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CASE STUDY

Enhancing sustainable solid waste management through separate source collection

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ABSTRACT

BACKGROUND AND OBJECTIVES: Municipal solid waste emerges as a pressing concern for environmental management and sustainability, particularly in urban areas with high rates of population growth and limited infrastructure. This study aims to assess the outputs and benefits of a separate source collection system, which separates recyclable materials at their point of origin. The study highlights the consequences of separate source collection on the community's economic, environmental and social context. The study forms part of a project that intends to upscale sustainable and efficient waste management approaches in a transition towards a circular economy model that utilizes and recycles waste and materials. The objectives encompass addressing urban challenges and providing key insights for environmental management and sustainability through separate source collection systems that improve efficiency, reduce cost and encourage sustainable community practices.

METHODS: The study was implemented in the Al-Radwan neighborhood in Amman, Jordan, and included 8,460 individuals and 3,124 households. Data on waste generation from residential and commercial activities were analyzed and used to design the separate source collection system, which included public awareness campaigns for individuals in the study area, waste composition investigations and maps for routes of waste collection trucks. Yellow and grey bins were used to collect recyclable and residual waste, respectively. Data on waste amount and composition were collected and interpreted for the 2020-2023 period. Data on fuel consumption, maintenance and depreciation were used to calculate the operational costs of separate source collection and the old system of municipal solid waste collection. Ground data were analyzed in terms of the individual's and households' adoption of waste-sorting practices. An overall assessment was carried out for the economic benefit of separate source collection.

FINDINGS: Analyses of waste generation in the study area showed that the average quantity of municipal waste was 0.89 kilogram per capita per day, and there is a trend that shows an increase in municipal solid waste quantities with respect to time. A significant amount of municipal solid waste (60 percent) has an organic composition, while recyclable waste constitutes about 12.5 percent of the total municipal solid waste. The study was a success, with a consistent increase in recyclable waste collection at 59 percent average purity and a 30 percent decrease in total yearly waste collection costs. The project contributed to job creation and improved community participation in municipal solid waste management. The beneficial impacts of awareness campaigns were the low level of required maintenance with respect to the separate source collection system and the high level of public participation and cooperation, particularly in municipal solid waste sorting.

CONCLUSION: The study highlighted the importance and effectiveness of the innovative separate source collection system and showed its economic and social benefits while considering its positive environmental impacts. The findings confirmed the system's economic viability and applicability, showing its potential for large-scale adoption in Jordan. The adoption and implementation of separate source collection will be highly emphasized as it will be needed for solving issues associated with municipal solid waste via creative solutions that promote sustainability and community well-being.

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
37	6	2

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INTRODUCTION

Waste can be defined as any material that has lost its value, is no longer in use, or is unwanted (Mohadesi *et al.*, 2024; Samimi, 2024). Wastes, which are generated from various sources including houses, farms and manufacturers, can exist in different forms (Kan, 2009; Samimi and Nouri, 2023). Municipal solid waste (MSW) is a term applied to any solid substance that has been discarded and sourced from residential areas, offices and commercial establishments (Palanivel and Sulaiman, 2014). It primarily comprises kitchen refuse, paper, metal, glass, plastic, rubber and various other items. The composition of MSW differs from one country to another, as it is significantly influenced by lifestyle and prevailing socioeconomic factors (Abdel-Shafy and Mansour, 2018). Inadequate MSW management exerts several environmental impacts, resulting in unsightly landscapes and detrimental effects on the national economy (Abubakar *et al.*, 2022). Also, it poses a significant threat to air, ground, surface water and land quality in the urban environment (Al-Dailami *et al.*, 2022). The management of MSW can reduce the adverse impacts of solid waste by providing systematic waste administration that includes collection, transfer, storage, recycling and disposal (Al-Dailami *et al.*, 2022). As waste management plays a pivotal role in achieving sustainability in the environment, it serves as a substantial driver in the transition towards a circular economy model in which materials are utilized and recycled within a closed-loop system (Guman and Wegner-Kozlova, 2020). Recycling refers to the practice of reusing wasted resources to create new products. It involves returning waste material, such as plastics, metal and glasses, paper and cartons, into the industrial chain. These recycled materials act as alternatives to virgin resources, preserving precious natural resources, such as petroleum, forests and coal (Coelho, 2011). Despite its importance and contribution to the environment and economy, managing MSW in urban areas faces many challenges, including rapid urbanization, inadequate waste management infrastructure, the need to shift public awareness and the behavior and complexity of waste composition (Abdel-Shafy and Mansour, 2018). The shifting composition of waste, which includes large amounts of hazardous materials and electronic waste, requires the development of specific facilities and methods to manage and handle such waste types (Attia *et al.*, 2021), and responsible waste disposal practices can be fostered among urban residents via behavioral change campaigns and community engagement (Debrah *et al.*, 2021). To address these challenges, cities should create integrated waste management plans that suit specific circumstances (Voukkali *et al.*, 2023). These plans promote cleaner environments and sustainable cities (Pai *et al.*, 2014). At present, landfilling is the most common traditional practice for waste management, particularly in developing countries where waste materials are degradable and saturated (Agamuthu, 2013; Yousefi *et al.*, 2023). Despite its widespread use, landfilling has faced substantial criticism and is perceived to be incompatible with sustainability principles (Osazee, 2021). The traditional non-segregated SWM practiced with landfilling faces several challenges, including inefficient resource recovery, high disposal costs, limited recycling opportunities and increased environmental impacts, including the contamination of recyclables and the health hazards associated with waste handling methods (Vaverkova, 2019; Abubakar *et al.*, 2022). The separate source collection (SSC) system involves segregating recyclables at the point of source to facilitate efficient recycling. Implementing the SSC system provides many environmental, economic, and social benefits (Lopez *et al.*, 2015). By separating recyclable materials at their point of origin, recycling practices become more efficient (Gunaseelan *et al.*, 2023). This not only reduces contamination in recyclables but also enhances the overall quality of materials, making them more suitable for recycling processes (Dolipas *et al.*, 2020; Stoeva and Alriksson, 2017). As part of the SSC system, waste separation at the source promotes energy recovery (Johnson *et al.*, 2013; Rajkamal *et al.*, 2014), minimizes landfill usage, reduces greenhouse gas (GHG) emissions (Al-Dailami *et al.*, 2022) and contributes to cost savings in waste management (Rangga *et al.*, 2022). In developed countries, the reduction in GHG (namely, carbon dioxide) reached more than 17 percent (%) when the SSC was enforced (Zhang *et al.*, 2023). Although the benefits of SSC have been indicated by many studies and its contribution to the circular economy is evident (Maletz *et al.*, 2018), its implementation and adoption require further investigation, as environmental and socioeconomic factors may not fully support these systems. In developing countries, community

