The possibility of applying Artificial Intelligence in Waste Management in the developing countries towards building smart cities: Jordan as a case study

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Rapid urbanization and increasing waste generation are intensifying pressure on Solid Waste Management (SWM) systems in developing countries, where limited resources, static planning practices, and operational inefficiencies remain prevalent. Although Artificial Intelligence (AI) is frequently promoted as a transformative solution for urban services, empirical evidence of its effectiveness and institutional applicability in resource-constrained SWM systems remains scarce. This study addresses this gap by conceptualizing AI as a decision-support tool that complements, rather than replaces, conventional waste management practices. Using Al-Radwan neighbourhood in Amman, Jordan, as a case study, the research develops and evaluates an AI-supported waste collection framework integrating Internet of Things (IoT) sensing, geospatial data, and heuristic optimization. The methodology incorporates qualitative analysis of an existing SWM system as well as quantitative simulation of AI-based routes for waste collection vehicles as well as capacities. Real-time levels of fill, spatial data from a Global Positioning System (GPS), as well as capacities of waste collection vehicles, are incorporated in order to create optimized routes. Performance of the system is evaluated through a comparative analysis of conventional and AI-optimized routes, whereby performance metrics are based on evaluation of distance travelled, route duration, and fuel consumption, as well as carbon produced. Importantly, the study demonstrates the institutional feasibility of AI adoption through a human-in-the-loop configuration that preserves municipal control and aligns with existing governance structures. The findings provide empirical evidence that AI can function as a practical lever for enhancing efficiency and sustainability in SWM systems without requiring costly infrastructure overhauls. The study offers actionable insights for Jordanian municipalities and other municipalities in comparable contexts and contributes to advancing sustainable urban planning objectives aligned with the Sustainable Development Goals (SDGs). Moreover, the study offers a foundation for future research on AI applications in urban sustainability and circular economy transitions.

Keywords: Artificial Intelligence; Solid Waste Management; route optimization; sustainable urban planning; environmental sustainability; developing countries

1. Introduction

Solid Waste Management (SWM) is a critical challenge globally, with improper disposal contributing to pollution, environmental degradation, and health risks ((Wilts et al., 2021). Rapid population growth, technological advancement, urbanization, and economic development have increased waste generation, with the World Bank (2018) projecting a rise from 2.01 billion tons in 2018 to 3.40 billion tons by 2050. Currently, over 43% of global solid waste is mishandled through incineration, illegal dumping, and uncontrolled landfills ((Abdallah et al., 2020; Kaza et al., 2018), leading to severe environmental and health consequences such as water and soil contamination, and poor air quality.

Rapid urbanization, population growth, and changing consumption patterns have intensified pressures on solid waste management systems worldwide. In developing countries, these pressures are often compounded by limited financial resources, fragmented governance structures, and insufficient technological integration. Jordan represents a particularly critical case, where accelerating urban growth, environmental vulnerability, and constrained municipal capacities have converged to make solid waste management one of the most pressing challenges for sustainable urban development and public service delivery.

Jordan's urban areas have experienced substantial demographic and spatial transformation over the past two decades. Municipalities are required to manage increasing waste volumes within dense urban fabrics while operating under restricted budgets and aging infrastructure. The SWM system remains largely dependent on conventional collection practices characterized by fixed schedules, static routing, and limited real-time data utilization. These practices have led to inefficient waste collection vehicle routing, unnecessary fuel consumption, uneven service coverage, and elevated environmental and public health risks, particularly in high-density residential neighbourhoods. Despite ongoing national efforts to improve environmental governance, waste collection remains weakly integrated into boarder smart urban planning frameworks.

From an urban planning perspective, waste management is not merely an operational service but a fundamental component of urban liveability, environmental quality, and infrastructure resilience. Inefficient waste collection directly affects street functionality, neighbourhood cleanliness, air quality, and occupational health and safety conditions. In Jordan, where municipalities are responsible for waste collection but often lack advanced decision-support tools, the absence of data-driven planning mechanisms limits the ability to optimize routes, allocate resources efficiency, and respond dynamically to spatial variations in waste generation.

Artificial Intelligence has emerged as a transformative enabler of smart urban services by supporting real-time decision-making, system optimization, and adaptive management. In the context of solid waste management, AI-based decision-support systems have demonstrated potential to improve collection efficiency through dynamic routing, capacity-based vehicle assignment, and real-time monitoring of waste generation patterns. However, in developing-country contexts such as Jordan, the application of AI in SWM remains limited and insufficiency tailored to local institutional, infrastructural, and governance realities. Existing studies often emphasize technological performance without adequately addressing operational feasibility, scalability, and integration into urban planning systems.

While AI is often portrayed as a disruptive or replacement technology, its application in urban planning and municipal service delivery should be understood primarily as a supportive and augmentative tool rather than a suitable for conventional planning methods (Abdallah et al., 2020; Fang et al., 2023). In the context of solid waste management, AI does not replicate existing planning processes; instead, it enhances them by improving data availability, analytical capacity, and real-time responsiveness. This distinction is particularly important in developing-country settings such as Jordan, where institutional structures, regulatory frameworks, and human expertise remain central to urban governance and service provision.

Despite the growing body of research on smart waste management systems, two significant research gaps persist. First, discrepancies exist between public and policymaker perceptions of AI in sloid waste management, particularly concerning its role in decision-making, its implications for employment and accountability, and its compatibility with existing governance frameworks. These perceptual gaps can act as barriers to adoption, even when technological solutions are technically feasible. Second, there is a notable lack of empirical, context-specific evidence demonstrating the effectiveness of AI-based decision-support systems in improving solid waste management processes in developing countries (Abdallah et al., 2020; Dawar et al., 2025). Many existing studies rely on simulations or conceptual models without sufficiently evaluating operational performance under real-time constraints.

This research addresses these gaps by empirically examining the application of an AI-enabled waste collection optimization system in Jordan, using Al-Radwan neighbourhood as a case study. The proposed system integrates Internet of Things (IoT) based sensing, cloud-based data management and AI-assisted decision-support to support municipal planners and operators in optimizing waste collection routes based on real-time conditions. Rather than pursuing full automation, the system is designed to operate within existing planning and operational frameworks, reinforcing a human-in-the-loop approach to decision-making.

