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ORIGINAL RESEARCH PAPER

Optimal Siting and Feasibility Analysis of Recycling Stations for Sustainable Urban Waste Management Using a GIS-Based Location–Allocation Model: A Case Study of Kerman City

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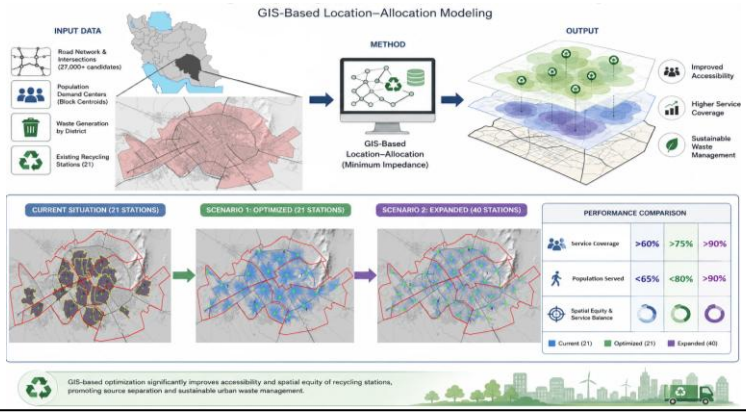
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A B S T R A C T

Developing effective recycling infrastructure is essential for sustainable municipal solid waste management, particularly in rapidly expanding urban environments. Recycling stations are pivotal in fostering source separation, boosting material recovery, and minimizing landfill dependence, though their success relies heavily on spatial accessibility and service coverage. This research evaluated and optimized the spatial distribution of recycling stations in Kerman, Iran, utilizing a Geographic Information System (GIS)-based Location–Allocation model. The study integrated urban road network data, population demand centers, waste generation rates across five municipal districts, and the specific locations of 21 existing recycling stations. Initial assessment of the current network revealed significant spatial imbalances, as numerous densely populated neighborhoods lacked adequate access to essential services. Consequently, two planning scenarios were examined: optimizing the existing 21 stations and expanding the network to 40 stations. The optimization scenario enhanced service coverage and accessibility without requiring additional facilities, underscoring the benefits of spatial reallocation for improving network performance. Furthermore, the expansion scenario proved highly effective, placing over 90% of residents within a 300-meter walking distance of a station while substantially mitigating service gaps in previously underserved areas. These findings demonstrate that integrating GIS-based spatial analysis with Location–Allocation modeling significantly improves spatial equity, encourages public participation in source separation initiatives, and bolsters the overall efficiency and long-term sustainability of municipal waste management systems within the city.



1. Introduction

Municipal solid waste management (MSWM) has emerged as one of the most significant environmental, economic, and managerial challenges facing urban areas in recent decades. Rapid urban population growth, physical expansion of cities, increasing consumerism, and changes in production and consumption patterns have led to substantial increases in both the quantity and complexity of municipal waste streams, placing considerable pressure on waste management infrastructure. In this context, the inefficiency of conventional

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waste collection and disposal systems has highlighted the urgent need for more sustainable and intelligent waste management approaches. According to the integrated waste management framework, waste reduction, source separation, recycling, and the reintegration of recoverable materials into production and consumption cycles constitute key strategies for achieving sustainable urban development [1]. Consequently, the development of infrastructure for the collection and recycling of dry recyclable waste has become a major priority for urban management, particularly in developing countries. Among the various components of urban recycling systems, recycling stations and collection centers for source-separated waste serve as critical interfaces between citizens and formal waste management systems. In addition to encouraging public participation in source separation programs, these facilities can contribute to reducing landfill disposal volumes, lowering transportation and disposal costs, increasing recycling rates, and improving the economic efficiency of municipal waste management systems [2]. However, the effectiveness of such infrastructure is highly dependent on its spatial distribution and appropriate location. Factors such as accessibility for residents, proximity to population centers, connectivity to urban transportation networks, distance from incompatible land uses, and spatial equity in service provision are among the key determinants influencing the success of recycling stations.

In recent years, Geographic Information Systems (GIS), remote sensing technologies, and multi-criteria decision-making models have become essential tools for planning and siting waste management infrastructure. Numerous studies have demonstrated that GIS-based spatial analyses can play an important role in identifying optimal locations for waste management facilities, reducing implementation costs, and improving the efficiency of waste collection and recycling systems. Billa and Pradhan [3] employed GIS-based modeling to identify suitable locations for waste transfer and separation facilities in Malaysia and demonstrated that integrating environmental, social, and economic criteria can lead to more efficient site selection with fewer social conflicts. Similarly, Farahbakhsh and Forghani [4], in a study conducted in Kerman, utilized GIS, the Analytic Hierarchy Process (AHP), and vehicle routing models to determine optimal locations for waste collection and separation centers, emphasizing the importance of social and cultural factors in the success of these facilities. Beyond purely spatial analyses, recent studies have increasingly focused on the managerial, economic, and social dimensions affecting the performance of urban recycling systems. Vahidi et al. [5] demonstrated that a substantial proportion of valuable waste collection in Kerman is conducted through informal recycling networks, which directly influence the performance of the formal waste management system. Furthermore, the findings of Vahidi et al. [6] indicated that the implementation of managerial instruments, economic incentives, and the regulation of recycling-related activities can significantly enhance public participation and improve the efficiency of formal waste collection systems. These findings further highlight the importance of developing accessible and well-organized infrastructure for the delivery of source-separated waste, including recycling stations.