perceptions on the provision of facilities for waste segregation and financial returns to the community from recycling business are important in order to promote the adoption of SSC systems (Kihila *et al*., 2021; Yeboah *et al*., 2021; Rangga *et al*., 2022). Upscaling SSC systems requires detailed analyses of data from pilot programs. The analysis shall include figures on waste amounts and composition, assessments of community participation and the periodic evaluation of the design and operation of the system. This study was implemented in an urban area in Amman City in Jordan to investigate the operation of the SSC and assess its benefits. The study holds considerable importance, as it delves into economic, environmental, and social aspects that SSC can affect. SSC has emerged as a multilateral solution, providing economic benefits by reducing the operational costs of the collection system and improving recycling efficiency. The study was conducted inside the Al-Radwan neighborhood in Amman as an example of an urban area that has both residential and commercial activities. Amman is the Capital of Jordan and has a population of 4.7 million, which represents 42 percent (%) of the country's population (DOS, 2022). Approximately half of the MSW in Jordan is directed to the Al-Ghabawi Landfill, while the remaining half is openly dumped across 17 disposal sites (Abu Hajar *et al*., 2020). The average organic composition of MSW in Jordan is estimated to be 51%, while plastic and cardboard comprise 13% each (MOMA, 2014). The presence of a high organic content in landfills poses several environmental and operational risks. One significant concern is the potential for methane gas generation during the anaerobic decomposition of organic materials (MOE, 2020). High organic contents can lead to the production of leachate, which may contain pollutants and contaminants, posing high risks to both ground and surface water quality (Ma *et al*., 2021). This study hypothesizes that the implementation of the SSC system in the urban area will improve economic efficiency, environmental sustainability and social well-being. This study is at the cutting edge of waste management innovation, employing the SSC system in the urbanized area of Al-Radwan, Amman, Jordan. The study not only explores the SSC system by comparing its aims with the critical dimensions of feasibility and suitability, but it also addresses the pressing need to identify restrictions and opportunities, as well as critical technical and financial parameters. As part of an innovative project that began in 2018 and concluded with container delivery in late 2019, the study provides a novel investigation with respect to the economic, environmental and social aspects affected by the SSC system. The study's findings have significant implications for the widespread implementation of innovative waste management strategies throughout Jordan. The study, which forms part of a pilot program, aligns with the proposed scenario for the country's MSW system and serves as a catalyst for revolutionary improvements in waste management approaches on a larger scale. Its thorough analysis and innovative approach make it an essential component of sustainable waste management as it provides an outline for feasible approaches that balance environmental issues with the changing demands of urban environments. From a broader perspective, such studies emerge as models for positive change that can create a more sustainable and resilient environment for communities at local and global scales. This study aims to assess the outputs and benefits of a separate source collection system, which separates recyclable materials at their point of origin. This study started in 2018, containers were distributed inside the study area during late 2019, and data collection and analysis were carried out during 2020-2023.

MATERIALS AND METHODS

Study area

The study area of the project is part of the Al-Radwan neighborhood located in the Zahran district within the Greater Amman Municipality (GAM), which includes 22 districts. The study area is located in the northern section of the Al-Radwan neighborhood at 35.894° E longitude and 31.958° N latitude (Fig. 1). The Climate of the study area is Mediterranean, with hot dry summers and cold winters. The hottest month is July with an average air temperature of 25 degrees Celsius (°C), while January is the coldest month with an average air temperature of 8°C. The mean annual rainfall is 400 millimeter (mm), with most rainfall occurring from December to February. In terms of solid waste, the amounts received in the Al-Ghabawi landfill steadily increased from 1.57 million tons (t) in 2012 to 2.65 million t in 2021, mirroring the increased population and consumption patterns. The linear

