement while reducing risk, time, cost, and energy. To identify developments in VRP models in the context of waste transportation, this study used a Systematic Literature Review (SLR), conducted in accordance with PRISMA guidelines, to review 96 articles. The SLR results indicate that VRP models have evolved from basic models such as CVRP and VRPTW to more constraint-rich models such as MTVRP, ARP, risk-aware VRP, EVRP, and multi-objective VRP. Hybrid and metaheuristic algorithms such as ALNS, GA, ACO, and SA have become the most popular in solving this problem due to their ability to handle large problem sizes and high operational complexity. Route planning can now utilize real-time data thanks to the integration of IoT, WSN, and GIS technologies. Overall, these results indicate that VRP research in waste transport is moving towards smarter, more adaptive, and sustainable approaches. These results also enable the development of more contextual models and algorithms in the future.

Keywords: GIS, IoT, Metaheuristics, Systematic Literature Review, Vehicle Routing Problem

INTRODUCTION

Waste transport is one of the most important components of urban waste management systems, and operational costs can account for more than 50% of the waste management budget. Waste transport fleets consume a lot of energy and produce high emissions, especially in large cities with high frequency of collection (Peña, Dorronsoro and Ruiz, 2024). Population growth, urban development, changing consumption patterns, infrastructure limitations, and ever-changing traffic conditions compound the complexity of these operations. One of the most common approaches to optimizing the waste transport process is the Vehicle Routing Problem (VRP). In a single day, the VRP model calculates vehicle capacity, travel time, distance between points, and frequency. This creates efficient and acceptable waste collection routes in densely populated cities (Silva *et al.*, 2023).

The Arc Routing Problem (ARP) method optimizes waste transport by focusing on road segments while balancing vehicle routing in more complex environments (Janela, Mourão and Santiago Pinto, 2022). A study indicates

that the Multi-Trip Vehicle Routing Problem (MTVRP) is more realistic and efficient for describing waste truck operations than the local DLH manual route. The data indicates that the need for ritasi is increasingly important in Indonesia (Marpaung *et al.*, 2025).

In addition, VRP is used to transport medical and infectious waste. One problem with vehicle routes in the healthcare facility waste collection system is that healthcare facility waste transport routes must be optimized by considering exposure risks and special service times that do not exist in regular domestic waste routes (Anderson and Sudarto, 2025). Another study used grouping, Nearest Neighbor, and Simulated Annealing (SA) methods to create safe and efficient routes for staff to address increased volumes of infectious waste (Niranjani and Umamaheswari, 2022). To reduce the possibility of contamination, another study emphasized the use of safe distance protocols when designing VRPTW routes (Eren and Rıfat Tuzkaya, 2021). Routine VRP planning is necessary for public service organizations in Indonesia to transport medical waste

(Anityasari, Rinardi and Warmadewanthi, 2025).

The ability to optimize VRP-based systems has been enhanced thanks to advances in digital technology, including the integration of the Internet of Things (IoT), sensors, and GIS. Because IoT-based smart waste management systems can detect container fullness levels and send data in real time, trucks do not need to visit waste collection points that are not yet full (Alsayaydeh *et al.*, 2025). Wireless network sensor information can improve route efficiency and reduce mileage by continuously dispatching trucks to locations that need service (Ramirez, Santiago, and Kamiyama, no date). Furthermore, research on the city of Turin shows that the use of GIS can help improve basic routes by eliminating U-turns, sub-tours, and other inefficiencies (Herrera-Granda *et al.*, 2024).

Machine learning (ML) methods are also beginning to support VRP, although still to a limited extent. Other studies demonstrate that we can predict service duration at TPS using factors like area type, population density, and road accessibility. This suggests that we can integrate more advanced ML models like XGBoost with operational VRP (Giel and Dabrowska, 2021).