Despite these advances, the effectiveness of recycling programs largely depends on the spatial accessibility of recycling infrastructure. In many cities, particularly in developing countries, the inefficiency of conventional waste collection and disposal systems has resulted in environmental pollution, escalating municipal management costs, land occupation, and deterioration of urban environmental quality. Under such circumstances, transitioning toward modern waste management strategies—including source separation, recycling, reuse, and landfill diversion—has become a central objective of urban planning. According to integrated waste management principles, the development of waste collection and recycling infrastructure can reduce landfill dependency, conserve natural resources, decrease transportation and disposal costs, and enhance urban environmental sustainability [1]. Within this framework, recycling stations and collection centers for source-separated waste have gained increasing importance as critical links between citizens and formal waste management systems. By providing residents with convenient opportunities to deliver recyclable dry waste, these facilities contribute significantly to enhancing public participation, increasing recycling rates, and promoting a culture of source separation. Nevertheless, the success of such facilities largely depends on their spatial allocation and accessibility. Poorly distributed recycling stations, excessive distance from residential areas, inadequate accessibility, and insufficient consideration of neighborhood social and physical characteristics may reduce citizen participation and compromise the effectiveness of recycling systems. Consequently, identifying optimal locations for recycling stations has become a key issue in urban planning and waste management.

Location theory and maximum coverage models seek to enhance service efficiency by minimizing travel distances and maximizing population coverage. Location–Allocation models developed within GIS environments are based on these principles and utilize road network data, population centers, and candidate sites to identify the most suitable locations for urban facilities [7,8]. Over recent decades, GIS and multi-criteria decision-making techniques have become indispensable tools for spatial analysis in waste management planning. These technologies facilitate the simultaneous evaluation of environmental, social, economic, and physical criteria, thereby improving the accuracy of decisions related to urban infrastructure siting. Billa and Pradhan [3] assessed suitable locations for waste transfer and separation stations in Malaysia using GIS-based modeling. Their findings revealed that criteria such as distance from residential areas, accessibility to major roads, proximity to industrial zones, and minimization of social conflicts play significant roles in optimal site selection. The study further demonstrated that GIS applications can reduce transportation costs and improve the efficiency of waste collection and recycling systems. Following this approach, numerous studies worldwide have adopted GIS-based multi-criteria decision-making models for siting waste management infrastructure.

A considerable proportion of previous research has focused on landfill siting and waste transfer station location selection. Mussa and Suryabhagavan [9], in a study conducted in Logia City, Ethiopia, employed the Analytic Hierarchy Process (AHP) and GIS-based overlay analysis to identify suitable landfill sites. Their analysis incorporated criteria such as terrain slope, distance from water resources, distance from residential areas, road networks, land-use patterns, and geological conditions. The results demonstrated that integrating multi-criteria decision-making techniques with spatial analyses can substantially reduce the environmental and social risks associated with inappropriate waste disposal. Similar findings have been reported by Ambaneh [10], Asefa and Mindahun [11], and Kebede and Ayenew [12], all of whom emphasized the effectiveness of geomatics technologies and spatial analysis tools in supporting accurate decision-making and optimal site selection for waste management infrastructure. In addition to landfill siting studies, several researchers have investigated the optimization of waste collection networks and recycling service distribution in urban environments. In Iran, numerous studies have focused on improving waste management infrastructure in major metropolitan areas. Ghobadi et al. [13], in Khorramabad, demonstrated that GIS-based analyses incorporating population density, road accessibility, and distance from residential areas can significantly reduce waste collection costs. Rahimi Madiseh et al. [14], in Isfahan, concluded that optimized placement of waste containers not only reduces visual pollution but also improves citizen satisfaction and public participation. Likewise, Farahbakhsh and Forghani [4] utilized GIS, AHP, and vehicle routing models to identify optimal locations for waste collection and separation centers in Kerman. One of the most distinctive aspects of their study was the inclusion of “waste separation culture” as a key siting criterion. Their findings indicated that the success of recycling stations depends not only on physical characteristics but also on social and cultural factors.

International experiences have likewise demonstrated successful approaches to optimizing waste collection and recycling systems. In European countries such as Germany and the Netherlands, the implementation of underground waste containers, intelligent collection systems, and automated waste reception technologies has substantially increased recycling rates while reducing collection costs. In Germany, the deposit-return system (Pfand) and the widespread use of Reverse Vending Machines have significantly improved the recovery rates of bottles and recyclable materials [2]. Similarly, in Asian countries such as Japan and South Korea, household-level waste segregation and multi-stream collection systems have resulted in remarkably high levels of public participation. These experiences indicate that successful recycling systems require not only infrastructure development but also effective spatial planning, convenient accessibility, and the promotion of environmental awareness among citizens. More recently, several studies have attempted to integrate managerial dimensions and social dynamics into spatial analyses of waste management systems. Wang et al. [15] combined GIS and System Dynamics modeling to develop a framework for waste management facility siting that incorporated not only spatial criteria but also variables such as population growth, waste generation trends, and infrastructure capacity. Their findings demonstrated that waste management infrastructure siting is not merely a physical planning issue but is strongly influenced by economic, social, and managerial factors. Continuing this line of research, Vahidi et al. [5] and Vahidi et al. [6] examined the interaction between formal and informal valuable-waste collection systems in Kerman. Their findings revealed that a substantial proportion of urban recycling activities are conducted by informal networks and that policies related to source separation and recycling infrastructure development should be formulated with a clear understanding of the economic and social relationships among formal and informal stakeholders.