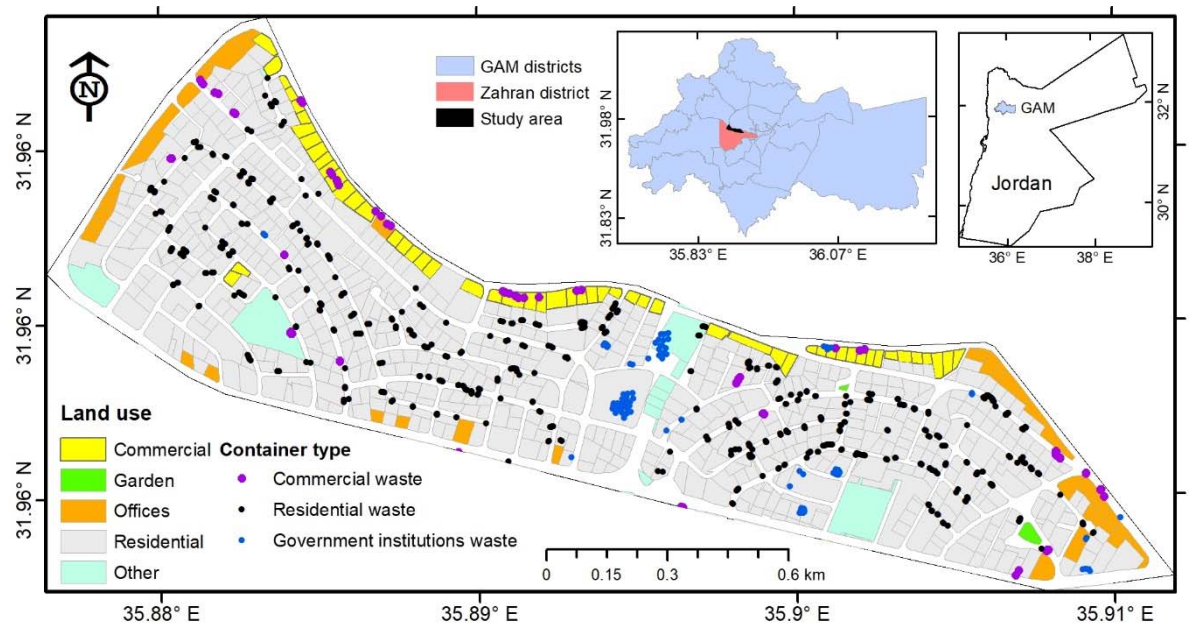

Fig. 1: Geographic location of the study area in Amman, Jordan

waste increase trend was disrupted by the lockdown during the coronavirus disease 2019 pandemic when the average waste received by the landfill was around 1.80 million t.

Demographic data

Al-Radwan has a total population of 16,920 individuals and 6,248 households at the start of the project in 2018 (DOS, 2015). The population of the study area is 8460, constituting about half the population of the Al-Radwan neighborhood. The study area has a total of 3,124 households and 822 parcels of land (Fig. 1).

MSW infrastructure before applying the SSC project

The waste collection system in GAM includes vehicles (compactor trucks) that collect waste from containers (large bins) and deliver it to a transfer station (TS) and then to a landfill. All compactor trucks are permanently monitored and tracked by the Tracking Department (TD), which collects data and produces monthly and annual reports on vehicle movements and waste transport. The solid waste collection system in the Zahran district and Al-Radwan neighborhood followed the GAM system. Analyses of 2018 data showed that residents typically disposed of their mixed waste in 238 metal containers of 1,100 liters (L) capacity, 94 plastic containers of 770 l capacity and 285 plastic containers of 240 l capacity. The containers were placed at waste collection points distributed throughout the neighborhood. Waste from containers was transferred into compactor trucks by waste collection staff (two workers per vehicle). It would take approximately a minute to empty a 1,100 l or 770 l container, whereas the 240 l container would be emptied in half a minute. The compactor truck made between two and five trips per day to transport waste to Al-Shaer TS in the East Amman area. Data from 2018 showed that six compactor trucks served the Zahran district and study area. The capacity of the trucks ranged from 4 to 12 t, with delivery frequencies ranging from 34 to 143 times per day. The area lacked a structural system for waste separation and recycling prior to this project. Prior to the SSC project, recyclable waste comprising plastic bottles, metal cans, and cardboard was collected from containers by waste pickers. To investigate the transport operations of waste collection trucks inside the study area, tracking data for compactor trucks were obtained from the TD. The tracking data were overlaid on the map of the study area using a geographic information system (GIS) to

