Solid Waste in the Virtual World: A Digital Twinning Approach for Waste Collection Planning

Iván Cárdenas, Mila Koeva, Calayde Davey, and Pirouz Nourian

Abstract Solid waste (SW) management is a crucial challenge for urban sustainability. With global waste generation exceeding two billion metric tons every year, it poses various negative impacts, including health risks and environmental contamination. Despite not being a primary SDG, addressing SW management is essential for achieving several goals, as it relates to 12 out of 17 SDGs. South Africa, in particular, struggles with issues as large generation, and inadequate waste collection services. To address these challenges, a dynamic model incorporating real-time monitoring, optimized collection routes, and citizen participation is proposed. This study case involves a real-time citizen engagement method to locate, identify, and visualize SW containers and littering sites via open-source tool called Epicollect5 based on geospatial information. This can be considered as a first step towards a Digital Twin for SW management. In a three-day data collection campaign, a total of 1270 containers and 820 littering sites were identified. The result show inadequate distribution of containers in public spaces, highlighting the need for citizen involvement in reporting container information to achieve a comprehensive understanding of their distribution. Additionally, the concentration of litter reports in peripheral park areas emphasizes the importance of providing well-distributed containers and prompt maintenance. The inclusion of photographs in reports helps identify areas requiring immediate attention, while citizen participation mitigates challenges associated with location accuracy and resource requirements. Digital twinning, multi-stakeholder engagement, and citizen participation provide insights into waste container distribution and combating illegal dumping. This approach benefits lower-income countries with limited resources, improving SW management practices.

Keywords Solid waste · Digital twins · Citizen participation · South Africa

This article was selected based on the results of a double-blind review of an extended abstract.

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T. H. Kolbe et al. (eds.), *Recent Advances in 3D Geoinformation Science*, Lecture Notes in Geoinformation and Cartography, https://doi.org/10.1007/978-3-031-43699-4_4

1 Introduction

Solid waste management is a crucial challenge for achieving city sustainability (Ismagilova et al. 2019). In 2020, it was estimated that around 2.24 billion metric tons of municipal solid waste were generated worldwide (Kaza et al. 2021). This waste increased later due to medical waste produced during the COVID-19 pandemic (Yousefi et al. 2021; Liang et al. 2021). Approximately 33% of the overall waste generated is not environmentally safe (Kaza et al. 2018). It has several negative impacts, including health risks, sewage system blockages, soil contamination, and potential disease vectors (Ziraba et al. 2016; Pervin et al. 2020; Sharma et al. 2018; USAID 2007). Despite not being included as a primary Sustainable Development Goal (SDG), addressing solid waste management is related to 12 of 17 SDGs, making it essential to achieve city sustainability (Rodić et al. 2017; Wilson et al. 2015).

In South Africa, 30.5 million tons of solid waste were generated in 2017, with only 34.5% being recycled and 11% not having adequate final disposal (Department of Environmental Affairs 2018; Department of Environment Forestry and Fisheries 2020). The country has an estimated generation of 1.48 kg/capita/day of solid waste, which is higher than the Sub-Saharan average and at similar levels to some countries in Europe and Central Asia (Kaza et al. 2018). One of the primary challenges in South Africa is reducing the waste disposed in landfills (Department of Environment Forestry and Fisheries 2020), which is hindered by littering, illegal dumping, lack of regular collection services, incomplete coverage, and historical spatial and service delivery inequalities (Polasi 2018; Polasi et al. 2020).

To improve solid waste management, a dynamic model that incorporates real-time monitoring, frequent collection route optimization, and active citizen participation is needed, as suggested by different authors (Ramson and Moni 2017; Karthik et al. 2021; Joshi et al. 2022; Chaudhari and Bhole 2018). However, this is difficult to be achieved (1) without understanding the local waste landscape and (2) without having a population active and aware of the waste issues.