To handle constraint-rich VRPs, this algorithm uses various metaheuristics. The combination of GRASP and ALNS has shown stable results and is better than conventional heuristic solutions (Suksee and Sindhuchao, 2021). Other research combines swarm intelligence methods with local search methods to improve performance in complex routes (Sahib, Mohd-Mokhtar and Mohd-Kassim, 2025). According to other research, memetic algorithms play an important role in adaptively and efficiently handling thousands of route points (Lan *et al.*, 2022). Conversely, facility location and route routing problems can be solved using an integrated framework relevant to administrative areas that require route sectorization (Yu *et al.*, 2022).

Sustainability is becoming increasingly important in VRP research. A multi-objective framework is used for route design. This framework combines environmental, economic, and social objectives (Niranjani and Umamaheswari, 2022). Additional studies indicate that evolutionary algorithms can be used to solve facility location and route decision problems on a biomass supply chain scale. This

model applies to agricultural and commercial waste (Li *et al.*, 2024).

The electrification of fleets also affects modern VRP models. Because VRPs require much more complex models to calculate energy consumption, such as route elevation, speed patterns, and regenerative braking capabilities, the development of VRP models must be much more complex than for conventional vehicles (Peña, Dorronsoro and Ruiz, 2024).

Although a large number of studies show significant progress in this field, there is still room for improvement. First, VRP does not integrate many advanced machine learning (ML) techniques such as XGBoost. Second, there is not much research that adapts VRP and metaheuristics to different road conditions, limited fleets, or high rotation constraints. Finally, there is little literature on the modification of metaheuristic operators, such as ALNS, based on ritasi. This is particularly relevant to the situation in Indonesia. Fourth, there is little research combining ML predictions, IoT, GIS, and VRP optimization. To describe the progress of this research, identify trends and key methods, and highlight new research opportunities that could help produce more efficient, adaptive, and sustainable waste transport solutions, this study presents a "Vehicle Routing Problem (VRP) Approaches for Waste Collection Optimization: A Systematic Literature Review."

LITERATURE REVIEW

2.1 Evolution of the VRP Model for Waste Transportation

VRP in waste transport has evolved from basic route models to rich VRP models that take into account capacity, rotation, service time, risk, energy, and environmental conditions. With the objective function of reducing travel distance, capacity-based VRP (Capacitated VRP) is considered the basis for ideal waste transport routes (Silva *et al.*, 2023):

$$\min \sum_{c \in C} \sum_{i \in V} \sum_{m \in M} x_{im}^c L_{im} \quad (1)$$

The study indicates that CVRP can optimize waste collection routes by informing service distribution and vehicle capacity.

Because it focuses on road segments that must be served rather than demand points, the Arc Routing Problem (ARP) approach offers a

better solution for more complex road network contexts. This mechanism works to balance the rotation between vehicles that is not available in conventional VRP (Janela, Mourão and Santiago Pinto, 2022).

In addition, multi-trip models are on the rise. An MTRP model allows cars to make more than one trip in a single service period, according to additional research (Marpaung *et al.*, 2025). The objective function is:

$$\min Z = \sum_{k=1}^M \sum_{t=1}^T \sum_{i=0}^N \sum_{j=0}^N c_{ij} x_{ijkt} \quad (2)$$

With this development, VRP has become more suited to more realistic operational conditions, such as densely populated areas or those with many waste treatment facilities.

2.2 VRP Model for Medical Waste

Due to safety regulations and the risk of infection exposure, the transport of medical waste adds a new dimension to VRP. Using a formula known as transportation risk (Zhang *et al.*, 2024):

$$TR_{ij}^k = P_{ij} p_{ij} \rho_{ij} \pi w_{ij}^2 d_{ij}^2 u_i^k x_{ij}^k \quad (3)$$

According to formula 3, VRP relates to public safety in addition to optimizing distance.

Through risk functions and safe distance constraints, health elements can be incorporated into VRP, according to pandemic studies. By applying relevant routing in hazardous waste management, this method expands the scope of classical VRP (Eren and Rifat Tuzkaya, 2021; Niranjani and Umamaheswari, 2022).