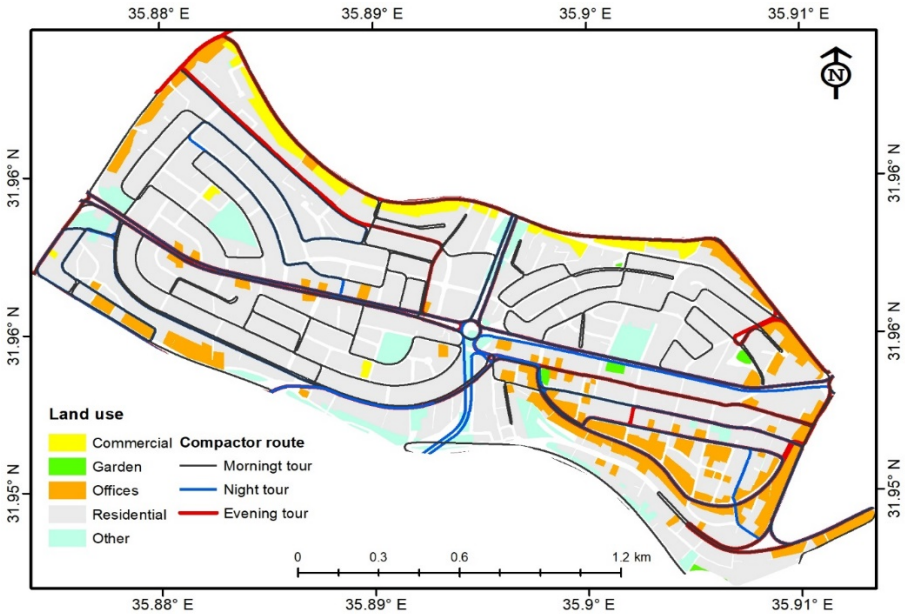

Fig. 2: Routes of MSW compactor trucks in Al-Radwan and the study area during January 21, 2018 (Map by J.T. Al-Bakri)

assess the spatial coverage of compactor trucks and identify areas with frequent visits where waste loads were relatively high. Fig. 2 shows the routes of the compactor trucks for the Al-Radwan neighborhood during January 2018. The GIS mapping confirmed that the waste collection service covered the entire Radwan neighborhood, with compactor trucks visiting all collection points on a daily basis. The GIS maps were used to identify the number of containers needed for implementing the SSC.

SSC system infrastructure

SSC was designed and its infrastructure was prepared in 2019 based on 2018 data. The system officially started in January 2020, when the collection service began and remained active. Each household was equipped with two bins: yellow bins designed for recyclable waste and grey bins for residual waste. The previous 1.1-cubic-meter (m^3) metal containers were eliminated as central drop-off points. Larger compound buildings that accommodated multiple households and commercial buildings were equipped with 1.1 m^3 containers (similarly designed in yellow and grey), corresponding to the number of households. Single households were equipped with 240 l grey and yellow bins. After the distribution of containers to houses and commercial buildings, two waste collection trucks were assigned to dispose of waste from the study area to the TS. The yellow bins were emptied once a week, while grey bins were collected twice a week. The number of yellow and gray bins is shown in Table 1. Recyclable wastes were manually sorted and weighed, while organic wastes were sent to the Ghabawi landfill, where another project used these wastes for biogas production. Weekly and monthly data for the 2020-2023 period were summarized, and different statistical functions were applied to derive the mean and the coefficient of variation (c.v.) for recyclable and residual waste. Since the population in the area was increasing with time, it was important to test whether waste amounts significantly changed during the period of 2020-2023. This was carried out by applying a two-tailed *t*-test that compared the weekly and monthly waste amounts of 2023 with that of 2020.

The primary challenge in implementing SSC was dividing the waste between wet and dry bins based on recyclable content and resident commitments. If the assumption of low recyclable content in the dry bin was invalid, adjustments based on performance monitoring would be needed to maximize the bin capacity by changing collection frequency or bin substitution rate. To enable these adjustments, the SSC system in this study relied

Table 1: Number and volume of yellow and grey bins

Parameter	Recyclables (yellow)			Residual (grey)		
	1.1 m^3	240 L	Total	1.1 m^3	240 L	Total
total number	139	519	658	152	595	747
number households	91	491		103	569	

significantly on advanced technology that included the implementation of a fixed waste collection schedule, conducting awareness campaigns via online calendars, implementing barcode systems on bins and establishing a mobile app. These advancements enabled accurate waste control and increased the overall efficiency of the SSC system. The SSC system was in line with existing legislation that aimed at promoting MSW management. The project was approved by, and implemented in collaboration with, the Ministry of Environment (MOE). Commercial businesses were benefiting from a 50% reduction in waste collection and disposal costs and taxes, with penalties for noncompliance with respect to the rules identified by the MOE.

Cost analysis for SSC

The cost analysis for the service is based on the service's efforts and expenditures, such as the number of pieces of equipment, driven mileage for collection and salaries. The unit costs for the salaries presented were based on figures from the design phase in 2018. Since Al-Radwan's collecting budget was not ring-fenced, several items had to be back-estimated from other budgets, particularly salaries. These were obtained from the data for the Zahran district. The number of staff members was taken as the share of the total staff active in Zahran District. The share for the Al-Radwan area was calculated as 11.4% based on the data evaluation for the collection service efforts during the design. The cost of waste collection trips (in terms of mileage spent) was calculated from the data of the TD, which showed that the trips in the Al-Radwan neighborhood comprised 26% of the trips in the Zahran district. The computation for equipment and vehicle maintenance and depreciation was based on planned and estimated replacement costs, which might differ from the actual expenditures for the equipment under this project. This method was chosen to make previous costs (before SSC) and present costs comparable.