Researchers have been investigating different methods for monitoring waste management. Some suggestions include designs for sensors to monitor solid waste containers, including ultrasonic sensors on container lids (Ramson and Moni 2017; Karthik et al. 2021; Joshi et al. 2022; Chaudhari and Bhole 2018; Mahajan et al. 2017), weight sensors at the bottom of containers (Rovetta et al. 2009), a combination of both (Vicentini et al. 2009; Ali et al. 2020), as well as infrared sensors (Singh et al. 2016) to detect fullness levels. However, many of these designs have only been tested at a prototype level, not in outdoor or large-scale conditions. While some studies have tested sensors outdoors, they have used operators for the containers or invited citizens to use them, which could create biases in the data. In the Netherlands, the city of Utrecht has successfully incorporated ultrasonic sensors, and daily rerouting based on fullness levels (Gemeente Utrecht 2021) but implementing these technologies in lower-income countries may be challenging.

The current research proposes a digital twinning approach to pilot the deployment of crowd-sourced processes in South Africa to improve solid waste management. It is aimed to record and monitor the spatial distribution and characteristics of collection points and identify the location of illegal dumping sites in a near-real time manner.

2 Methods

This section details the characteristics of the study area and the methodology employed, including data collection and subsequent data processing and analysis.

2.1 *Study Area*

The study focused on the Hatfield and Hillcrest neighborhoods of the city of Tshwane, Greater Pretoria, in South Africa. The area comprises 9.45 km^2 surrounding the University of Pretoria (UP) main campus (see Fig. 1) with different land uses such as residential, institutional (embassies), commercial, agricultural, and educational. This area is part of the ongoing project of African Future Cities from the Department of Architecture in the Faculty of Engineering, Built Environment, and Information Technology of the University of Pretoria.

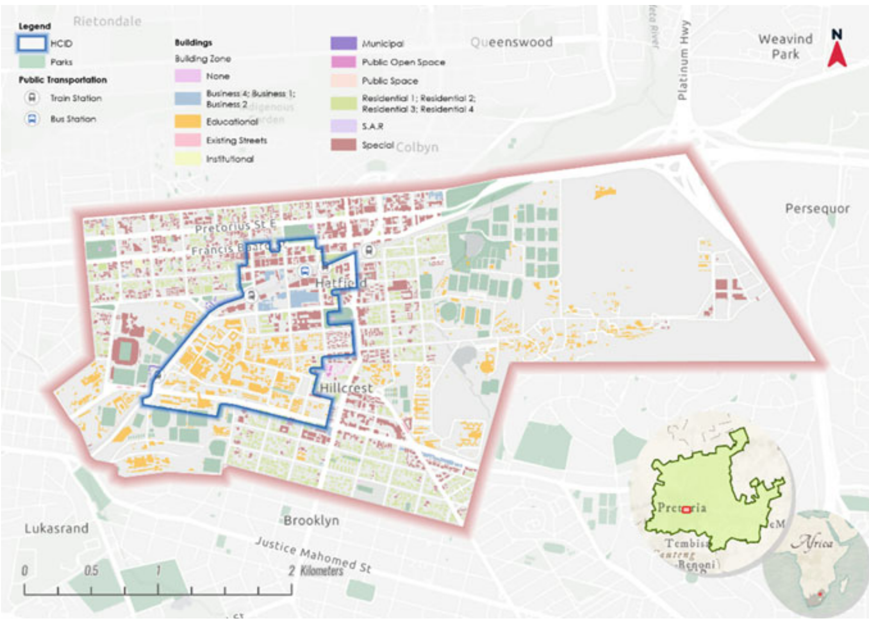

Fig. 1 Hatfield digital twin city study area

The area also includes the Hatfield City Improvement District (HCID). This non-profit and private organization performs corporate governance of the area. It is funded by a taxpayer's property levy collected by the municipality and transferred to the HCID for operation, providing additional services such as cleaning and maintaining public spaces, private security, and urban embellishment.

2.2 Methodology

The primary data collection relied on the open-source Epcicollect5 tool (Aanensen et al. 2014), an application that is both freely accessible and highly adaptable. It works on smartphones for iOS and Android and is designed for on-field information gathering. The app does not require a constant network connection and can store records on the device and later be updated to the cloud when a Wi-Fi connection is available. This is a particularly important function for South African citizens since constant internet connection might be a challenge.

On this app, a survey including the questions shown in Table 1 created focusing on container capacity, dimension, and littering reporting in three levels of severity (minimal, moderate, and severe), engaging students, as citizen pilots, in the Hatfield and Brooklyn neighborhoods of the City of Tshwane. By involving students in this pilot initiative, the feasibility and effectiveness of crowd-sourced data collection in addressing solid waste management challenges is assed.