A review of the existing literature indicates that while numerous studies have addressed landfill siting, transfer station location selection, and optimization of waste collection networks, comparatively limited attention has been devoted to the siting of recycling stations and source-separated waste collection centers from a citizen participation perspective. Furthermore, many previous studies have not adequately addressed issues related to spatial equity in recycling service distribution, accessibility across different urban neighborhoods, and the socio-cultural characteristics of service areas. Despite its unique climatic conditions, spatial population distribution, and the growing importance of sustainable waste management, Kerman has not yet been the subject of a comprehensive study focused on the optimal siting of recycling stations using Location–Allocation models. Accordingly, the present study aims to develop an optimal spatial framework for recycling station allocation in Kerman City by employing a GIS-based Location–Allocation model and incorporating environmental, demographic, physical, and service-related criteria. In addition to spatial analysis, the study considers the social and managerial dimensions associated with citizen participation in source separation programs. The findings are expected to contribute to the development of intelligent and

sustainable municipal waste management systems and to promote greater spatial equity in the distribution of recycling services.

Unlike previous studies that primarily focused on landfill siting and transfer stations, this study specifically addresses the optimization of recycling stations at the neighborhood scale while incorporating accessibility and spatial equity considerations through a GIS-based Location–Allocation approach.

2. Method

The present study is classified as applied research in terms of its objective and as descriptive–analytical research in terms of its methodological approach. The study was conducted with the aim of evaluating and optimizing the spatial allocation of recycling stations in Kerman City. The methodological framework was based on Location–Allocation modeling within a Geographic Information System (GIS) environment, and the analytical procedures were designed according to the principles and methodologies proposed by Daskin [8] and Malczewski [16]. Overall, the research process consisted of four main stages: (i) data collection and preparation, (ii) assessment of the existing recycling station network, (iii) implementation of Location–Allocation models under different scenarios, and (iv) validation and field verification of the obtained results.

2.1. Data Collection and Preparation

The datasets used in this study were categorized into four primary groups:

1.Urban transportation network data, including the road network and intersections of Kerman City, comprising more than 27,000 intersection points that served as candidate locations for recycling station allocation. The road network dataset was obtained from Kerman Municipality GIS database and verified through field observations;

2.Population and demand data, represented by the centroids of residential urban blocks and population distribution patterns across the city;

3.Municipal solid waste generation data, including waste production rates within the five municipal districts of Kerman City;

4.Existing recycling station data, consisting of the geographic locations of the 21 currently operating recycling stations.

Following data acquisition, all spatial datasets were processed within the ArcGIS (10.8) environment and converted into Shapefile format to facilitate network analysis and spatial modeling procedures. To ensure analytical accuracy and consistency, all spatial layers were examined and corrected with respect to coordinate systems, network topology, connectivity, and spatial overlap. Particular attention was given to the integrity of the transportation network dataset, as accurate network connectivity is essential for reliable accessibility and Location–Allocation analyses.

2.2. Assessment of the Existing Recycling Station Network

The first stage of analysis focused on evaluating the current configuration of recycling stations throughout Kerman City. For this purpose, the Location–Allocation tool within the ArcGIS Network Analyst extension was employed to assign each demand point to its nearest recycling station based on network distance.

Service coverage and accessibility were assessed under two pedestrian accessibility scenarios with service radii of 300 m and 500 m. These thresholds were selected based on previous studies addressing urban service accessibility and citizen travel behavior related to neighborhood-scale facilities [۷]. The outputs generated at this stage included service coverage maps, service areas associated with each recycling station, and estimates of the population served by individual facilities. These results provided a basis for identifying spatial deficiencies, service gaps, and inefficiencies within the existing recycling infrastructure network.

2.3. Scenario 1: Optimization of the Existing Recycling Station Network

The first optimization scenario was designed to evaluate the potential improvement of the recycling station network through the relocation and optimal redistribution of the existing 21 facilities. In this scenario, all intersections within the urban road network were introduced into the model as candidate facility locations. The model was required to select 21 optimal locations from among these candidate sites in such a manner that the total weighted travel distance between demand points and their nearest recycling station was minimized.

The Minimum Impedance algorithm was employed for this purpose. Minimum Impedance was selected because minimizing travel distance was considered the primary objective of the study. This algorithm is among the most widely used Location–Allocation approaches in urban service planning and accessibility analysis [8]. Under this framework, the network distance between demand locations and the nearest facility is defined as the objective function, and the model identifies facility locations that minimize overall accessibility costs. The results of this scenario enabled a direct comparison between the existing distribution of recycling stations and the optimized spatial configuration proposed by the model.

The Minimum Impedance model seeks to minimize the cumulative weighted network distance between demand points and candidate facilities. Unlike Euclidean optimization approaches, the algorithm utilizes actual travel distances along the urban road network, thereby providing more realistic accessibility estimates. Each demand point is assigned to its nearest facility while the optimization process iteratively searches for the combination of candidate locations that minimizes the total travel cost. In the present study, residential block centroids represented demand points, whereas road intersections served as candidate facility locations.