The study contributes to the fields of smart urban planning and sustainable waste management in three key ways. First, it provides a context-specific analysis of Jordan's solid waste management challenges, linking operational inefficiencies to broader issues of environmental governance and urban planning. Second, it offers empirical evidence on the effectiveness of AI-based decision-support systems in improving waste collection efficiency, enhancing resource utilization and operational performance, reducing operational costs, and lowering carbon emissions within developing-country context (Hu et al., 2024; Shen et al., 2023). Third, it demonstrates how intelligent waste management systems can serve as strategic planning tools that support Sustainable Development Goal (SDG) 11 (Sustainable Cities and Communities) through improved urban service delivery and Sustainable Development Goal (SDG) 12 (Responsible Consumption and Production) through optimized resource use and reduced environmental impacts (United Nations, 2019; UN-Habitat, 2020).

By positioning AI as an enabling rather than disruptive force, this research advances a pragmatic and ethically grounded approach to smart city development. It highlights how AI-supported solid waste management systems can be responsibly into urban planning processes, enhancing sustainability, resilience, and service efficiency in resource-constrained urban environments.

2. Literature review

2.1.Environmental governance and solid waste management progress in Jordan

The major characteristics of environmental governance in Jordan can be described as a centralized approach in policy formulation and a decentralized approach in service delivery. While the government's Ministry of Environment regulates and strategizes on issues of environmental regulation and management in general terms in the country, various municipalities are mandated to administer and govern in practice solid waste management services on a ground level in various parts of Jordan. Different policies and strategic frames to advance waste management services in Jordan have come to pass in the country's regulatory channels in the wake of a series of years dedicated to promoting environmental management in line with various international policies and guidelines on environmental sustainability in various parts of the world.

Despite the progress being made in the improvement of the regulatory environment and the push for the practice of sustainable waste management best practices in the country, the framework for solid waste management in Jordan still faces a number of operational challenges pertaining to the service provided in the country. For instance, solid waste management in Jordan still largely involves the conventional methods of service delivery in the country, with limited applications of digital technologies in the service delivery framework relative to other options available in the industry today. In this case, the improvement in governance in the country can thus not be said to have had a direct influence on the service delivery provided in the country through the conventional methods used in the industry today. An opportunity thus presents itself in the employment of AI-based Decision Support System (DSS) technologies in the country in a manner fitting its governance system while promoting transparent service delivery in the country.

2.2.The vulnerability of solid waste management systems in developing countries

On one hand, solid waste management in developing countries faces a number of risks, especially in such countries where solid waste management has been considered a vulnerable system given the high rate of urbanization, a high population growth rate, a lack of institutional capacity, limited financial, infrequent technical infrastructure, and a lack of integrated institutional arrangements, which would normally make a solid waste management system in such countries often inflexible in coping with the changes in waste management that may emerge at any given time, frequent route-based approaches, a lack of sufficient information in the system, a lack of a planning culture, limited efficiency in solid waste management, limited capacity in coping with such inflexibilities in urban areas that are inherently associated with growth in informal areas, given the complexity in a heterogeneous waste management system that might emerge in the process.

In this context, the addition of advanced technologies will have to be very carefully considered; over-complex or capital-intensive solutions carry a very real risk of exacerbating extant inequalities and operational challenges. AI, framed as a decision-support rather than replacement tool, offers a context-sensitive pathway toward strengthening system resilience. By enabling data-driven optimization of collection routes, waste collection vehicle deployment, and service scheduling, AI can enhance operational efficiency without requiring fundamental restructuring of existing waste management institutions. This is a supportive role that is highly pertinent to developing-country contexts, where incremental and adaptable innovations are likelier to achieve long-term sustainability and institutional acceptance.

2.3. Solid waste management within Environment, Health, and Safety (EHS) frameworks

Ineffective retrieval and disposal of wastes can result in waste accumulation and even air pollution-related problems resulting from burning. In developing countries, the occupational health and safety of those involved in handling wastes is compromised. The handlers of waste collection face additional threats of improper and unpredictable collection schedules and overcrowded containers, making the efficiency of an effective system of SWM a health and safety issue.

Moreover, it is postulated that data-based planning and integration in the working processes of the SWM could yield a number of positive impacts with regards to the operation and performance in EHS management. These include a transition from a "reacting" to a more "pro-acting" management paradigm. Moreover, the systems could reduce exposures at the workplace and the overall impact on the natural environment through an emphasis on saving fuel and its environmental ramifications (Hu et al., 2024; Shen et al., 2023). It is also crucial to note that an emphasis on an auxiliary function for AI systems in the overall development and working processes of the EHS management protocols serves to underscore its adoption and integration when considering the overall facets and imperatives towards a more sustainable and socially conscious disposal system.

2.4.Aspects to be considered in Solid Waste Management

While effective solid waste management entails incorporating a combination of technical, spatial, institutional, and social factors, key operational aspects involve waste generation rates, container spatial distribution, collection frequency, waste collection vehicle capacity, and routing efficiency. These factors are strongly influenced by urban form, land-use patterns, population density, and temporal variations in waste production. In developing-country contexts, further complication factors include limited budgets, aging infrastructure, and workforce capacity that must be carefully accounted for to ensure waste management strategies remain feasible and scalable.

In particular, beyond technical considerations, governance structures, stakeholder coordination, and public acceptance have often determined the SWM performance. Community behaviour, compliance with waste disposal practices, and trust in municipal services directly impinge on the effectiveness of systems. Planning approaches that rely on static models or top-down decision-making can easily fail to capture on-the-ground realities, underscoring a dire need for adaptive, data-informed planning tools to aid human decision-makers by integrating operational data, spatial dynamics, and institutional constraints-enabling conditions for AI-assisted systems to augment, rather than disrupt, conventional waste management practices.

2.5. The importance and role of Artificial Intelligence in sustainable Solid Waste Management in the developing countries

Artificial Intelligence has come out as an important factor which helps us achieve the sustainability of the Solid Waste Management through an increased ability of urban areas towards the processing, evaluation, and acting on complex operational information. For a nation which is a developing country, the ability of the areas involved with the waste management in those nations is usually limited, along with the presence of inadequate information. Here, the use of Artificial Intelligence has the ability to present a great opportunity through the better evaluation of the areas involved with the provision of services. This helps us solve critical limitations present within conventional planning.