The data was collected, in a three-day period, between 28 February and 02 March, by 15 bachelor's students in their final year of the Architecture program at the University of Pretoria. The survey was sent to the students with a detailed guide on downloading and using Epicollect5 on a mobile phone (Fig. 2).

Likewise, an introductory session explaining the tool's usage was delivered to students, and they were asked to keep an accuracy of at least 5 m at the moment of collection. The records with an accuracy of less than 20 m were excluded from the final dataset as a larger distance would overlap with other containers, and data quality could not be assured. The obtained data was extracted using Epicollect5 API through the PyEpiCollect library developed by Principe and Masera (2020), transformed using Geopandas, and stored as a GeoJSON file and ESRI's Shapefile.

Data was geolocated and immediately visualized in a 2D GIS environment to monitor the data collection process and constantly communicate with students. After data was collected, a 3D representation of the study area was created in a GIS online environment to visualize the results and have a monitoring tool using 3D buildings as context for navigation. To reach better realism, the solid waste containers were represented according to their geometries and scaled according to their volume to increase the contrast against the built environment. The littering reports were visualized using point 3D objects represented according to the severity of the report: minimal: one can of soda; moderate: a trash bag; severe: a pile of trash bags (see Fig. 3).

Table 1 Survey design for solid waste containers and littering identification

Category	Question	Data type	Domains	Required	Optional
Basic information					
	Report date	Date		X	
	Report time	Date		X	
	Where is the report located?	Geopoint		X	
Report type					
	What kind of report do you want to make?	String	Litter report	X	
			Register a trash bin		
			Other report		
Trash bin information	What is the status of the container	Boolean	Broken	X	
			Non-broken		
	Is the bin movable?	Boolean	Movable	X	
			Fixed (static)		
	Height (in m)	Double			X
	Radius in m (if circle)	Double			X
	Length in m (if rectangular)	Double			X
	Width in m (if rectangular)	Double			X
	Can you estimate the capacity (in Cubic meters)	Double			X
	Please include a photograph of the container	Photo			X
	Comments	String			X
Litter report					
	Severity (How much trash is there)	Integer	Minimal (1)	X	
			Moderate (3)		
			Severe (5)		
	Please include a photograph of the container	Photo			X
	Comments	String			X

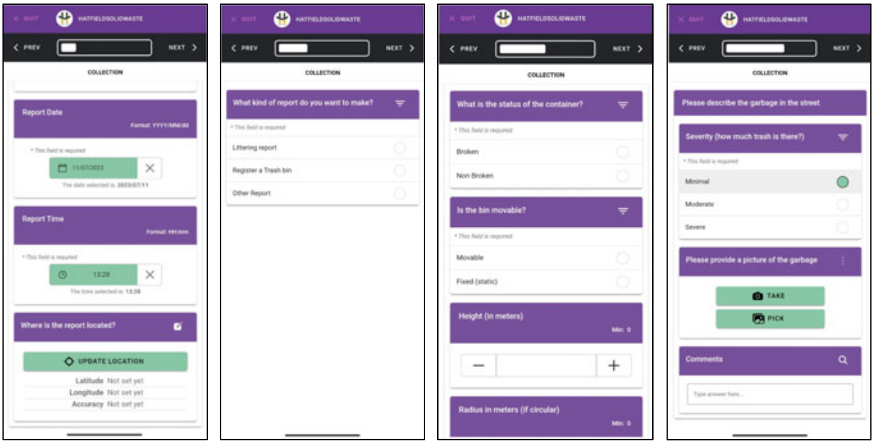

Fig. 2 Epicollect5 Mobile collection app screenshots

The visualization includes various features to help viewers navigate and interact with the data, such as a 240L standard bin 3D model used to visualize the containers and color-coded for broken (red) and good state (green) containers. The survey results were analyzed in their relation to closeness to transport nodes and land use.

3 Results

The data collection results showed 2.236 reports. Of them, 3.04% were invalid, i.e., without coordinates or points without information, and 3.76% were inaccurate. A total of 1.270 containers were identified, with 4.16% reported as broken (see Figs. 4 and 5). Also, 136 ashtrays were identified inside the main campus and only one outside.