Household surveys and awareness campaigns

Prior to SSC operation, an awareness campaign was implemented in the study area. The aim of this campaign was to assess the framework conditions for potential SSC activities. These included the available space for recyclable storage at both the household and building levels; the distribution of responsibilities for waste management within households; people's attitudes towards the processes of separation and storage; the potential commitment and willingness to pay; and individuals' experiences, wishes and complaints related to waste management practices. The awareness campaign encompassed schools, residences, commercial properties and governmental institutions. A household survey was conducted from 7 to 9 August 2018 and included a questionnaire that was filled out during 17 visits to 50 households. The planned SSC activities were introduced to residents during a meeting held with an active neighborhood community group on the 6th of August 2018. The questionnaire, filled during household visits, aimed to collect data on the characteristics of the population in the study area, the mechanism of waste disposal and attitudes towards waste separation and recycling. The members of Future Pioneers for Empowering Communities (FPECs) were responsible for developing, designing and conducting a comprehensive awareness campaign that implemented a gender-sensitive approach. The awareness-raising campaign involved a team of 20 members and 60 volunteers. The training included volunteers with essential knowledge of SWM. Door-to-door visits were carried out by 16 trained volunteers and commenced on the 25th of November 2020. Initial findings prompted adjustments to the plan, resulting in the recruitment of 30 additional volunteers and a shift in focus to morning and holiday visits. The FPEC campaign aimed to raise public awareness among the community of the pilot area and provide instructions on source separation so that a long-lasting, high number of waste generators

could be sensitized for participation in the source separation of waste. The key objectives and messages of the campaign were as follows:

- Tailor-made awareness and education activities to target key community sectors;
- Emphasize benefits for health and environment resulting from the proper handling of MSW;
- Simple messages conveyed through multiple media;
- Maximize participation in source separation/ recycling;
- Build on existing neighborhood practices and experiences with the involvement of local representatives and working groups; foster public participation in planning and implementation of activities;
- Increase the visibility and credibility of waste management activities with increased community engagement;
- Addresse cultural practices and beliefs;
- Conducted awareness workshops for elementary and secondary school students to reinforce project-related concepts.

RESULTS AND DISCUSSION

Waste quantities

Results indicated a fluctuating pattern in recyclable and residual waste quantities from January 2020 to December 2023. Recyclable waste varies between 13 and 43 t, with the highest amount of recyclable waste recorded in October 2023. Residual waste quantities ranged from 118 to 228 t, peaking in June 2022 at 257 t. Fig. 3 illustrates the amount of recyclable and residual waste collected from the Al-Radwan neighborhood from January 2020 to December 2023. Statistical analysis showed that the mean monthly quantities of waste were 25.85 and 181.33 t for recyclable and residual, respectively. The c.v. for monthly waste was 20.8% for recyclable waste and 15.3% for residual waste. Monthly averages showed that recyclable waste comprised 12.5% of the total waste in the study area.

The data collected from 2020 to 2023 indicate a consistent generation of recyclable waste, with quantities of 311 t in 2020, 290 t in 2021, 296 t in 2022, and 344 t in 2023. In terms of residual waste, there was a notable increase in residual waste generation over the same period. The quantities of residual waste generated from the Al-Radwan neighborhood were 1893, 2054, 2350, and 2400 t for 2020, 2021, 2022, and 2023, respectively. The increase in total MSW during the 2020-2023 period was statistically insignificant (p>0.05), as indicated by the t-test for annual and monthly means. In terms of SSC operations, the increase in waste was monitored, and the collection frequency or bin substitution rate was modified according to the waste quantity. Fig. 4 shows the amount of recyclable and residual waste collected from the study area. The average MSW generation was 0.89 kg per capita, which was slightly less than the country's average of 1.0 kg MSW per capita, as reported by Abu Hajar *et al.*(2020), or the average of 1.15 kg per capita forecasted by MOMA (2014). The average MSW in the study agreed with