2.4. Scenario 2: Expansion of the Recycling Station Network

The second scenario investigated the effects of increasing the number of recycling stations on service coverage and citizen accessibility. In this stage, the Location–Allocation model was executed using the same analytical structure and parameter settings as those applied in Scenario 1; however, the number of facilities was increased from 21 to 40 recycling stations.

The expansion to 40 recycling stations was selected based on preliminary spatial simulations conducted during the planning phase together with recommendations from the Kerman Municipality Waste Management Organization. Several alternative scenarios were initially evaluated, and the 40-station scenario represented the most balanced solution capable of providing citywide accessibility (more than 90% population coverage within 300 m) while remaining economically and operationally feasible.

The primary objective of this scenario was to determine whether expanding the recycling station network could enhance spatial equity, reduce accessibility distances, and improve service provision in underserved urban areas. Similar to the previous scenario, the optimization process was based on minimizing network distances between demand points and their nearest recycling station [16]. The outputs generated under this scenario included maps of the proposed recycling station distribution, quantitative assessments of changes in service coverage, and comparative analyses of accessibility indicators under existing and proposed network configurations.

2.5. Validation and Field Verification

To enhance the reliability and practical applicability of the results, a validation and field verification stage was incorporated into the research framework. During this phase, the candidate locations identified by the Location–Allocation model were evaluated with respect to their feasibility for physical implementation.

Several criteria were considered during this assessment, including.

- Accessibility and ease of public access;
- Traffic safety considerations;
- Land ownership and availability;
- Physical suitability for station installation;
- Compatibility with surrounding land uses;
- Absence of conflicts with sensitive urban functions; and;
- Operational feasibility and implementation potential.

Furthermore, selected proposed locations were compared with actual field conditions to ensure that the model-generated solutions were compatible with real-world urban environments. This verification process played a critical role in translating theoretical optimization outcomes into practical and implementable planning alternatives [14].

The evaluation criteria used in this study—including accessibility, traffic safety, land availability, compatibility with surrounding land use, and implementation feasibility—were identified through three complementary sources: (i) a review of previous GIS-based facility location studies, (ii) municipal waste management regulations and planning documents, and (iii) expert consultation sessions with engineers and managers of the Kerman Municipality Waste Management Organization.

Finally, the integrated results of the GIS-based spatial analyses and field evaluations were utilized to develop an optimal spatial allocation framework for recycling stations in Kerman City. The proposed framework provides a scientifically grounded basis for improving accessibility, enhancing service coverage, and promoting more efficient and equitable municipal recycling infrastructure.

Before applying the proposed GIS-based Location–Allocation model, it is essential to understand the geographical, demographic, and waste management characteristics of the study area. These characteristics directly influence spatial demand patterns, accessibility analyses, and the optimization of recycling

station locations. Therefore, a brief overview of Kerman City is presented below.

2.6. Study Area

Kerman City, the capital of Kerman Province, is located in southeastern Iran and is recognized as one of the most important population, economic, and service centers in the region. According to the latest national census conducted by the Statistical Center of Iran (2016), Kerman City has a population of approximately 537,718 inhabitants. This population distribution constitutes the primary source of municipal solid waste generation and forms the basis for estimating service demand within the present study. The city is situated at an elevation of approximately 1,756 m above sea level and is characterized by a hot arid climate, with an average annual precipitation ranging from approximately 130 to 150 mm. Limited water resources, high evaporation rates, frequent dust dispersion, and prolonged dry climatic conditions have made environmental management issues—particularly municipal solid waste management—highly significant in the city. Under such circumstances, deficiencies in waste collection, storage, and recycling systems may adversely affect urban environmental quality, public health, and the overall urban landscape.

From an administrative perspective, Kerman City is divided into five municipal districts and twelve urban zones (Figure 1). Variations in urban morphology, population density, land-use patterns, and levels of socioeconomic development among different districts have resulted in substantial differences in waste generation rates and spatial waste distribution patterns. Based on municipal records and field surveys, the daily generation of municipal solid waste varies considerably among the city's districts, ranging from approximately 18 tons day^{-1} in District 5 to more than 103 tons day^{-1} in District 3. The total municipal solid waste generation in Kerman is estimated at approximately 325 tons per day (Table 1).

Table 1. Municipal solid waste generation in the five municipal districts of Kerman

Municipal District	Daily Waste Generation (ton/day)
District 1	50.1
District 2	93.8
District 3	103.1
District 4	59.9
District 5	18.1

Source: Research findings

As shown in Table (1), municipal solid waste generation varies considerably among the five municipal districts, reflecting differences in population density, land use characteristics, and socioeconomic conditions.

The composition of municipal waste in Kerman includes a substantial proportion of organic materials as well as recyclable dry waste fractions such as plastics, paper, metals, and glass. This composition indicates considerable potential for expanding recycling activities and reducing landfill dependency. Nevertheless, a significant proportion of these valuable waste streams still enters the landfill disposal system or is recovered through informal collection networks, creating economic, managerial, and environmental challenges for the municipality [7].