However the effectiveness of AI in SWM depends on its integration as a decision-support mechanism rather than as a replacement for established planning and management practices. AI systems are most impactful when they complement human expertise, support municipal decision-makers, and enhance transparency in operational processes. This supportive role is particularly important in developing-country settings, where trust, institutional stability, and policy coherence remain critical success factors. By reinforcing existing governance frameworks and improving evidence-based decision-making, AI-enabled SWM systems contribute to environmental sustainability, cost efficiency, and service reliability while maintaining the central role of human planning judgement.

2.6.AI application areas in Solid Waste Management

The AI applications in the management of solid waste management include all aspects of the waste management hierarchy, ranging from waste generation monitoring to waste collection and treatment. In practical terms, AI facilitates the data gathering and assimilation with sensor data and spatial data to promote decision-making in various forms. It is worth noting that these AI applications have practical implications in urban areas characterized by heterogeneous waste generation. Accordingly, AI helps urban areas transform fragmented data into useful information to move away from reactive waste management to proactive waste management.

As far as developing country-specific situations are concerned, application areas of AI must emphasize operational viability in these situations. Thus, instead of being highly automated and capital-centric in nature, AI interventions in these situations can potentially prove useful in eliminating operational bottlenecks in existing processes such as inefficient routes of waste collection, underutilized capacity of existing machines in waste disposal processes, inefficient handling of overflow situations in waste disposal processes, etc. Thus, application areas involving AI in processes such as waste monitoring, waste collection process optimizations, etc., can potentially prove more useful in these situations. These areas are directly in line with improving operational efficiencies while concurrently emphasizing existing planning paradigms and paving the way for various AI-specific instances discussed in subsequent subtopics.

2.6.1. Estimation of smart bin fill levels

Estimation of waste accumulation levels at bin levels is an essential feature of an effective and intelligent form of waste management solutions. It allows an intelligent bin or bin levels to monitor waste deposition and to continuously monitor and anticipate changes in waste deposition levels across different urban settings. This would enable municipalities to effectively assess temporal changes in waste deposition levels in different settings. This would enable effective and informed decision-making that would otherwise rely simply on scheduled waste collection routines and would find applications in scenarios characterized by varying waste generation levels and urban land usage diversity.

If we view the issue from the operations viewpoint, the application of AI-aided fill estimation will lead to more precise operational planning, thus serving as input to service prioritization as well as demand-driven collection activities. With the application of the predictive models, imminent potential problems of overflowing will be deduced, thus facilitating pre-emptive operations leading to more dependable service delivery while elevating the general results in sanitation services. In the context of the developing countries, where the associated information can sometimes be bridled, the application of these AI-aided models is conceived as an attainable alternative to guarantee the optimization of the accessible information. If fill estimation is envisioned as an input to the decision support model, human control will still be upheld while operational planning is more informed.

2.6.2. Collection improvements: Waste collection, vehicle routing and route optimizing

Optimization of the collected waste can be done through a technical process where there is integration of real-time data with operational information, which is done using a sophisticated optimization approach. This includes the continuous collection of data, which is done through a network of sensors. This data is also geographically positioned through the use of Global File System (GFS), as well as verification/identification through the use of radio frequency identification. This information is aggregated through a database, which includes the calculation of the entire quantity of the waste as well as the allocated resources. This information ensures the allocation of the task to the appropriate waste collection vehicle, whose capacity is able to accommodate the entire quantity.

The routing system is a vehicle routing problem, and a solution is achieved through applying AI-aided optimization techniques involving geospatial computing and navigation APIs (Karadimas et al., 2007; Rossit et al., 2021). It processes information such as distance matrices and collection priority to create routes for fleet management systems involving Global Positioning System (GPS) tracking to ensure efficient monitoring. By reducing idle travel, fuel consumption, and redundant trips, the optimized routing process contributes to lower carbon emissions and improved fleet efficiency (Hu et al., 2024; Shen et al., 2023). Moreover, the process is institutionally compatible and accountable for the country's waste management systems in the process. The efficiency and effectiveness of the system have ensured better waste management in different regions and will contribute to a better waste management system for the country.

This is clear through the literature, which shows the emerging role of AI as an aid for better decision-making in the optimization of SWM, particularly during the collection phase. While AI applications also extend to post-collection processes such as waste sorting, these are addressed as directions for future research. Thus, recognizing the gaps within the stakeholder perceptions regarding the operational effectiveness of AI, as well as the existing literature, a case-oriented methodology was employed in the study for the evaluation of the optimization role of AI for SWM in an urban city in Jordan. An overview of the methodology is presented in the following section.

3. Methodology

The methodology employed in the research has followed a qualitative research approach validated and complemented by quantitative data and AI system quantitative evaluation (Figure 1). The approach is employed in validating and proving the applicability of Artificial Intelligence in the management of Solid Waste. The focus of the study, with reference to the particular example from Jordan, considers and evaluates Artificial Intelligence from an intelligent decision support system approach. The focus is on an intelligent decision support system where data is interpreted and utilized in enhancing routes and services and operational efficiency (Abdallah et al., 2020). The use of Artificial Intelligence is beneficial from an environmental sustainability position and an economic sustainability position. It reduces the use of fuels and operational costs. It reduces the operational emission of wastes from municipal solid wastes and fleet optimization. Additionally, the system can facilitate the collection based on specific conditions rather than schedules through its support for consumer responsibility in the usage of the system and the improvement of the robustness of city waste services in a developing country environment.

The proposed methodological framework is based on a smart approach to waste management through a specific architecture that includes phases related to data acquisition, processing, decision, evaluation, etc. At the data acquisition level, each waste container is equipped with ultrasonic fill-level sensor, a GPS receiver, and a unique Radio Frequency Identification (RFID) tag, forming an Internet of Things (IoT)-enabled sensing unit. The ultrasonic sensor continuously measures the real-time waste accumulation levels within each container, allowing dynamic identification of collection demand. The GPS receiver provides precise spatial coordinates for both waste containers and collection vehicles, enabling geospatial visualization of waste containers and collection vehicles within the urban road network. The RFID tag uniquely identifies each container and is scanned during the emptying process by collection personnel, activating a control flag that confirms service completion and updates the system status.