2.3 Metaheuristics for VRP Optimisation

Since VRP is an NP-hard problem, modern research typically uses metaheuristics. Adaptive methods are widely discussed in the literature. These include hybrid methods, Genetic Algorithms (GA), Simulated Annealing (SA), Adaptive Large Neighbourhood Search (ALNS), and other genetic algorithms.

According to Marpaung *et al.* (2025), the objective of the SA completion penalty is as follows (Marpaung *et al.*, 2025):

$$Cost = TotDistance + \sum_{r \in R} Penalty_r \quad (4)$$

The following are the requirements for SA acceptance:

$$P(accept) = e^{-\Delta/T} \quad (5)$$

This value is then used for various ALNS variants that rely on probabilistic acceptance.

An alternative method used for Ant Colony Optimization (ACO) is the probability rule (Sahib, Mohd-Mokhtar and Mohd-Kassim, 2025):

$$P_{ij} = \frac{\tau_{ij}^\alpha \eta_{ij}^\beta}{\sum_{k \in J} \tau_{ik}^\alpha \eta_{ik}^\beta} \quad (6)$$

Metaheuristics can handle various operational problems specific to waste transport, such as dynamic capacity, demand variation, route constraints, and irritation.

2.4 GIS and IoT Technology as Support for VRP

Combining Internet of Things (IoT), Wireless Sensor Network (WSN), and GIS technologies has improved current VRP inputs. Container fullness levels can be measured with ultrasonic sensors (Alsayaydeh *et al.*, 2025). This allows routes to be dynamically optimized to adapt to field conditions. WSN is also used to determine location status and change routes based on fullness thresholds (Ramirez, Santiago and Kamiyama, no date). Additionally, road network analysis is used to determine more effective and conflict-free routes (Herrera-Granda *et al.*, 2024). Although this digital technology is not available in mathematical equation form, it functions as a data-driven routing enhancer, improving VRP results in real time.

2.5 Prediction and Machine Learning as Complements to VRP

Regression models can be used to predict service times (Giel and Dabrowska, 2021):

$$Y = b_0 + b_1 X_1 + b_2 X_2 + \dots + b_p X_p \quad (7)$$

This study shows significant time variations between locations, indicating that VRP parameters should not be static. This finding is important because these predictions are a crucial part of time-based VRP

formulation. ML complements VRP to improve the accuracy of input parameters rather than replacing VRP itself.

2.6 Energy and Sustainability Based VRP

The need for environmentally friendly cars has prompted studies that incorporate energy consumption into VRP. Distance and elevation changes form the EV energy model. The main focus of the model shifts VRP from reducing distance to reducing emissions and energy (Peña, Dorransoro and Ruiz, 2024). This is despite the complexity of the mathematics involved. As the study shows, VRP has shifted its focus from cost to environmental optimization, which is increasingly important in cities with sustainability plans.

Previous research has indicated that VRP is the most common method for optimizing waste collection routes. This study also provides a strong theoretical basis for the comprehensive review in this journal.

METHOD

3.1 Literature Search Design and Strategy

In this study, the Systematic Literature Review (SLR) method was used to gain a deeper understanding of the evolution of the Vehicle Routing Problem (VRP) method for waste transport optimization. The use of SLR is recommended by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to produce a structured, transparent, and replicable scientific synthesis. Using this technique, each relevant publication was thoroughly examined, starting from the identification, screening, and eligibility assessment processes and then to the inclusion stage. The article selection process in this study is described through the PRISMA figure, which can be seen in Figure 1, and it provides a strong methodological basis for the credibility of the review process.

The literature search was conducted using the Scopus database on 20 October 2025, with the query TITLE-ABS-KEY ('waste' AND 'collection' AND "routing" AND 'problem'). After the initial search yielded 790 articles, only 367 articles from 2021–2025 remained. This initial stage was conducted to ensure that the literature obtained was truly new and relevant to the VRP problem in the context of waste transport.