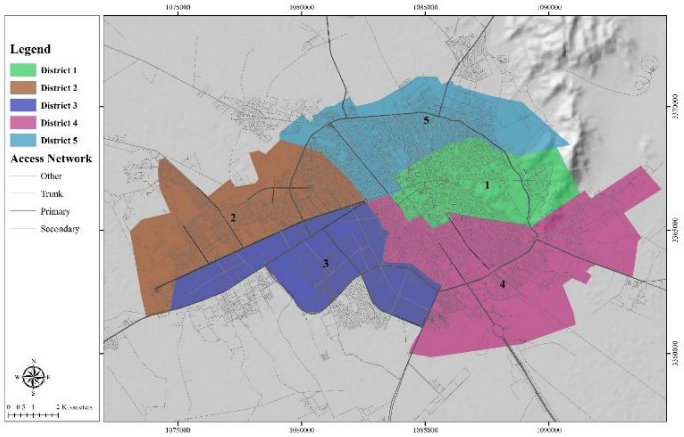


Figure 1. Geographic location and administrative divisions of Kerman City

.At present, 21 recycling stations are operating throughout Kerman City. These facilities are responsible for receiving source-separated recyclable dry waste from residents and constitute an important component of the formal municipal waste management infrastructure. Recycling stations play a crucial role in promoting source separation practices and increasing public participation in recycling programs.

However, field observations and spatial analyses indicate that the current distribution of recycling stations does not follow an efficient spatial pattern and exhibits considerable imbalance across the urban area. In some districts, particularly central and relatively developed neighborhoods, recycling stations are relatively concentrated, whereas many densely populated, peripheral, and underserved areas lack adequate access to recycling services. Figure (2) illustrates the current spatial distribution of recycling stations across Kerman City.

This uneven distribution not only reduces spatial equity in the provision of municipal services but may also limit citizen participation in source separation and recyclable waste delivery programs. Previous studies have demonstrated that accessibility and convenience of recycling infrastructure are among the most influential factors affecting public participation in waste management initiatives [4]. Furthermore, the hot and arid climatic conditions of Kerman, combined with the potential for waste dispersion within urban spaces, further emphasize the importance of developing efficient collection and recycling infrastructure.

Under these circumstances, the scientific and optimal allocation of recycling stations can play a significant role in reducing uncontrolled waste disposal, improving environmental hygiene, increasing recycling rates, and enhancing the overall efficiency of the municipal solid waste management system.

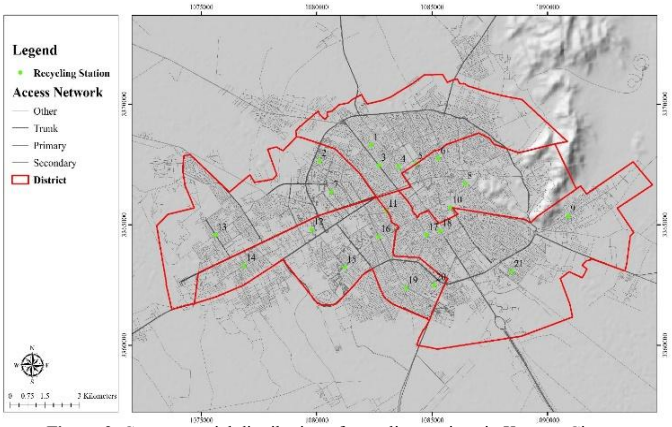


Figure 2. Current spatial distribution of recycling stations in Kerman City

3. Results and Discussion

3.1. Analysis of the Current Situation

The evaluation of the current distribution of recycling stations in Kerman City indicates that the spatial allocation pattern of these facilities is neither balanced nor systematically organized. The spatial distribution map of existing recycling stations (Figure 3) reveals that a substantial proportion of the 21 active stations are concentrated in central, relatively well-serviced, and more accessible urban areas, forming a clustered distribution pattern.

In contrast, many densely populated and developing urban districts, particularly parts of Districts 2 and 3, lack adequate coverage of recycling services. This spatial imbalance has resulted in limited accessibility for residents in several neighborhoods, where the distance to the nearest recycling station exceeds 1 km in some cases. This value is significantly higher than the desirable walking accessibility threshold for neighborhood-level recycling services, which is approximately 300 m. Such excessive travel distances can play a critical role in reducing citizen participation in source separation and recyclable waste delivery programs.

Beyond spatial distribution inefficiencies, field investigations also indicate that a number of existing recycling stations are constrained by physical and operational limitations. Many of these facilities have been implemented as small, temporary container-based structures (portable kiosks) and lack appropriate infrastructure for the proper storage of dry recyclable materials, the presence of dedicated operational staff, or the provision of auxiliary services to citizens.

In several cases, limited spatial capacity, suboptimal design, and inappropriate placement along urba n road edges have negatively affected the functional performance of these facilities. Furthermore, the absence of adequate amenities and supporting infrastructure may adversely influence service quality, citizen willingness to utilize these stations, and the overall urban visual environment.

These observations suggest that the issue of recycling stations in Kerman City is not merely a question of their number. Rather, their spatial allocation, physical quality, accessibility level, and compatibility with the urban spatial structure require comprehensive reassessment and optimization. In essence, if a recycling station resembles an overlooked temporary container placed on the roadside, it is unlikely that citizens will perceive it as part of a modern and efficient municipal solid waste management system.