Container volumes vary between 28 L and 10.58 m^3 on 67 different types of containers (Fig. 6). The ones of 118 L are the most frequent, with 426 (33.54%) of the total recorded. This type of container corresponds to a standardized concrete or metal container (see Fig. 7a and b). Likewise, the containers 240L correspond to standard plastic movable containers (see Fig. 7c), which are distributed to each home by the municipality as they help load waste to the waste collection trucks. The identified containers also include 26 dumpsters known as skips (see Fig. 7d). These skips can be attached to collectors facilitating collection. The skips are loaded one at a time, compared to plastic containers which are collected in several bins in the same vehicle.

Near-real-time monitoring of the reports allowed us to understand that containers were mainly inside the UP campus and the HCID. On the live monitoring of the 02 March, it was possible to observe containers whose distribution obeyed to streets

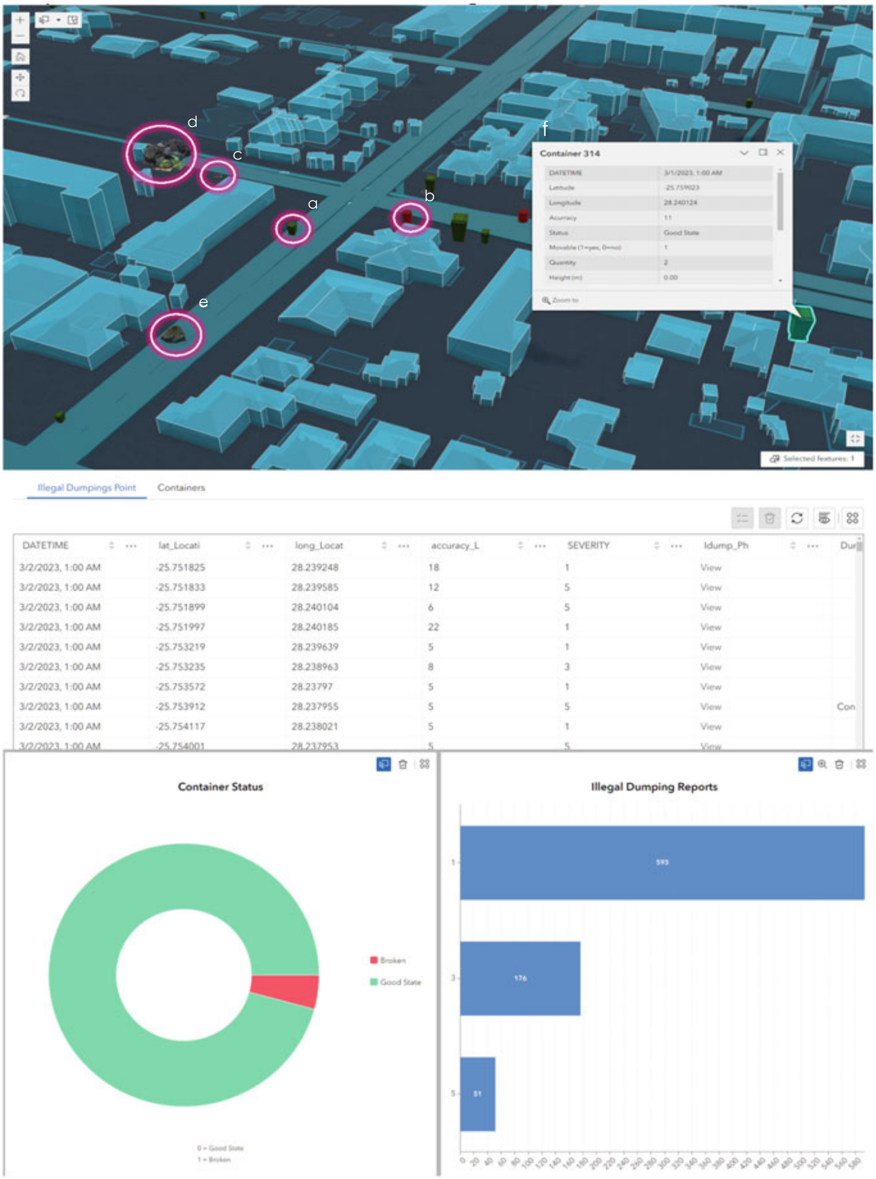

Fig. 3 Visualization of Containers and Illegal dumping sites. **a** Good state container. **b** broken container. **c** Minimal severity illegal dumping report. **d** Moderate severity illegal dumping report. **e** Severe illegal dumping report. **f** Container query attributes