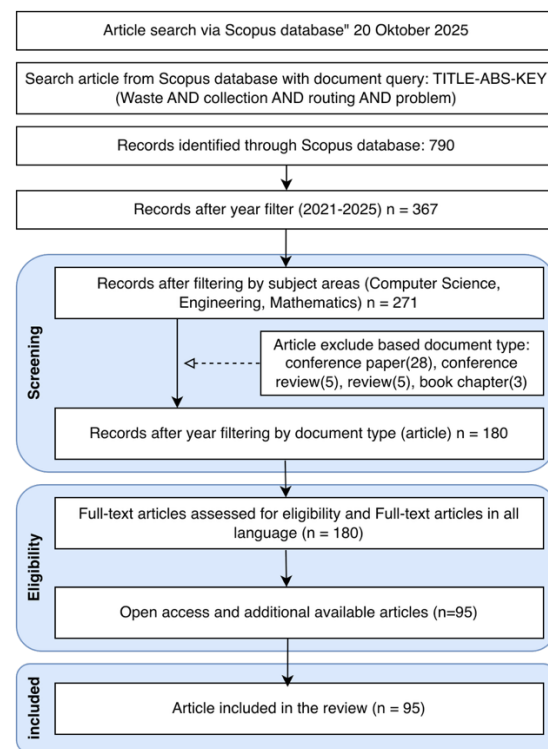


Figure 1. PRISMA for SLR

3.2 Article Selection Criteria

Screening, eligibility assessment, and final inclusion determination are multi-layered processes used to select articles. Initial screening looked at the suitability of scientific fields such as mathematics, computer science, and engineering, which resulted in 271 articles. The document type was then limited to journal articles, with the exception of conference papers, conference reviews, reviews, and book chapters, leaving only 180 articles. Next, eligibility was assessed by thoroughly reading the text and abstract to ensure that the article contained a VRP model or its variants (such as CVRP, VRPTW, MTRVP, ARP, multi-objective VRP, risk-aware VRP, or EVRP) and focused on the transport of biomass, domestic waste, or industrial waste. At this point, 95 articles met the criteria of methodological relevance and accessibility. Figure 1 shows that 95 articles were deemed eligible and included in the final analysis.

3.3 Data Extraction and Analysis

Each article was examined as part of the data extraction process to identify the VRP formulation used, the type of objective function,

the mathematical form of the model, the optimization algorithm, and the context of the case study analyzed. Many VRP variants were reviewed. These included the classic capacity-based formulation, time-based models, road-based approaches, multi-trip models, and multi-objective models that take into account risk, cost, and energy. Each article containing mathematical equations was evaluated to determine the objective functions and constraints used in waste transport routes. Conversely, studies were conducted on the computational characteristics and effectiveness of the ALNS, GA, ACO, SA, and hybrid metaheuristic optimization algorithms. Analyses were conducted comparatively and thematically to identify trends and gaps in research.

Methodological validity is ensured through the use of a uniform data extraction template, consistent application of PRISMA criteria and procedures, and manual review of article content suitability. The PRISMA figure illustrates the literature selection process, which began with article identification and ended with the determination of 96 final articles evaluated in this study. The figure makes the literature selection process clearer.

RESULT AND DISCUSSION

4.1 SLR Results

The results of SLR from 96 articles show that research on the Vehicle Routing Problem (VRP) in waste transport is moving towards increasingly complex and multidimensional models. In terms of models, the literature shows a shift from basic formulations such as CVRP and VRPTW to rich VRPs such as Multi-Trip VRP (MTVRP), Arc Routing Problem (ARP), risk-aware VRP, multi-objective VRP, and Electric VRP (EVRP). In terms of solution methods, more than two-thirds of the articles use metaheuristics as the main approach. ALNS, GA, ACO, and SA methods are the most popular due to their scalability and flexibility in solving large and complex real-world problems. In addition to algorithmic elements, SLR also sees a trend towards the integration of digital technologies such as the Internet of Things, WSN, and GIS. By using data on container conditions, fullness status, and road network information, the character of data-driven routing is strengthened. Sustainability is also a concern, especially in VRP and green EVRP models that

add elements such as emissions, energy, and the environment to the objective function. The results show that VRP research in waste transport indicates a paradigm shift towards long-term sustainability, adaptivity, and intelligence-based optimization.