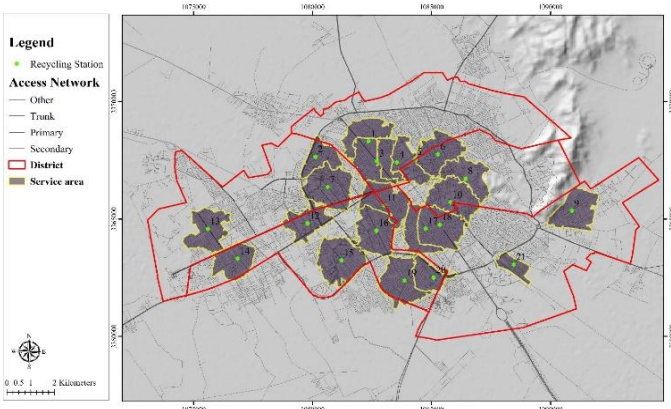


Figure 3. Service area overlap of recycling stations in Kerman City based on the current coverage radius

3.2. Scenario 1: Relocation of 21 Recycling Stations (Optimization)

In the first scenario, the Location–Allocation model was applied while maintaining the existing number of recycling stations (21 facilities) in order to identify and propose optimal spatial locations for their relocation. The primary objective of this scenario was to enhance the efficiency of the recycling service network through spatial redistribution of facilities, without incurring additional costs associated with establishing new stations.

The results of the model indicated that the optimized configuration exhibits a more balanced and efficient spatial distribution compared to the current condition. As illustrated in Figure (4), a considerable concentration of recycling stations in the central urban areas was reduced, and the facilities were redistributed more evenly across different districts of the city. This spatial reallocation enabled previously underserved areas, which lacked adequate access to recycling services, to be brought under service coverage.

The analytical results demonstrated that the optimal siting of recycling stations in this scenario significantly improved service coverage at the local scale. Many densely populated and underserved neighborhoods that were outside the effective service areas under the current configuration became connected to the nearest recycling stations in the optimized model, resulting in reduced accessibility distances for residents.

This improvement contributes not only to enhancing spatial equity in urban service provision but also plays a key role in increasing public participation in source separation and recyclable waste delivery programs. Furthermore, the findings indicate that even without increasing the number of facilities or incurring additional infrastructural costs, substantial improvements in the performance of the urban recycling network can be achieved solely through spatial reconfiguration and the application of Location–Allocation modeling techniques.

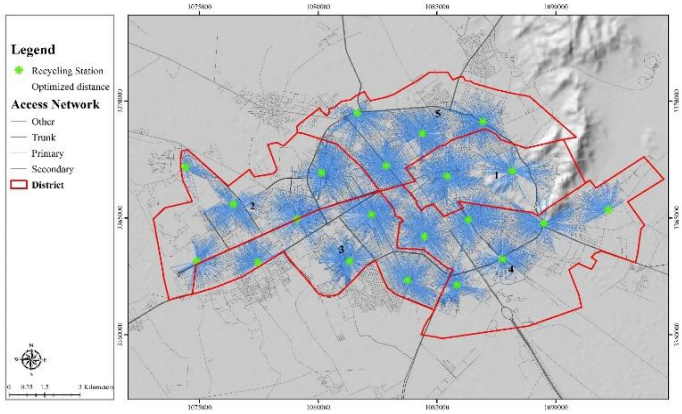


Figure 4. Optimized spatial allocation of recycling stations in Kerman City (Scenario 1 – 21 stations)

3.3. Scenario 2: Expansion of Recycling Stations to 40 Units

In the second scenario, in order to evaluate the impact of expanding the recycling infrastructure on citizen accessibility, the number of recycling stations was increased from 21 to 40, and the Location–Allocation model was re-executed using the same analytical framework. The results revealed that increasing the number of recycling stations has a substantial positive effect on improving service coverage and reducing accessibility distances for residents. As shown in Figure (5), the spatial distribution of the proposed stations in this scenario is more balanced, and a significant proportion of existing service gaps across the city has been effectively covered.

Network-based analyses indicated that, on average, the service radius of each recycling station decreased by approximately 30%, leading to a marked improvement in local accessibility to recycling stations. According to the results, more than 90% of Kerman's residents would be located within a 300-meter walking distance of a recycling station, which is consistent with standard benchmarks for neighborhood-level urban services.

This improvement is particularly pronounced in densely populated, peripheral, and underserved areas that remained inadequately served under both the current configuration and Scenario 1. The reduction in accessibility distance can significantly contribute to increasing citizen participation in source separation programs, reducing illegal or informal waste disposal in urban spaces, and enhancing the volume of recyclable materials delivered to the formal municipal waste management system.

Moreover, the results of this scenario demonstrate that the quantitative expansion of recycling station networks, when combined with scientifically based spatial optimization, can effectively enhance spatial equity in municipal waste management service distribution.

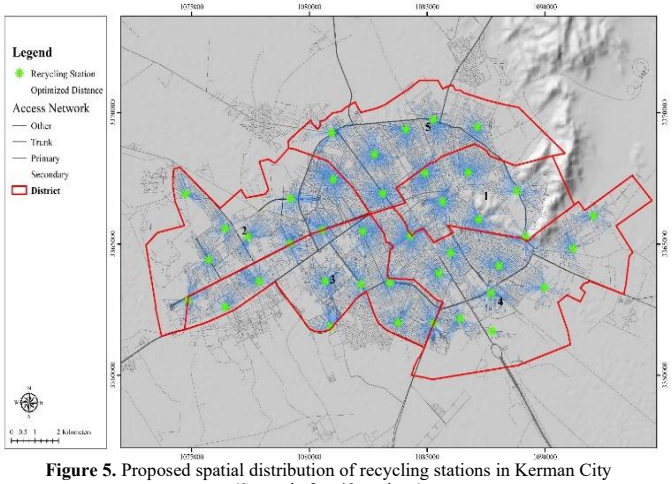


Figure 5. Proposed spatial distribution of recycling stations in Kerman City (Scenario 2 – 40 stations)

To provide a concise comparison of the evaluated alternatives, Table (2) summarizes the principal performance indicators of the existing recycling network and the two proposed Location–Allocation scenarios. The comparison highlights improvements in service coverage, and population served following spatial optimization and network expansion.