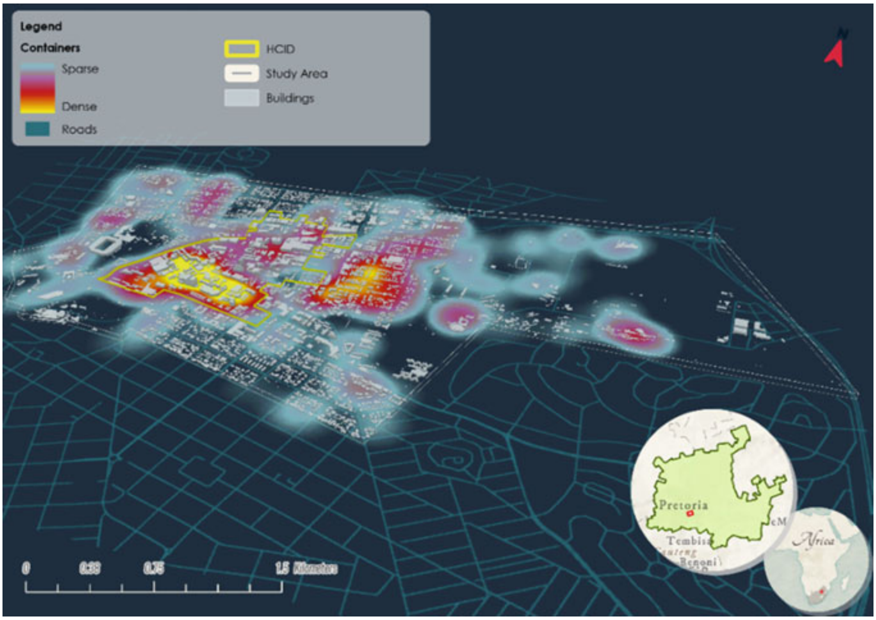

Fig. 4 Containers distribution—heatmap—in study area

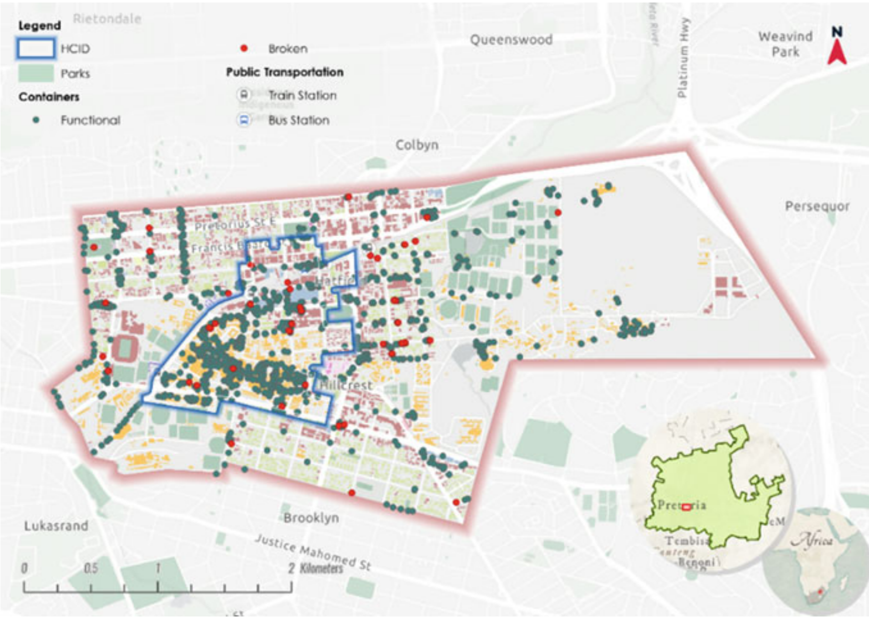

Fig. 5 Container's location and functionality (Broken—functional)