All the sensor-collected data, including fill levels, RFID tags, and location, is received and stored in a single cloud-based database. This serves as a store of structured data, which guarantees consistency, verifiability, and time synchronization for the data collection process. Smart city optimization incorporates a fundamental principle through the use of real-time data, which results in the shift from a time-configured approach for the collection of waste materials to a condition-configured approach.

At the processing and decision support stage, the system uses AI-aided logic based on heuristic optimization and rules. Initially, the waste containers are filtered based on a predetermined level of fill. Only those containers with levels of filling above a specified level are chosen. The levels and the total quantity of containers are added and utilized in calculating the quantity of waste that requires attention. The estimation of the quantity of waste constitutes the most significant decision among other considerations.

Vehicle assignment employs a capacity matching mechanism that effectively compares the volume of the waste with the capacity of waste compactor trucks available for waste collection. For the decision to be reached, the system automatically selects the most appropriate vehicle that is larger in capacity compared to the volume of the waste that is calculated, thereby avoiding overloading while effectively exploiting the potential of the available capacity. The decision reached is based on the fundamental concept of decision support by an artificial intelligence system.

After vehicle assignment, waste collection vehicle routes are generated using computer algorithms to optimize waste collection routes with the assistance of Artificial Intelligence in geospatial techniques. The vehicle routing dilemma is conceptualized as a restricted variant of a Vehicle Routing Problem (VRP), considering different waste collection points and their capacity as well as vehicle terminals (Karadimas et al., 2007). The process of optimizing vehicle routes leads to the minimization of different objective functions regarding travel distances and times while providing full coverage of designated waste containers.

The performance of the suggested AI-based waste collection process will be evaluated through quantified performance measures that will be obtained through the calculation of some spatial and operational metrics. This will enable the efficiency of optimized scenarios to be compared with standard routes based on some quantified criteria such as total distance travelled, total expected collection time, number of containers served, and vehicle capacities used for serving such containers.

Besides achievement in the operation of the waste collection system, sustainability outcome achievement is gauged in terms of the quantity of fuel estimated as needed in the routing as derived from the optimization. Through the integration of routing efficiency with environment performance indicators, the evaluation framework facilitated the comparative evaluation of the economic and environment benefits of the AI-based DSS in the enhancement of the waste collection efficiency in the context of developing countries.

Overall, the proposed methodology indicates that the application of decision support technologies that leverage AI, the utilization of IoT sensor technologies, coupled with the implementation of cloud technologies, have the potential to significantly elevate certain practices related to the management of solid waste in the developing countries. This is exemplified via the ability to maximize routing decisions while remaining transparent.

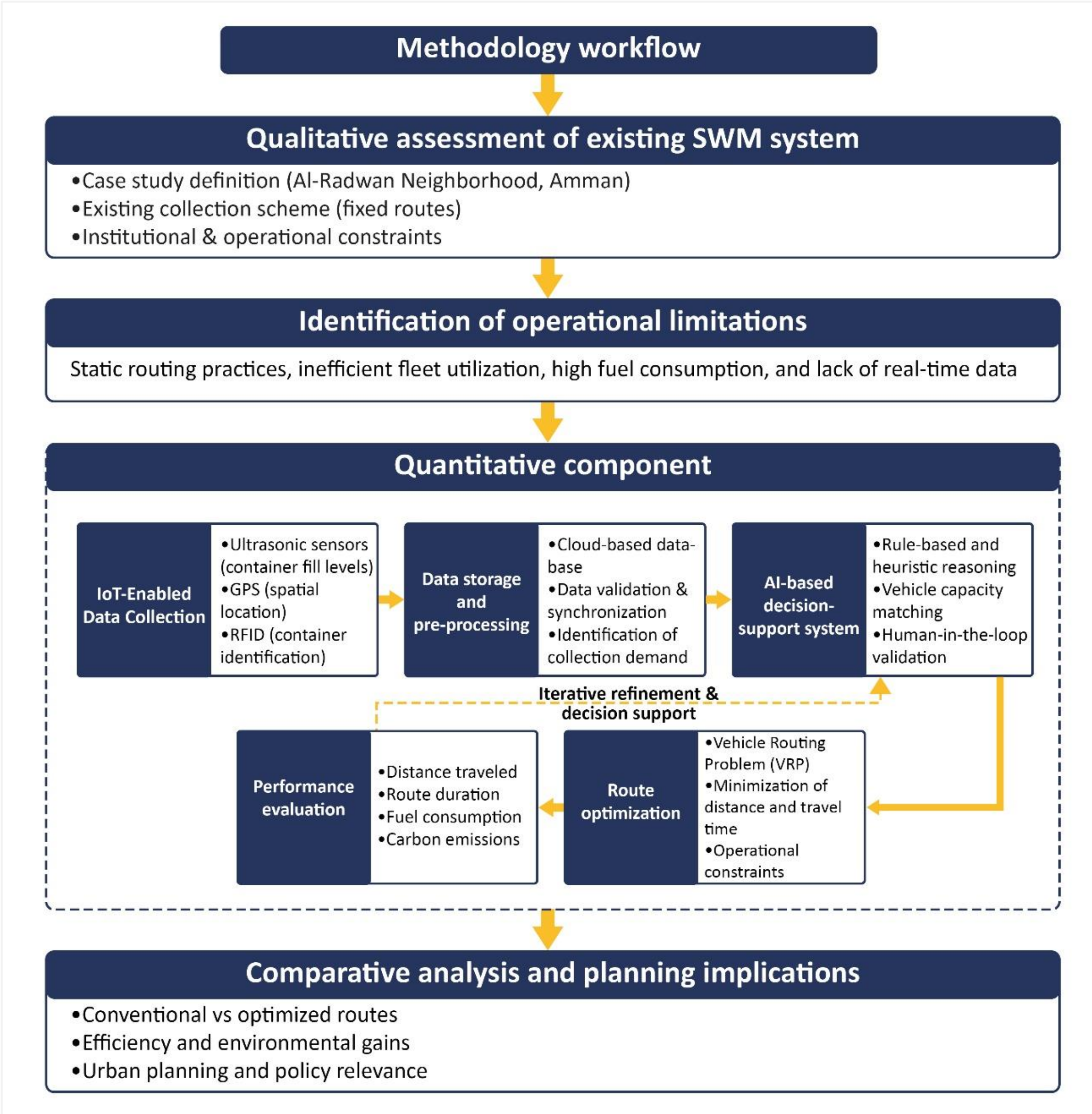

Figure 1. Methodological workflow for AI-enabled solid waste collection and route optimization. Source: (Author’s own work, 2024).