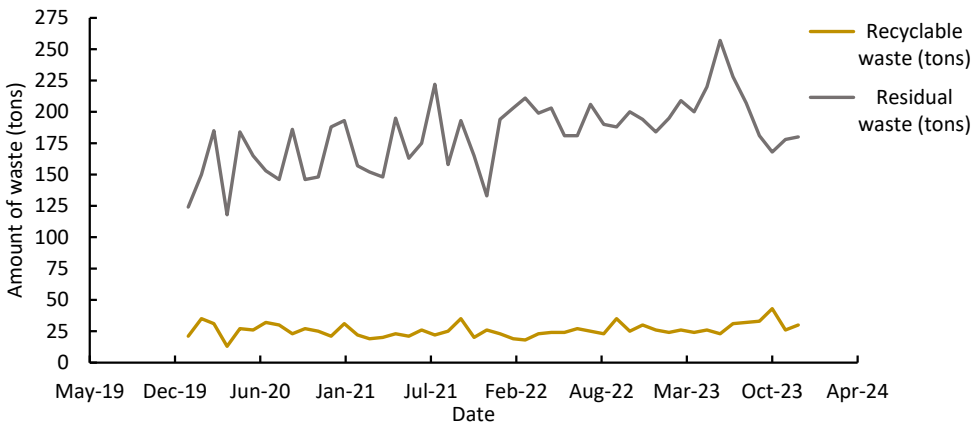

Fig. 3: Monthly quantities of waste collected from the study area

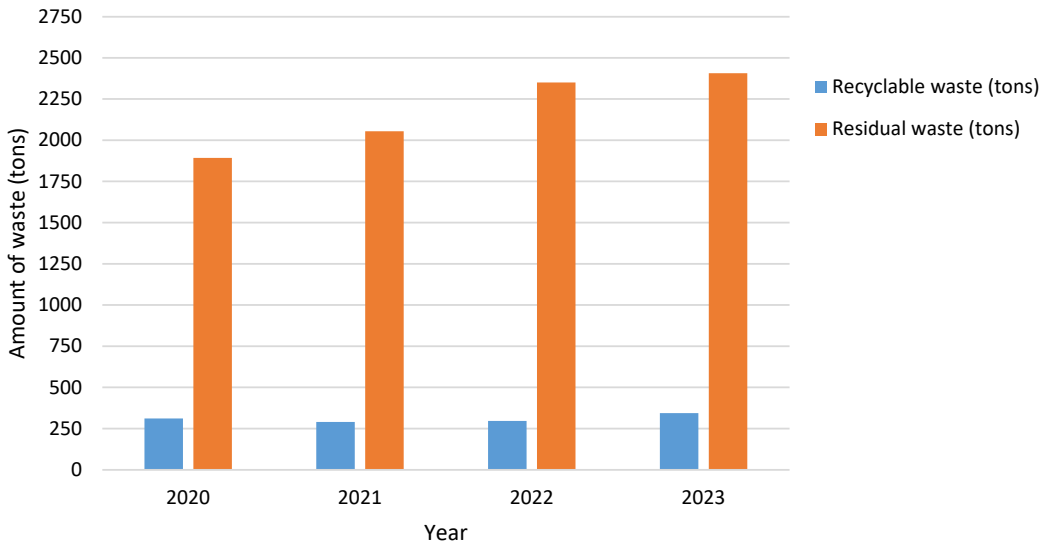

Fig. 4: Yearly quantities of waste collected from the study area

Jordan's average MSW of 0.9 kg per capita, as reported by Thabit *et al*. (2023) and GIZ (2014). Compared with countries and regions, the average daily MSW in kg per capita was within the range (0.3-1.4) reported for Europe and slightly higher than the average in Africa (0.78) and some countries in the Middle East (Abubakar *et al.*, 2022; Thabit *et al*., 2023). These variations in MSW could be attributed to the average income level among different countries.

Waste Composition

To assess the quantities of recyclables and biodegradable materials in household waste generated in the Al-Radwan neighborhood, an initial screening of waste in containers at a collection point was carried out. Figure 6 shows the results of the MSW composition screening. The results showed that 60% of the collected MSW was biodegradable (food and garden waste), 21% consisted of recyclable materials, and the remaining 19% comprised inert waste (Fig. 5). The MSW composition in the study area was higher with respect to biodegradable waste and lower with respect to recyclables when compared with figures reported for Jordan (GIZ, 2014; Abu Hajar *et al*., 2020). The sorting of a mixed waste sample of 330 kg out of the delivered MSW of 770 kg at the TS showed that the recyclable waste composition included valuable materials for recycling. These included mixed paper (36%), plastic foil (29%), polyethylene terephthalate (PET), plastic (22%) and other packaging materials (8%). The MSW composition in terms of organic biodegradable material was pretty close to that for most countries in the Middle East and North Africa (MENA), while for other components, the composition was different, as indicated by figures summarized by Thabit *et al*. (2023). Comparisons with other urbanized areas outside MENA were not carried out, as significant differences were expected due to the prevailing socioeconomic factors in these areas, particularly in developed countries and touristic areas (Voukkali *et al*., 2023).

Separation performance

The purity of recyclable content has a major impact on the overall material balance. In 2020, the yellow bins contained the following: 40-60% comprised plastic, 20-30% comprised paper and cardboard (PPC) and there was a small portion of metals. In 2023, the percentages of plastic, PPC and metals were 28.3%, 45.9% and 2.0%, respectively. The results of the separation process (Fig. 6) showed that waste compositions varied during the 2020-2023 period. Purity sharply dropped from 90% in 2020 to 60% in 2021 and 35% in 2022, indicating that sorting was less effective. The reason for this recession in purity could be attributed to some non-committed individuals who left their waste bins exposed to waste pickers.

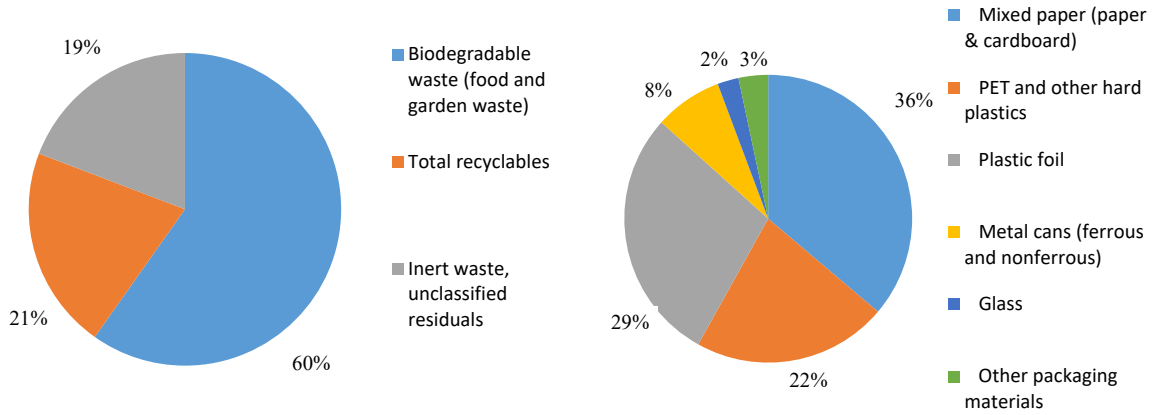

Fig. 5: Waste composition in the Al-Radwan neighborhood (left) and recyclable waste composition (right)