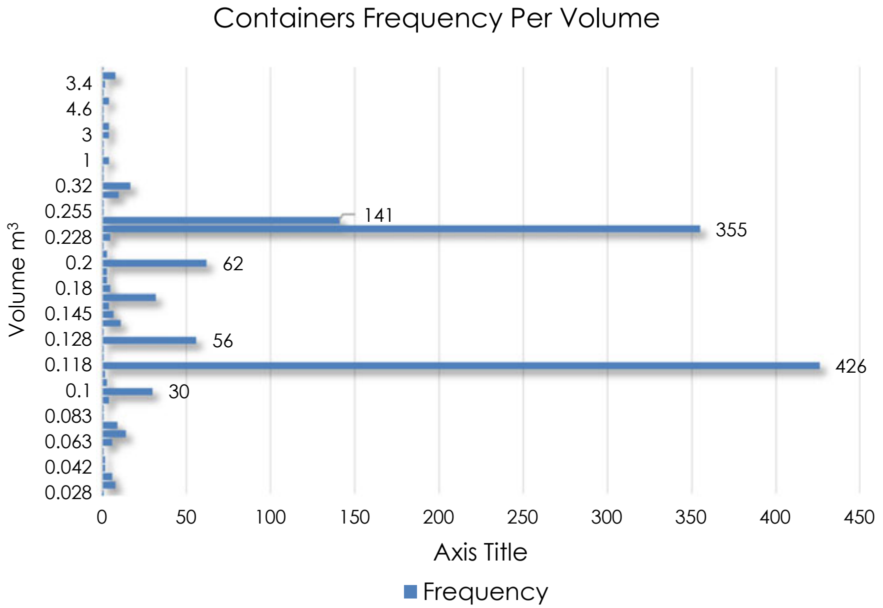

Fig. 6 Containers' volume frequency distribution

that had their assigned collection on the same day that data was collected, which relates to residential buildings and residents locating their containers on the curbside (Fig. 5).

On the illegal dumping and littering side, 820 reports were made and distributed in 593 minimal (72.3%), 176 moderate (21.5%), and 51 severe reports (6.2%) (see Fig. 8). The photographs taken by students to report on the illegal dumping show that areas underneath the trees are being used as the frequent place for littering, which adds up to the biowaste of tree maintenance and the natural accumulation of bark and leaves (see Fig. 9).

Fig. 7 Main observed type of containers. **a** Concrete 0.118 m^3 **b** Metal 0.118 m^3 **c** Plastic 0.240 m^3 **d** Skip 4 m^3

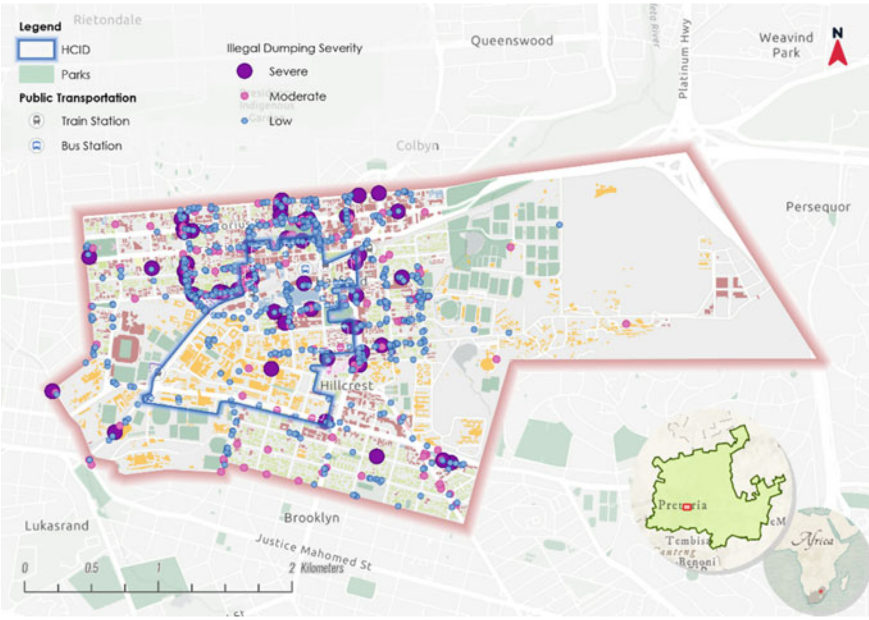

Fig. 8 Illegal dumping severity and distribution

Fig. 9 Illegal dumping reports. **a** Event residues inside UP campus. **b** Car bumper disposed under a tree. **c** Littering under tree. **d** Biowaste, littering, and illegal dumping under trees