3.1.Case selection

The case study approach was used as a basis to allow an in-depth examination of the applicability of the concept of AI. Al-Radwan neighbourhood in Jordan was chosen as the study area since it is a good representation of the normal characteristics of urban/semi-rural areas, mainly offering a medium population density, variety of land use, and conventional waste collection services. Within the neighbourhood, there are challenges associated with waste collection services that are mostly universal to the various municipalities across Jordan, incorporating a fixed collection program with low adaptability and a lack of efficient routeing.

In addition to its representative nature, another advantage lies in its practical nature that can aid in carrying out empirical research, especially with regard to its accessibility of operational data, manageable spatial scale, as well as its clearly defined collection routes. These are essential factors that can enable researchers to simulate comparative study on conducting a conventional approach, as well as an AI-based approach, to waste collection activities.

3.1.1. Existing SWM service and infrastructure

The conventional mixed waste collection system in Al-Radwan neighbourhood follows a conventional system in which the routes taken by the vehicles carrying the waste are fixed, as well as the frequency of the collection services. However, residents in this neighbourhood discharge their solid waste in communal containers primarily -metal bins with a capacity of 1,000 litres and a plastic bins of 770 and 240 litres- distributed across designated collection points within residential streets. Waste collection is conducted daily by municipal compactor trucks with capacities ranging from 4 to 12 tons, and all collected waste is transported to Al-Shaer Transfer Station, located approximately 13 km from the study area. The system does not include formal source separation or organized recycling.

Furthermore, the waste collection process utilizes a ‘static routing’ system, which does not accommodate the accumulation of waste in real-time. The waste collection process in Al-Radwan neighbourhood, Al-Zahran district, utilizes a total of six compactor trucks, where each vehicle operates with a predetermined collection route despite the levels of waste in the container, as depicted in Figure 2. As such, collection vehicles often travel substantial distances before reaching full capacity, ranging from 17-24 km per trip for smaller trucks and 37-49 km for large trucks. Lack of real-time monitoring, data-driven decision support, and dynamic routing mechanisms dampens responsiveness and operational efficiency on the part of the municipality. These attributes represent a concrete point of reference against which the performance improvement of AI-supported, demand-driven waste collection system can be systematically measured.

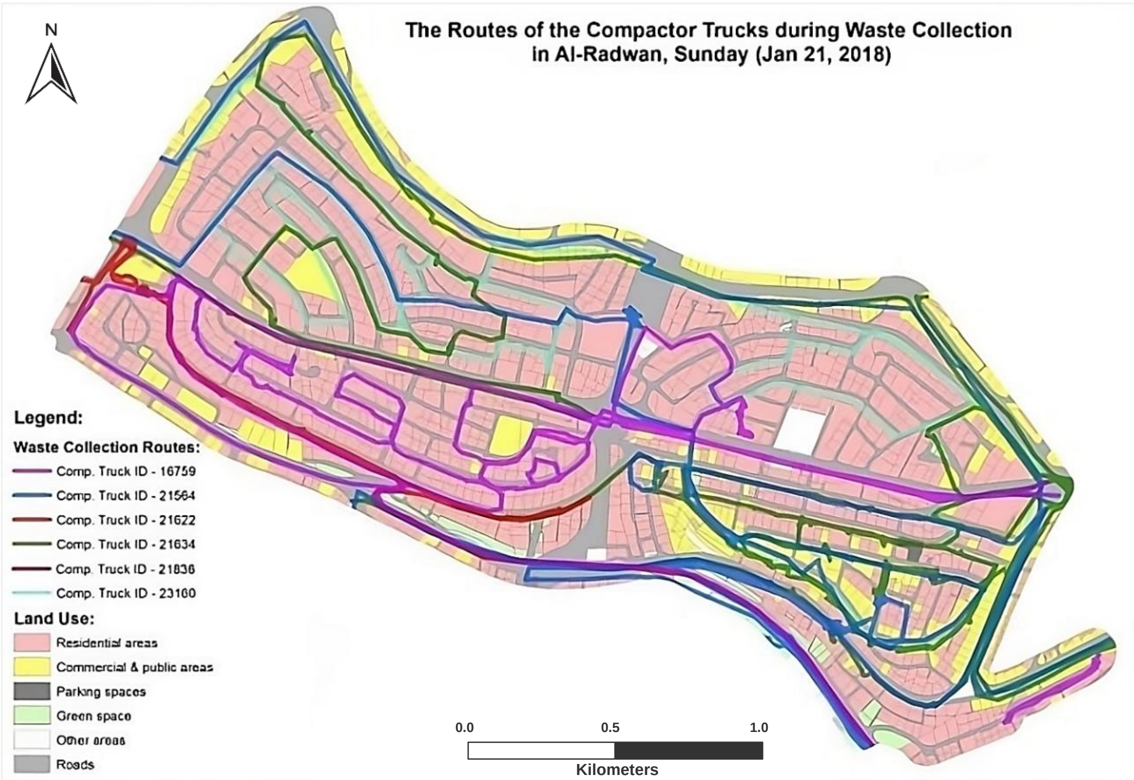

Figure 2. GPS tracks of compactor trucks during waste collection in Al-Radwan, Jan 21, 2018. Source: (Al-Zahran Municipality, 2024).

3.1.2. AI simulation model

To achieve the assessment of the operational benefits of AI-supported collection, the simulation model was developed to mimic the various operational scenarios of traditional collection as well as optimized AI-supported collection in Al-Radwan neighbourhood. Traditionally, the simulation model will entail the usual operational characteristics of the municipality, including routes, timetables, and service areas. However, the operational characteristics of the AI-supported collection will also be considered as optimized collection routes.