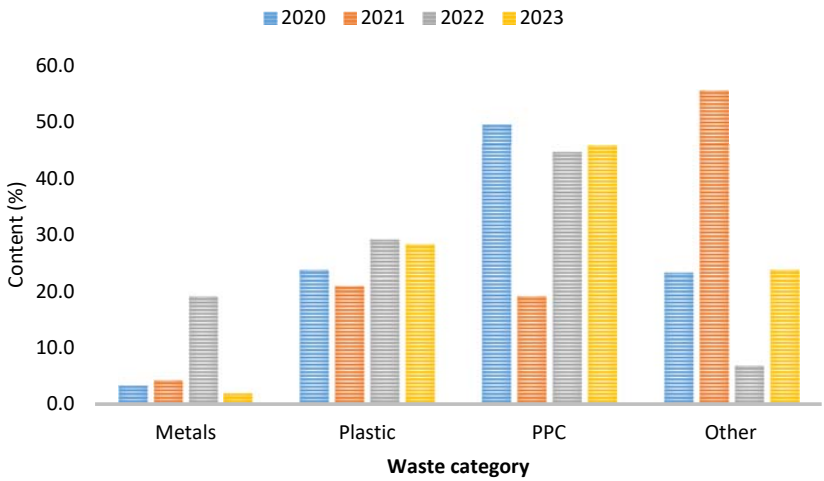

Fig. 6: Recyclable waste composition

The new families who moved into the study area were also unaware of the waste-sorting processes. The problem of decreased purity was fixed through the project's awareness activities in 2022. As a result, recyclable purity increased to 50% in 2023.

Cost analysis

The cost summary in Table 2 shows that the total annual costs for waste collection in the study area decreased by more than 31%. Results from a case study in Malaysia (Rangga *et al.*, 2022) showed that implementation of the SSC system could reduce collection costs by 37%. The cost reductions were mainly due to the significantly lower fuel cost, which decreased by 65%, as a result of a lower driven mileage. Maintenance and depreciation costs were also lower because of decreased wear and tear on vehicles. The additional costs for yellow and grey bins and containers were relatively small. Considering that the maintenance costs of these bins were cheaper than the previously used metal bins, depreciation might even be lower than the value calculated since the technical lifetime and producer's warranty for plastic bins have regularly been higher for 10 years. The salaries for the previous and current SSC service schemes remained unchanged because no change took place in the number of staff working in the study area and the district. It should be observed that the

Table 2: Operation expenditures for the SSC system vs. the old system

Cost item	Cost/unit	Number of units	Annual costs (USD)	Number of units	Annual costs (USD)
		SSC		Old System	
Salaries:	USD/year		59,129		59,129
Fuel consumptions:	USD/km		28,863		82,140
Fuel for compactor trucks—recyclables	0,77	8,760	7,369	0	0
Fuel for compactor trucks—residual waste	0,77	25,550	21,494	97,638	82,140
Maintenance:	USD/year		20,172		25,034
Compactor trucks (10% of initial cost/unit):	12.000	1	13,139	1,5	19,709
770/1100 L bins (5% of initial cost/unit):	13	291	3,983	332	4,544
240 L bins (5% of initial cost/unit):	3	1114	3,049	285	780
Depreciation:	USD/year		27,204		30,358
Compactor trucks (life span 10 years):	12.000	1	13,139	1,5	19,709
1100 L bins (life span 10 years):	25	291	7,966	332	9,088
240 L bins (life span 10 years):	5	1114	6,099	285	1,560
Total operation cost (USD /year):			135,370		196,661
Total waste (t/year)			2,414		2,414
Unit costs (USD/t)			61		88

lower mileage of trucks reduced the efforts of the staff without reflections implemented in the salaries listed in Table 2; thus, additional savings could be achieved if staff reductions are applied. The results of this analysis showed that the unit cost for waste collection in the SSC system was 61 USD/t, while the cost of the old system was 88 USD/t. The reduction in the MSW collection system (35%) was not only important in terms of economic return and feasibility but also because it contributed to a reduction in GHG emissions in the area, without substantial changes to waste collection infrastructure. This impact could be tangible when the SSC system is upscaled for large cities similar to Amman, as considerable reductions in GHG emissions could be achieved (Al-Dailami *et al.*, 2022; Zhang *et al*., 2023).