4 Discussion

The designed survey on Epicollect5 works as a tool for reporting waste containers, illegal dumping, and littering. It provides a fast method of information collection where citizens can engage rapidly and keep track of the waste system in public and private spaces. This allows anyone with access to a mobile device to inform authorities of waste status and help make decisions in improving Urban solid waste management.

The data showed that public spaces do not have an even distribution of solid waste containers. This is seen in areas where no record of solid waste containers was documented. They correspond to exclusively residential areas in the North and South of the study area, outside the HCID, where containers are located in private areas, not in public spaces. Therefore, its information was not collected, which is a limitation of this research. To have a complete understanding of the distribution of waste containers, it is necessary to include the residents of the area and ask them to report their containers, capacity, and frequency on which they refuse waste. Collecting information on the type and status of containers can help the city and HCID management, where maintenance is required, and progressively standardize the type of containers to ease recognition and collection of waste.

The main concentration of the litter reports was in the periphery of the parks, green areas, and playgrounds, such as Springbok Park and Hatfield Playpark, suggesting that the recreational and resting areas are common places for illegal dumping and require larger containers. Likewise, these parks show containers in the center of them and no containers in the periphery. Areas of the parks surrounding the container do not have reports of litter, which shows the importance of providing sufficient and well-distributed containers. Additionally, reports that include photographs help understand the process of waste accumulation. For instance, the pictures in Fig. 9 indicate that maintenance of green areas requires a rapid response from the collection company to avoid accumulating and attracting other litter and disease vectors.

The research faced some adversities as the proposed data collection method did not consider regional numerical format. Some of the collecting devices could not include decimal separators (iOS), and data was informed in the comments section of the report. This generates anomalies in the monitoring as geometrical properties could not be visualized on the spot.

Contrary to assumptions, students found the study area to be cleaner than expected and recognized the importance of container distribution and governance on their waste flows. The littering reports did not consider the type of waste thrown in the inappropriate location. Nonetheless, students reported biowaste and construction waste on the streets. The live information retrieved from these waste flows can also be used by composting farms and circular economy companies that take advantage of these residues and reduce the amount of waste that goes to landfill.

Although the monitoring was designed to be in a 3D environment to create a closer to the real-life visualisation, it showed no advantages compared to the 2D environment monitoring system. Nonetheless, 3D model can help citizens and non-technical users provide a better context, improve the situation's mental image, and provide an immersive decision-making medium (Herbert and Chen 2015; Bouzguenda et al. 2022).

By involving citizen participation, this method reduces challenges, such as location accuracy, high resource requirements, and disagreement on labeling, identified in Artificial Intelligence computer vision detection research (Moral et al. 2022). It also confirms the importance of citizen testimony in mapping solid waste (Al-Joburi 2018). The real-time monitoring helps address the randomness of minor severity littering for improved solid waste management, including multiple stakeholders.

5 Conclusion

The research concluded that digital twinning, multi-stakeholder engagement, and citizen participation could provide valuable insights into the distribution of solid waste containers and the occurrence of illegal dumping and littering. It can be a hybrid and collective approach for addressing solid waste management challenges in lower-income countries without large financial and technological capacity.

By developing digital counterparts of waste management infrastructure and mapping out their spatial distribution, policymakers and stakeholders comprehensively understand the current state of solid waste container placement. This knowledge serves as a foundation for evidence-based decision-making and targeted interventions. Through collective efforts and integration of technology and community engagement, improved solid waste management can be achieved, even in resource-constrained settings.

6 Further Research

The next steps in developing a Digital Twin for solid waste management include calculating solid waste production per building, considering their total floor area and their relationship with each container. Waste collection managers can also use the frequent report of container saturation status and littering locations to optimize the collection system via Capacitated Vehicle Routing Problem (CVRP). Further research could explore the effectiveness of interventions informed by this data, such as targeted container placement or increased cleaning frequency in areas with high littering.

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