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Circular economy and household e-waste management in India. Part II: A case study on informal e-waste collectors (Kabadiwalas) in India

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ABSTRACT

Rapid advances in electronics and telecommunications technologies have contributed significantly to making e-waste one of the largest and fastest-growing solid waste streams. India produces over 3.23 million tonnes of e-waste each year. Over 90% of the total e-waste generated in the country is processed by the informal waste management sector. Informal waste collectors in India are known as 'kabadiwalas'. Many people in India employ their services to discard household solid waste items, including e-waste. However, the percentage of people disposing of their e-waste to kabadiwalas is unknown. Moreover, detailed research studies on kabadiwalas' waste collection activities are very limited to date. A case study was therefore formulated to determine the likelihood of e-waste disposal to kabadiwalas and their solid waste collection strategies, including e-waste fraction. A global positioning system (GPS) based real-time waste collection route tracking method was employed. The results indicated that many people in India (~45% of survey respondents) prefer to dispose of their e-waste to kabadiwalas. Based on the GPS tracking results, the informal waste collectors were found to travel considerable distances using manual and modified three-wheeler vehicles (20–30 km per day) to collect household waste, out of which e-waste accounted for about 10%. It was deduced that their large workforce and low operating costs enable them to collect e-waste from households all over the country effectively. The results from this study indicate that kabadiwalas play an integral role in the e-waste management system of India and that their integration into the existing formal e-waste industry could help establish improved e-waste management and value recovery operations in India.

1. Introduction

Rapid evolution in technology and the ever-growing demand for electrical and electronic equipment (EEE) has resulted in the generation of significantly large quantities of electronic waste (e-waste) worldwide (Panda et al., 2020). Other factors such as planned obsolescence (Tesfaye et al., 2017), shorter replacement intervals (Nivedha and Sutha, 2020), limited options and higher costs for repair and lack of reuse interests (Sengupta et al., 2022) have all contributed to making e-waste one of the fastest growing solid waste streams. The e-waste stream is considered to provide good economic opportunity if effectively recycled (Panchal et al., 2021), as it contains large quantities of valuable base and precious metals such as copper, silver, gold, and palladium (Ilankoon et al., 2018; Do et al., 2023). These metal concentrations are substantially higher in e-waste than in their respective ores (Montecino, 2016). Responsible and efficient recycling of e-waste can not only yield resource sustainability and economic gains (e.g. diversify critical metals supply chains, including copper) (Kang et al., 2023), but it can also help significantly reduce the environmental impacts of waste electrical and electronic equipment (WEEE) that subjected to artisanal recycling and

Abbreviations: DSLR, Digital single-lens reflex; EEE, Electrical and electronic equipment; EPR, Extended producer responsibility; GDP, Gross domestic product; GPS, Global positioning system; NCR, National capital region; OHS, Occupational health and safety; PBBs, Polybrominated biphenyls; PBDEs, Polybrominated diphenyl ethers; PCBs, Polychlorinated biphenyls; PCCs, Pollution control committees; PCDDs, Polychlorinated dibenzo-p-dioxins; PCDFs, Polychlorinated dibenzofurans; POPs, Persistent organic pollutants; PPE, Personal protective equipment; Rs, Indian Rupees; RWA, Resident welfare association; SDGs, Sustainable development goals; SPCBs, State pollution control boards; TBBPA, Tetrabromobisphenol-A; USD, United States Dollar; VCRs, Video cassette recorders; WEEE, Waste electrical and electronic equipment.

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disposed of in landfills (Wäger et al., 2012).

In addition to the metal fraction, e-waste consists of a non-metallic fraction, though it is considered to have lower economic significance (Kumar et al., 2018). In recent days, the non-metallic fraction of e-waste has received significant attention as it can provide good recovery value due to its large quantities, lightweight, good thermal stability (Qiu et al., 2021), and excellent performance in harsh environmental conditions during chemical treatments (Duan et al., 2012). Researchers claim recycling is the best option for disposing of glass fibre fraction in e-waste (e.g. Gu et al., 2017). Even though e-waste recycling (recovery of both metals and non-metals) appears to be a lucrative solution, the processes involved are often challenging due to the presence of toxic metals (e.g. lead, mercury) and chemical substances (e.g. halogenated flame retardants) present in e-waste (Spalvins et al., 2008). Exposure to these toxic substances can pose a severe threat to health and the environment (Awasthi et al., 2016) if these substances are mobilised (Ilankoon et al., 2018).