Awareness raising

Findings from the early stages of project implementation during November 2020 showed that the engagement level was around 50%, which revealed positive attitudes of the community with respect to participation. By December 2020, more than 76% of the questionnaires (2,123) were filled by households, and substantial progress towards participation in the project was revealed. The awareness-raising campaign extended to educational institutions with interactive waste-sorting activities at two major schools in the region. Despite the challenges posed by COVID-19 and the subsequent lockdowns, the team's awareness campaigns continued through online platforms. The post-survey analysis showed a significant positive shift in public behavior regarding waste management. Notable highlights included increased community awareness of waste's impact on health and the environment, a sharp increase (from 14% to 96%) in actual waste-sorting practices and the collective willingness to promote waste sorting among the community. Prior to SSC implementation, the results of the questionnaire distributed in July 2018 provided valuable insights regarding the community's demographic profile. Important findings included the presence of a predominantly affluent community with high income levels living in one-story buildings (villas), the family size of which was 3.5 for 90% of the households and the average area of the household living space exceeded 300 m^2 for 75% of the households. In terms of education, all respondents held, at minimum, a bachelor's degree. These findings were important and indicated the possibility of high community engagement and commitment in waste sorting that could result in a healthy environment. A technical assessment of the SCC system in 2023 showed that 91% of the waste bins were in good condition, 4.3% required maintenance and 4.6% required replacement. Remarkably, 98.7% of households actively sorted their waste, and 73.8% of these households chose to store waste bins inside their houses, while 26.2% preferred to place their bins outdoors due to insufficient indoor space. The technical assessment highlighted the success of waste sorting, with

99.4% of respondents recognizing its significance, demonstrating the beneficial impact of awareness training sessions. Around 96.3% of respondents were aware of the destination for recyclable waste. The population's degree of collaboration with the project was remarkable (98.0%). The assessment underscored the effectiveness of waste sorting, with a staggering 99.4% of respondents acknowledging its utility, reflecting the positive impact of awareness sessions. About 96.3% of respondents were aware of the destination for recyclable wastes, attributing this knowledge to the awareness campaigns. The level of cooperation with the project was noteworthy, with more than 96% of participants regularly cleaning their waste bins. These findings collectively highlighted the success of awareness campaigns and sessions in fostering positive waste management practices and garnering strong community support for the project. The awareness sessions were also important for obtaining feedback from the community to improve the SSC system's operation.

CONCLUSION

The study demonstrated the transformational impact of the SSC system in the urban environment with respect to sustainable cities and communities. The study showed that the implementation of SSC would require in-depth analyses of existing socioeconomic and environmental factors in the design stage so that modifications to the system during operations could be minimized. This would require the adoption of advanced technology for tracking delivered MSW and community engagement. The study showed that the most important factors at the initial stage of the SSC operation were activities related to public awareness, which were crucial for MSW separation and purity. From a technical perspective, the results reflected weekly, monthly and annual MSW quantity and quality. The average amount of MSW in the area (0.89 kg per capita per day) was comparable, with figures projected for the urban area of Amman City, as well as with figures reported for MENA. The composition of the MSW included a considerable proportion (60%) of biodegradable waste and recyclable materials, which reflected the success of waste segregation efforts deployed through the SSC. The implementation of the SSC system resulted in considerable economic, environmental and social advantages that could enable a shift towards a circular economy. The economic advantage stemmed from a reduction in fuel consumption during waste collection, followed by conventional waste management and collection systems. The improved effectiveness of recycling processes introduced additional economic value, and the SSC project played an important role in creating jobs and opportunities for employment. The technical review in 2023 confirmed the project's performance and highlighted the level of community commitment, cooperation and engagement in waste sorting. This performance, however, could not have been achieved without awareness campaigns. These findings highlight the importance of the SSC system in encouraging effective waste management techniques and gaining widespread community acceptance. Currently, the GAM aims to use these results as an outline for future large-scale initiatives, promoting the SSC system as an example of effective waste management, with the ability to promote significant socioeconomic and environmental change. As Jordan seeks sustainable solutions for urban waste management, the findings of this study provide valuable guidance for the expansion and replication of similar projects on a larger scale, highlighting the study's innovation, significance and novelty in the field of waste management research. In terms of environmental benefits, the impact of upscaling the SSC system with respect to reductions in GHG emissions will be studied and included in the cost–benefit analysis. The impact of the SSC system on the existing landfill is another future research direction that will be investigated.

AUTHOR CONTRIBUTIONS

O. Arabiyat played a crucial role in monitoring and evaluating the project, conducting a thorough review of the project's design, supervising the awareness campaigns, writing the manuscript and actively participating in the analysis of the results. J.T. Al-Bakri contributed significantly in writing the manuscript, preparing the maps and participating in the analysis of results. F. Kölsch was instrumental in designing and implementing the project, as well as monitoring and evaluating its progress. S. Al-Omari made substantial contributions by writing the manuscript and participating in the analysis of the results. H. Aladwan played a key role in the hands-on implementation of the project, contributing to its success.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism; informed consent; misconduct; data fabrication and/or falsification; double publication and/or submission; and redundancy have been completely observed by the authors.

ABBREVIATIONS

%	Percent
^{O}C	Degree Celsius
BMZ	Federal Ministry for Economic Cooperation and Development
c.v.	Coefficient of variation
DOS	Department of Statistics, Jordan
Fig.	Figure
FPEC	Future Pioneers for Empowering Communities' members
GAM	Greater Amman Municipality
GHG	Greenhouse gas
GIS	Geographic information system
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
kg	Kilogram
km	Kilometer
L	Liter
MENA	Middle East and North Africa
mm	Millimeter
m^3	Cubic meter
MOE	Ministry of Environment, Jordan
MOMA	Ministry of Municipal Affairs, Jordan
MSW	Municipal solid waste
m^3	Cubic meter
p	Probability level
PPC	Paper and cardboard
SSC	Separate source collection
SW	Solid waste
SWM	Solid waste management
t	Ton
TD	Tracking Department
TS	Transfer station
USD	United States dollar

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