The simulation methodology allows direct comparison between the two scenarios using similar spatial data, characteristics of the vehicles, and parameters of service. The performance measures of total travel distance, computed collection times, services containers, and capacity use of the vehicle can be obtained from the two scenarios. In comparison with other approaches or methodologies, the controlled nature of the simulation methodology allows the study to focus on the influence of AI-assisted decision support.

3.1.3. Key elements for AI implementation in Al-Radwan neighborhood

The development and implementation of the proposed AI-based waste management system in Al-Radwan neighbourhood is contingent upon a set of essential enablers categorized along technological, institutional, and operational dimensions. Regarding the technological dimension, there is a need to deploy IoT-based smart bins with ultrasonic sensors, GPS devices, and RFID tags, in addition to cloud storage and computing services (Ali et al., 2023).

From the institutional perspective, the successful implementation of the system is also dependent on the capability of the decision support system based on Artificial Intelligence to match the existing workflow processes in the municipal institutions. The human operators are an essential part in the oversight of the decision support system, which includes the validation of the outputs by the human operators.

4. Results

In this section, the results of the simulation concerning the waste collection activities in Al-Radwan neighbourhood with the support of AI technology are presented in the context of the efficiency in the operations conducted through the standard fixed route method, taking into consideration the performance in the route optimization technique used in this simulation (Figure 3). The results have been set up in a manner that best aligns with the indicators of the evaluation presented in the methodology.

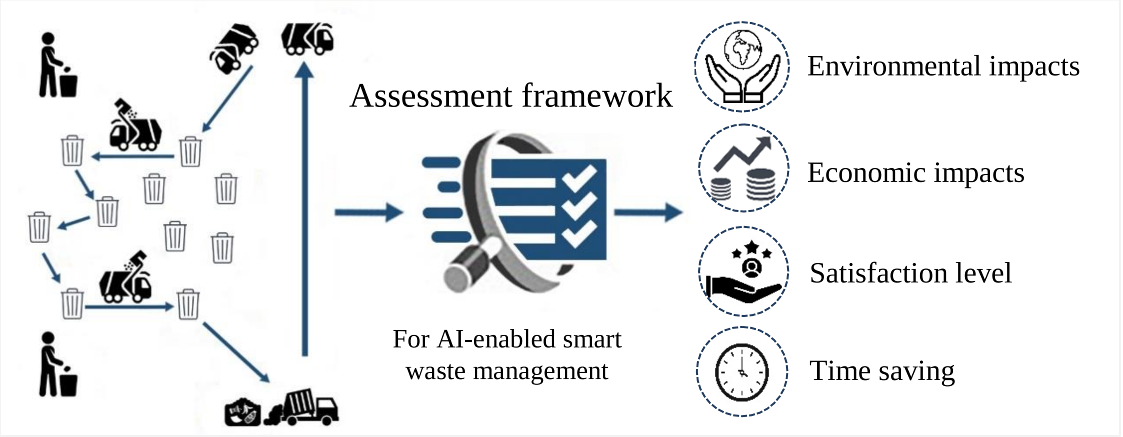

Figure 3. Assessment framework for AI-Enabled smart Waste Management. Source: (Authors' own work, 2024).

4.1.Performance of AI-based route optimization

The AI-assisted routing system achieved considerable gains in waste collection efficiency compared to the standard fixed route system in Al-Radwan neighbourhood. The system was able to omit waste collection stopovers based on real-time container fill level values, hence avoiding wastage in vehicle movements over urban corridors. This type of demand response system differs greatly from the standard system in place, which does not take into account spatial and temporal waste generation trends.

Quantitatively, comparing the regular route (Figure 4) with the optimized one (Figure 5), the AI-optimized route reduced total route time from 2 hours and 11 minutes under the regular system to 44 minutes, yielding a time saver of 1 hour and 27 minutes per collection cycle. The actual reduced times taken to simply drive through the route were reduced from 1 hour, 53 minutes to only 41 minutes, thus saving approximately 1 hour and 12 minutes of actual drive times. These efficiencies can be said to have arisen due to the optimized route path taken as well as the elimination of the less utilized containers from the route path. Concurrently, the distances covered were reduced from 47.25 km to only 16.45 km, thus saving approximately 30.80 km or approximately 65% of the actual distance covered due to the application of the constrained Vehicle Routing Problem (VRP) through the application of AI. These reductions in route time, driving time, distance, and fuel consumption are summarized in Table 1.

More notably, however, the better performance was attained without any change in the present structure or form that the waste collection process presently takes. This proved the significance or value that human intervention held with regard to the decision-making process concerning the usage or validation of the routes that the vehicles take.