Table 2. Performance Comparison of the Existing and Optimized Recycling Station Networks

Indicator	Existing	Scenario 1 (Optimized 21 Stations)	Scenario 2 (40 Stations)	Improvement vs Existing
Number of stations	21	21	40	+90.5%
Service coverage (%)	>60	>75	>90	+46.8%
Population served (%)	<65	<80	>90	+40.6%

Source: Research findibngs

The comparative results indicate that optimizing the spatial distribution of existing recycling stations substantially improves network efficiency without increasing infrastructure costs. Nevertheless, the expansion scenario achieved the highest performance across all evaluated indicators, demonstrating that the combination of GIS-based spatial optimization and strategic network expansion offers the most effective solution for enhancing accessibility, spatial equity, and the operational efficiency of municipal recycling services in Kerman City.

The results of this study indicate that the current distribution of recycling stations in Kerman City does not follow a balanced spatial pattern, and the existing siting strategy has failed to provide adequate service coverage across all urban areas. The observed concentration of facilities in central and relatively well-served districts, alongside the pronounced lack of services in densely populated and underserved neighborhoods, reflects the absence of a systematic and scientifically grounded planning approach in the deployment of this infrastructure.

These findings are consistent with previous studies conducted in other Iranian cities. Ghobadi et al. [13], in Khorramabad, and Rahimi Madiseh et al. [14], in Isfahan, similarly demonstrated that the inappropriate spatial distribution of waste collection and recycling infrastructure not only increases operational costs but also reduces service efficiency and leads to citizen dissatisfaction. Moreover, the study by Farahbakhsh and Forghani [4] in Kerman highlighted that insufficient attention to the spatial configuration of waste collection

facilities can significantly reduce public participation in source separation programs. Accordingly, the present study confirms that the primary challenge in many municipal solid waste management systems is not merely infrastructure scarcity, but rather the spatial allocation pattern and service accessibility, both of which play a decisive role in system performance. The results of Scenario 1 demonstrated that substantial improvements in the efficiency of the existing network can be achieved without increasing the number of facilities, solely through spatial redistribution and scientifically based relocation. The Location–Allocation model, while maintaining 21 stations, significantly improved service coverage and enhanced accessibility in previously underserved areas. This finding underscores the importance of GIS-based spatial analysis and location optimization models in improving urban service delivery systems.

International studies also support these findings. Billa and Pradhan [3] showed that GIS-based optimization can reduce transportation costs, travel times, and social conflicts by identifying more suitable facility locations. Therefore, Scenario 1 of this study demonstrates that analytical spatial modeling can enhance system efficiency without imposing substantial infrastructure development costs. Despite the improvements achieved in Scenario 1, the results of Scenario 2 revealed that achieving adequate spatial coverage and urban service equity requires an expansion of the recycling station network. Increasing the number of stations to 40 resulted in more than 90% of the population being located within a 300-meter walking distance of a recycling facility. This outcome aligns with service accessibility standards observed in developed countries.

In European countries such as Germany and the Netherlands, one of the key principles underlying successful recycling systems is the provision of convenient, localized access to waste delivery infrastructure [2]. Similarly, in Japan and South Korea, the development of neighborhood-scale collection networks and multi-stream waste separation systems has significantly increased recycling rates and public participation [1]. Accordingly, the findings of this study suggest that combining quantitative expansion of infrastructure with scientifically optimized spatial planning can significantly enhance spatial equity, reduce accessibility gaps, and improve citizen participation in source separation programs. Another important finding of this study relates to the role of physical and infrastructural conditions in the effectiveness of recycling stations. Field observations revealed that many existing stations suffer from inadequate physical design, limited operational capacity, and insufficient supporting facilities. The use of small container-based structures, lack of proper storage space for sorted waste, absence of digital weighing and recording systems, and insufficient amenities for operators were among the key limitations identified. This indicates that the success of recycling infrastructure is not solely dependent on optimal spatial allocation but also on the physical and functional quality of facilities. In many developed countries, recycling stations are designed as integral components of modern urban services, incorporating aesthetic considerations, smart technologies, and user-friendly features alongside waste collection functions. Therefore, future development of recycling infrastructure in Kerman should integrate spatial optimization with physical redesign and technological upgrading of facilities.

Finally, the results highlight that urban recycling system planning should extend beyond purely spatial considerations and incorporate social, managerial, and economic dimensions. Studies by Vahidi et al. [5,6] demonstrated that a significant proportion of valuable waste in Kerman is collected through informal networks, which directly influence the efficiency of the formal municipal system. In this context, expanding formal recycling stations can serve as an effective mechanism to strengthen the formal system, enhance managerial control, and increase public participation. Additionally, reducing accessibility distances can encourage higher delivery rates of recyclable materials and reduce uncontrolled waste disposal in urban spaces.