4.1.1 Thematic Summary of VRP Research

Table 1 illustrates the overall SLR results in five main themes. These results show the direction in which VRP research on waste transport is moving. The results indicate that VRP is no longer limited to distance optimization and has now become a multidimensional model. This model includes the use of Internet of Things-GIS technology, risk, energy sustainability, and several issues, such as vehicle rotation and heterogeneity. Given their ability to handle complex problems, ALNS and modern metaheuristics appear to be the most popular approaches. This thematic structure provides a comprehensive figure of the VRP research environment and serves as an important foundation for the development of more adaptive models and algorithms in the future.

A visual figure summarizing the various important elements in the literature is required to provide an in-depth understanding of how VRP research in waste transportation has developed and interacted with each other. Figure 2 displays the VRP Research Map. This figure shows how the application context, VRP model development, optimization algorithms used, and supporting technologies such as the Internet of Things, WSN, GIS, and machine learning are related to each other. The VRP approach has evolved into a research framework that encompasses various aspects, including smart technology integration, energy sustainability, and high-level metaheuristic models. Figure 2 shows new research trends and research prospects, as well as the position of each theme in SLR.

Figure 2 illustrates the relationship between application context, VRP model categories, metaheuristic optimization methods, and supporting technologies such as the Internet of Things, WSN, GIS, and machine learning. This map, based on the results of an SLR of 96 articles, explains how VRP research has developed and shows the path towards

integrating VRP into efficient, adaptive, and sustainable waste transport systems.

Table 1. Summary of SLR Findings

Theme	Main Summary (Ref)
Medical & Risk VRP	The main focus is to reduce the risk of exposure to infectious waste, create a safe environment, and establish ideal sterile routes. The types of models used include risk-aware VRP, VRPTW, and LRP-VRP, while the hybrid MILP, SA, and ALNS methods are the most common. (Eren and Rifat Tuzkaya, 2021; Suksee and Sindhuchao, 2021; Erdem, 2022; Niranjani and Umamaheswari, 2022; Zhang <i>et al.</i> , 2024)
IoT-WSN-GIS-based VRP	Utilizing IoT/WSN for routes that can be adjusted based on the number of containers and environmental conditions. Routes based on actual road networks are created using GIS. This procedure saves time and reduces empty journeys. (Ramirez, Santiago and Kamiyama, no date; Ghahramani <i>et al.</i> , 2022; Ramamoorthy and Syrotiuk, 2024; Alsayaydeh <i>et al.</i> , 2025)
Sustainability & Energy VRP & EVRP)	EVRP models the energy profile and SOC of EVs, while Green VRP focuses on carbon footprint. Multiobjective VRP combines cost, energy, and emissions. (Li <i>et al.</i> , 2023, 2024; Shen <i>et al.</i> , 2023; Peña, Dorronsoro and Ruiz, 2024)
Multi-Trip & Rich VRP	Solving time constraints, multi-compartments, rotation, and vehicle heterogeneity. This approach is particularly well-suited for large cities that generate a significant amount of waste. Common algorithms are SA, ALNS, and GA. (Ostermeier <i>et al.</i> , 2021; Lavigne <i>et al.</i> , 2023; Marpaung <i>et al.</i> , 2025)
ALNS and Modern Metaheuristics	ALNS is the most popular algorithm, excelling in handling adaptive settlement and destroy-repair operators. Many studies combine it with GRASP, GA, or VNS for large-scale efficiency. (Hurkmans <i>et al.</i> , 2021; Suksee and Sindhuchao, 2021; Algethami, 2023)