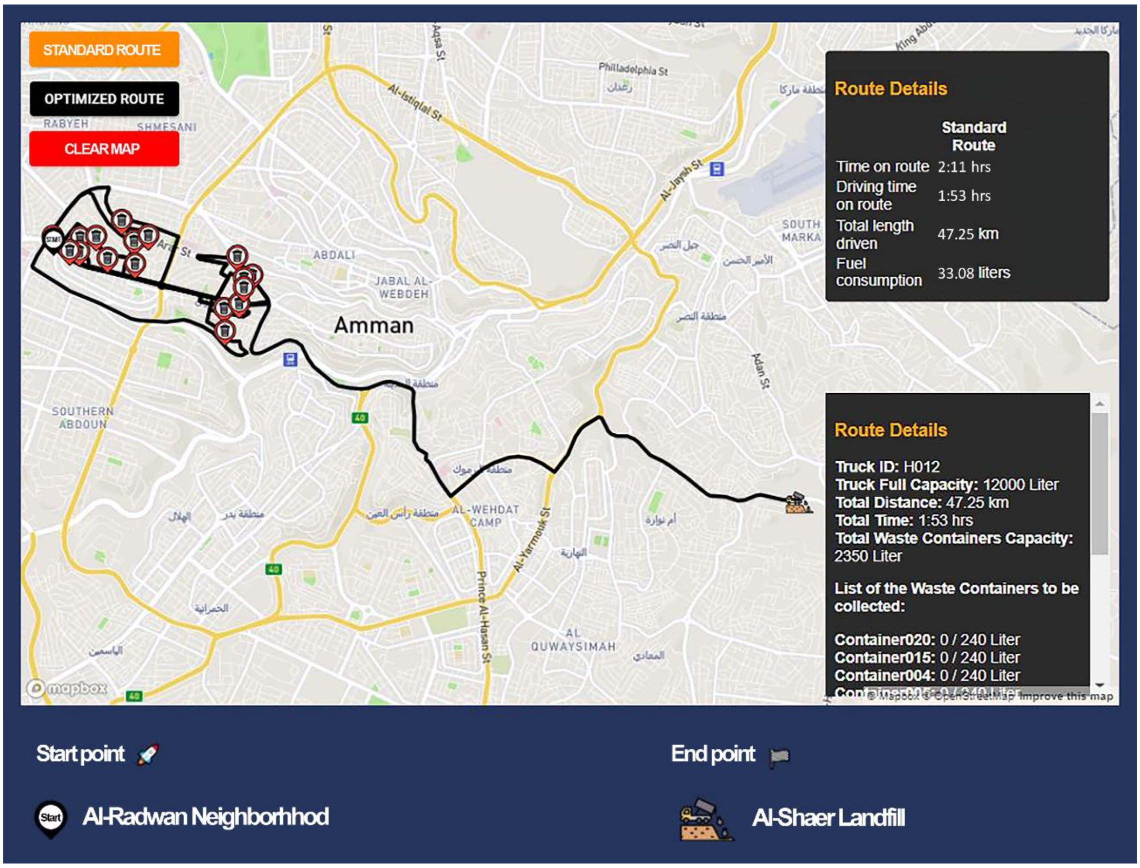

Figure 4. Standard/ regular route details during waste collection in Al-Radwan neighbourhood. Source: (The authors developed AI simulation model using OpenStreetMap, 2024).

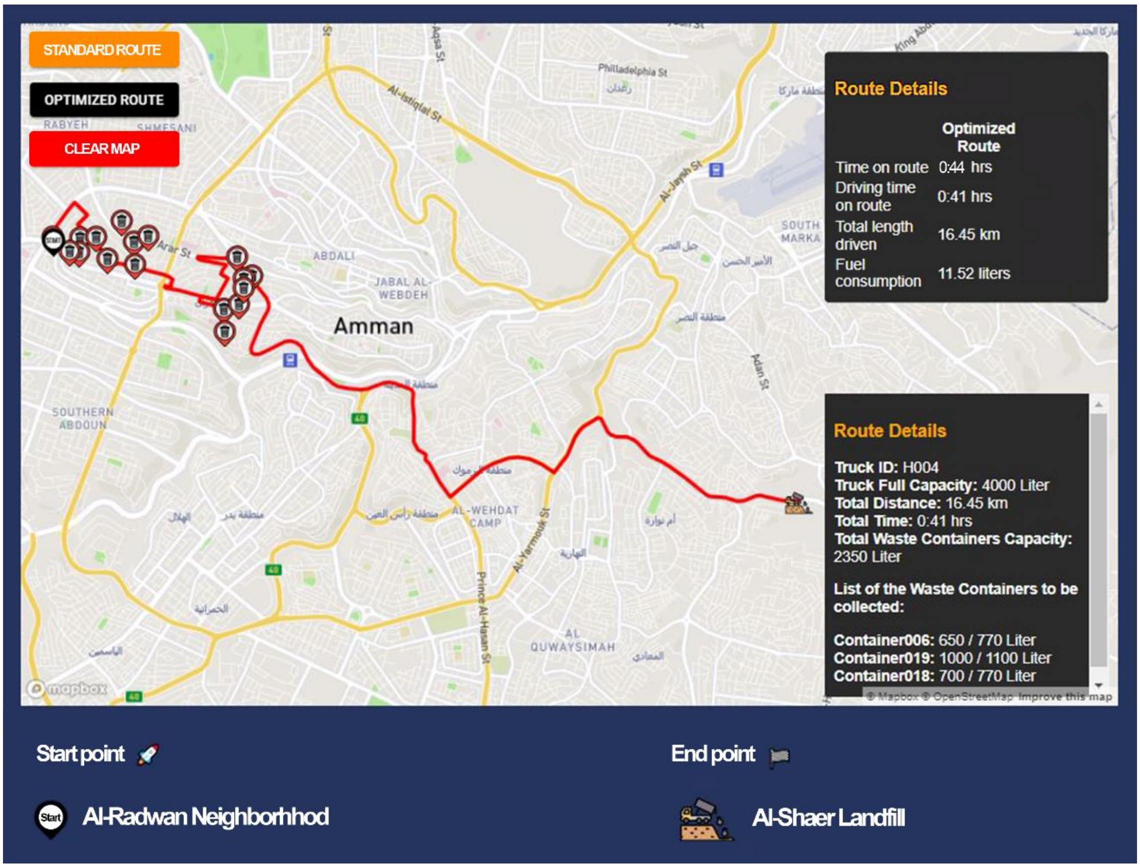

Figure 5. Optimized route details during waste collection in Al-Radwan neighbourhood. Source: (The authors developed AI simulation model using OpenStreetMap, 2024).

	Regular route	Optimized route	Reduction/ improvement
Time on route, h:m	2:11	0:44	1:27 (~66%)
Driving time on route, h:m	1:53	0:41	1:12 (~63%)
Total distance driven, km	47.25	16.45	30.80 (~65%)
Fuel consumption, (70 l/km)	33.08	11.52	21.56 (~65%)
Redundant stops	High	Minimal	Significant reduction

Table 1. Comparison between the regular and the optimized routes. Source: (Data has been derived from the authors developed AI simulation model, 2024).

4.2.Fleet utilization and vehicle assignment efficiency

The capacity-matching mechanism included in the decision support system based on the 'AI model' ensured better utilization of the fleet. Combining the volume of the containers before assigning the vehicle ensured that the compactor trucks that were chosen had sufficient capacity after the calculation of the waste volume, yet not too much spare capacity was available to prevent the return of the trucks to the transfer station too early.

It should be noted that compared to the divided route approach that utilized standard fixed routes –such as where the full capacities were achieved only during long distances of travel –the results obtained from an artificial intelligence support mechanism indicated efficiency in the distribution of work done with relation to the number of supported fleet sizes that were utilized in this case.