3.4. Policy and Environmental Implications for Sustainable Urban Waste Management

The findings of this study extend beyond spatial optimization and provide important implications for municipal waste management policy and environmental sustainability. From a policy perspective, the results demonstrate that GIS-based Location–Allocation modeling can serve as an effective decision-support tool for optimizing the spatial distribution of recycling stations based on objective accessibility criteria rather than conventional planning practices. The first optimization scenario showed that substantial improvements in service accessibility can be achieved without increasing the number of recycling stations, indicating that municipalities with limited financial resources may significantly enhance recycling services through spatial reconfiguration alone. Conversely, the second scenario demonstrated that strategic expansion of the recycling network can further improve spatial equity and ensure convenient access to recycling stations for the vast majority of urban residents. These findings provide practical guidance for municipalities seeking to maximize service efficiency while minimizing unnecessary infrastructure investments.

From an environmental perspective, improving accessibility to recycling stations is expected to generate multiple environmental benefits by facilitating greater public participation in source separation programs. Shorter walking distances and improved convenience increase the likelihood that residents will deliver recyclable materials to the formal collection system rather than disposing of them as mixed municipal waste. Consequently, greater recovery of recyclable materials can reduce the volume of waste transported to landfill sites, decrease greenhouse gas emissions associated with waste collection and disposal, conserve natural resources through material recovery, and reduce environmental pollution caused by uncontrolled waste disposal. Improved recycling accessibility may also contribute to cleaner urban environments by reducing littering and illegal dumping, particularly in densely populated neighborhoods where insufficient recycling infrastructure often discourages public participation.

Furthermore, the proposed optimization framework supports the broader objectives of sustainable urban development by promoting spatial equity in public service provision. Equitable access to recycling stations ensures that residents across different socioeconomic and geographic areas have comparable opportunities to participate in municipal recycling programs. This contributes not only to improved environmental performance but also to greater social inclusion and more efficient allocation of municipal resources. The methodological framework presented in this study is readily transferable to other developing cities facing similar challenges related to rapid urbanization, uneven service distribution, and increasing municipal solid waste generation. Integrating GIS-based spatial optimization into routine municipal planning can therefore enhance evidence-based decision-making and support the transition toward more resilient, resource-efficient, and environmentally sustainable urban waste management systems.

Beyond operational improvements, enhanced accessibility to recycling stations supports the transition toward a circular economy by increasing the recovery of recyclable materials and reducing the consumption of virgin resources. By strengthening the formal recycling system and encouraging higher participation in source separation programs, municipalities can improve resource efficiency, reduce environmental externalities associated with landfill disposal, and create long-term economic and environmental value. Therefore, integrating GIS-based spatial optimization into municipal recycling planning represents not only an infrastructure management strategy but also an important step toward achieving sustainable resource management and circular urban development.

4. Conclusions

This study aimed to evaluate and optimize the spatial allocation of recycling stations in Kerman City using a Location–Allocation model within a Geographic Information System (GIS) environment. The spatial analyses revealed that the current distribution of recycling stations does not follow an efficient or balanced pattern, and a considerable proportion of urban areas—particularly densely populated and underserved districts—lack adequate access to recycling services. The clustered distribution of stations in central urban areas has led to inequities in service provision, with accessibility distances in some neighborhoods significantly exceeding the acceptable standards for neighborhood-level services. This spatial imbalance may contribute to reduced citizen participation in source separation and lower rates of recyclable waste delivery to the formal system. The results of Scenario 1 demonstrated that substantial improvements in service coverage can be achieved without increasing the number of facilities, solely through spatial reallocation of the existing 21 recycling stations. The Location–Allocation model effectively redistributed facilities in a more balanced manner, significantly reducing accessibility gaps and improving coverage in previously underserved areas. This finding indicates that the application of spatial analytical methods can enhance the efficiency of existing infrastructure without requiring substantial capital investment.

However, the results of Scenario 2 indicated that achieving optimal spatial coverage and urban service equity requires quantitative expansion of the recycling station network. Increasing the number of stations to 40 reduced average accessibility distances by approximately 30%, and more than 90% of the urban population was placed within a 300-meter walking distance of a recycling facility. This improvement was particularly significant in densely populated and underserved areas that remained inadequately served under both the current configuration and Scenario 1. Accordingly, the findings suggest that combining scientifically optimized spatial planning with gradual infrastructure expansion can significantly enhance public participation, increase recycling rates, and improve spatial equity in municipal service delivery. The study further revealed that the success of recycling programs is not limited to optimal spatial allocation. Physical and functional characteristics of recycling stations play a crucial role in system performance. Many existing facilities suffer from limitations in terms of size, operational infrastructure, storage capacity, and service quality. Therefore, future development strategies should integrate spatial optimization with physical redesign, modernization, and smart system implementation. The use of digital monitoring systems, sensor-based waste tracking, and standardized facility design can significantly improve efficiency and user satisfaction. Based on the findings, it is recommended that the Municipality of Kerman prioritize the implementation of Scenario 1 in the short term by optimizing the spatial allocation of existing recycling stations. In the medium term, gradual expansion of the network to 40 stations should be pursued. In addition, the development of standardized design guidelines for recycling stations—including adequate space allocation, operator facilities, storage systems, and smart technologies—is essential. Furthermore, establishing regional centralized recycling hubs with higher capacity for

specialized waste handling, public education, and advanced waste processing services could further enhance system efficiency and sustainability.

Author Contributions

All authors contributed equally to the conception, preparation, and writing of this manuscript.

Conflict of Interest

The authors, while observing publication ethics in the referencing, declare the absence of interest of conflict.

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