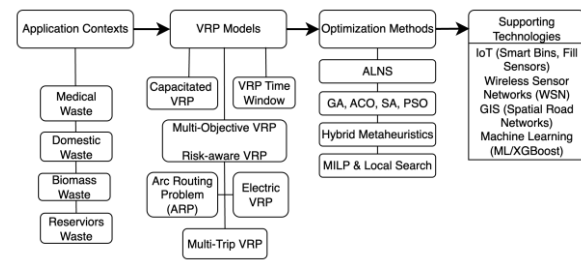


Figure 2. VRP Research Map in Waste Transportation

4.2 Discussion

4.2.1 Thematic Interpretation

The thematic breakdown in Table 1 shows that VRP in waste transport has many uses, such as high-risk medical waste transport and sensor-dependent domestic services. The medical and risk VRP themes show how important public safety is in situations where the objective function involves the possibility of infection. Risk-aware VRP and VRPTW models can be effectively utilized in the context of pandemics or hospital routes.

Conversely, adaptive routes resulting from the integration of IoT, WSN, and GIS are changing the paradigm. Articles discussing this issue state that traditional routes based on schedules are no longer suitable for large cities with variable waste volumes. Sensor technology enhances the intelligence and responsiveness of VRP.

Sustainability is increasingly important as global efforts to reduce emissions intensify. EVRP and Green VRP models offer new perspectives on distance and cost by incorporating energy and environmental elements. The results indicate that waste transport is part of urban maintenance strategies and logistical challenges.

4.2.2 The Dominant Role of ALNS in The Evolution of VRP

The SLR results indicate that ALNS is the most flexible and powerful algorithm for solving rich VRPs in waste collection. The main advantage of ALNS is its unloading and repair mechanism, which can be adapted to various operators, allowing the algorithm to explore a wide solution space without getting stuck in the best place.

ALNS has been proven effective for (1) large-scale VRPs, covering hundreds to thousands of nodes; (2) VRPs with multiple objectives (cost, risk, and emissions); (3) VRPs with multiple trips and multiple compartments; (4) VRPs and sustainable biomass; and (5) Internet of Things and GIS-based VRPs with dynamic data.

The literature frequently uses hybrid ALNS, such as GRASP and ALNS, and typically yields the best results. This finding reinforces the position of ALNS as the best approach for complex, dynamic, and constraint-rich VRP research.

4.2.3 Lack of Integration of ML, Internet of Things, GIS, and VRP

Although research has shown significant progress in the use of VRP, the Internet of Things, GIS, and metaheuristics, there is still little research that integrates all of these components with machine learning (ML) algorithms. Not many studies combine ML predictions, real-time IoT/WSN sensor readings, GIS spatial mapping, and VRP optimization in a single integrated framework. Instead, most studies only use IoT or GIS separately to obtain dynamic routes. However, such integration has the potential to create a smarter, more flexible, and environmentally friendly waste transport system, especially in developing countries such as Indonesia. This gap shows the importance of conducting further research on the topic.

In general, the discussion shows that VRP in waste transportation is developing in three main dimensions: (1) model complexity, (2) digital intelligence of the system, and (3) energy and environmental sustainability. The use of metaheuristics, particularly ALNS, is becoming a methodological trend due to its consistent performance across various VRP categories. These results provide a strong foundation for future VRP research focusing on smarter, more responsive, and sustainable waste transportation systems.

CONCLUSION

This systematic review shows that the Vehicle Routing Problem (VRP) is the primary approach to waste transport optimization due to the emergence of constraint models such as CVRP, VRPTW, ARP, MTPVRP, and multi-objective models. It has been proven that hybrid

approaches and metaheuristic methods such as ALNS, GA, ACO, and SA are most effective in solving rich VRPs. This is due to their ability to adapt to different levels of difficulty and complexity of operations. In addition, electric vehicle energy models that combine IoT, WSN, GIS, and GIS show that VRP has evolved to improve route efficiency, as well as enhance sustainability and risk mitigation. Overall, this SLR indicates that VRP research on waste transport is moving towards smarter, more dynamic, and environmentally oriented methods. Furthermore, it paves the way for further research on the integration of real-time data, machine learning, and a more contextual algorithm design for future waste logistics systems.

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