4.3.Environmental and operational sustainability impacts

The operational efficiency gained through AI-based routing was directly equivalent to a number of environmental and sustainable developments. For instance, the reduction in trip lengths and collection times was indicative of a notable decrease in fuel consumption per trip. Assuming a rate of 0.70 litres per km for fuel consumption, the difference between 33.08 litres per trip for a regular route and 11.52 litres for an optimized route was a saving per collection cycle of 21.56 litres. Although actual emission levels were not monitored for a full-scale validation per trip per route, the savings gained per trip through better fuel management was a significant indicative factor for a reduction in greenhouse emissions.

Apart from the environment-related issues, the routing efficiency positively affected fleet efficiency in general. This is because vehicles were matched with the aggregate volume of the waste to be collected. Consequently, the fleet was correctly utilized; vehicles were not engaged in underutilization activities as their loads were matched appropriately. This implied the engines were not subjected to unnecessary loading cycles. This situation is particularly valuable in developing countries where resource scarcity is characteristic.

These findings represent a significant contribution to the advancement of AI applications from a border urban sustainability perspective and demonstrate that such AI-enabled decision-support systems can meaningfully contribute to smart city objectives through improved service efficiency, reduced environmental externalities, and evidence-based planning. The results align directly with Sustainable Development Goal 11 of the United Nations (Sustainable Cities and Communities) by enhancing efficiency in the delivery of urban services; they align with Sustainable Development Goal 12 (Responsible Consumption and Production) by optimizing resource use and reducing fuel consumption. These collective results provide empirical validation of the capability of AI to underpin sustainable solid waste management without compromising existing arrangements relative to governance and operational frameworks.

4.4.Comparative evaluation with conventional collection process

A comparison of the standard fixed routes with the optimised route proposed by an AI system shows how conventional approaches can be inefficient and how the urban environment affects service delivery. The regular routes, although easy to manage from an administrative level, cannot respond to fluctuating spatial and temporal patterns of waste generation. The AI system can manage the services more efficiently.

Overall, these findings present empirical support demonstrating a significant potential improvement in SWM processes using AI in a developing country scenario. They support a major research gap in demonstrating both the operational viability of AI in a realistic SWM environment and maintaining compatibility to existing institutional structures and human-centric planning processes.

5. Conclusions

This research shows, with Jordan as an empirical case study, how AI can be an appropriate and efficient decision-support tool in enhancing solid waste management in developing-country urban contexts. Rather than any technologically disruptive or institutionally burdensome transformation, the research has also underlined the incremental integrations that AI might have with existing municipal systems to enhance operational efficiencies, resource use, and environmental performance. The proposed framework couples IoT-enabled data acquisition with AI-assisted routing and vehicle assignment to deliver measurable improvements in collection efficiency, fuel consumption, and fleet utilization without changing established governance structures.

The results have targeted two key knowledge gaps: first, the gap between public and institutional perceptions on the one hand, and the nature of AI as a disruptive or replacement technology; and second, the relative rarity of empirical evidence that can demonstrate AI's real-world effectiveness in enhancing solid waste management operations. By quantifying the difference between conventional and AI-optimized collection routes, this study gives substantial proof that AI-supported decision-making can significantly reduce travel distance, operational time, and fuel consumption. These findings further develop the conceptualization of AI as an enabling intelligence layer that enhances traditional planning practices rather than substitutes them.

The wider sustainability benefits of this work in relation to smart urban planning debate will revolve around the contribution that this study adds in proving that a data-driven approach towards optimizing efficiencies in municipal city servicing will also contribute toward Sustainable Development Goals 11 and 12.

6. Policy-oriented conclusions for Jordanian municipalities

The results of the study have direct and actionable implications for Jordanian municipalities. Jordan's solid waste management sector has long faced challenges in the forms of limited financial resources, increasing waste generation, rising fuel costs, and institutional capacity constraints. Against this backdrop, the research presented here demonstrates that AI-based systems do not necessarily need an abrupt change in the current infrastructure in order to provide meaningful benefits. Rather, AI might be deployed as a strategic lever to build system intelligence into current operations and enhance the rationality and efficiency that can exist under existing constraints.

This example from Al-Radwan proves that even a slight technological boost, like measuring the fill levels, routing through GPS, or decision-logic through AI, can significantly boost service quality. In many municipalities, budget constraints invoke the need to adopt a slight boost as a remedy. Instead of gaining reliability through large investments in expanding infrastructure or fleet sizes, municipalities can focus more on optimizing current assets. By utilizing AI routing, as already stated, a lower number of trips, optimizable asset utilization, and fuel savings promise immediate benefits.

Significantly, the study highlights the need to maintain the human component within the governance structure of AI implementation. Thus, the people within local government institutions remain the focal points with regards to oversight functions. As a result, the need is emphasized within the governance structure or framework for AI implementation, which is deemed very crucial within the development of acceptance among local policymakers.

7. Recommendations

Based on the findings, the following recommendations are proposed for Jordanian municipalities and relevant national authorities:

(1) Embrace the concept of using AI not in place of, but in addition to, current planning and operational hierarchies.

(2) Prioritization of demand-driven waste collection: There is a need to shift from a schedule-driven system towards a condition-driven waste routing system.

(3) Invest in modular and scalable technologies such as IoT-based containers to support continuous system development.

(4) Enhance capacities at the city level through specific training to allow staff to decipher AI output and incorporate it within their operations.

(5) Establishing appropriate data governance structures to ensure data security, privacy, and interoperability among various departments in municipal governments.

(6) Through the incorporation of AI-based waste management systems, make sustainable waste management policies into national agendas under smart cities and environmentally sustainable initiatives.

8. Further future research

Although this current study specifically deals with the different applications of AI in waste collection and optimization of routes, there still remain several areas of investigation to be undertaken in the coming days. Firstly, waste sorting and material collection processes assisted through AI facilities such as those at waste transfer and treatment stations. Second, conducting an empirical investigation on the governance and implementation of policies by policymakers.

Furthermore, with regard to further research, there is a need to conduct longitudinal research that considers the long-term operational, financial, and environmental effects of AI-based systems. Research based on various Jordanian cities and other emerging nations could improve further. Moreover, incorporation of AI-based waste management solutions with other infrastructural dimensions such as energy, transportation, and land-use planning reveals additional favourable prospects for furthering smart city development approaches.

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