According to the Global E-waste Monitor Report 2020, 53.6 million tonnes of e-waste were generated globally in 2019, indicating a generation rate of 7.8 kg per capita. In 2019, out of the total generated e-waste, 9.3 million tonnes (17.4%) were formally documented, collected and recycled. The remaining 44.3 million tonnes (82.6%) of e-waste remained unaccounted for (Forti et al., 2020). The majority of the undocumented e-waste comprises the fraction generated by households and small businesses, wherein e-waste is often disposed of collectively with other waste streams, such as plastic and food waste. In such cases, some easily recyclable e-waste components get recycled along with plastic or metal waste. However, the informal sector often performs these recycling activities under inferior conditions polluting the environment and without recovering all the valuable materials (Forti et al., 2020). This form of mixed recycling can lead to the exposure and generation of highly toxic substances called persistent organic pollutants (POPs) (Arya et al., 2021). Polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), polychlorinated biphenyls (PCBs) and tetrabromobisphenol-A (TBBPA) are some POPs that are commonly present in the non-metallic fraction of e-waste. In addition, open burning of e-waste plastic leads to the release of POPs such as polychlorinated dibenzofurans (PCDFs) and polychlorinated dibenzo-p-dioxins (PCDDs) (Alabi et al., 2021). Exposure to POPs can cause serious ailments such as cancers, birth defects, dysfunctional immune and reproductive systems, and damage to the central and peripheral nervous systems (Stockholm Convention, 2001). Thus, e-waste recycling with other waste streams or improper disposal practices are not preferred. The Stockholm Convention (signed on May 2001, effective since May 2004) is one of the primary international environmental treaties that aims to eliminate or restrict the generation (both primary and secondary) and use of POPs.

In most high-income countries, an effective waste recycling infrastructure exists wherein large quantities of the generated e-waste are formally recycled. Approximately 8% of the e-waste in these countries is discarded in waste bins and subsequently landfilled or incinerated (Forti et al., 2020). Among the remaining 92%, large quantities (exact quantities are often not reported) of e-waste are also exported to low and middle-income countries through transboundary movement (Ilankoon et al., 2018) for refurbishing, recycling, or disposal. Forti et al. (2020) stated that approximately 7–20% of the total e-waste generated worldwide is exported through such transboundary movements indicating the insufficiency of the Basel Convention in prohibiting the transboundary movement of e-waste. India ratified the Basel Convention in 1992 and was among the first few countries to urge a ban on hazardous waste exports to developing countries (Ipen, 2020). However, to this day, considerably large quantities of e-waste are imported into the country from developed nations (Ilankoon et al., 2018). This is often done illegally (Sepúlveda et al., 2010) under the guise of being for reuse or pretending to be scrap metal. In developing countries, the e-waste management infrastructure is still in its early stages of development, whereas the formal e-waste recycling sector cannot handle the influx of generated e-waste. In such countries, most of the e-waste is recycled by the informal sector.

India is the third largest e-waste-generating country in the world, generating over 3.23 million tonnes of e-waste each year (Forti et al., 2020). Being a developing country, the e-waste management system in India is dominated by the informal sector (2 sides here: informal e-waste collection and informal value recovery operations), wherein 1% of the country's population is estimated to be involved in informal waste management activities, including informal waste collection and recycling (Arya and Kumar, 2020; Sengupta et al., 2022). The informal e-waste sector in India is known to collect and recycle about 95% of the total generated e-waste (Dutta and Goel, 2021). Their widespread operation often causes the existing formal recyclers to operate at lower capacities (Borthakur and Sinha, 2013) due to limited access to e-waste supply chains in the country (Bhardwaj, 2016). Large workforce, cheap labour, inexpensive collection methods, artisanal value recovery operations, and low operating costs are crucial factors that favour informal e-waste collection, supply chains and value recovery operations in India (Sengupta et al., 2022).

In India, informal waste collectors are known as 'kabadiwalas'. They collect all end-of-life items, such as newspapers, cardboard, scrap metal pieces, plastic bottles, tires, and e-waste (Radulovic, 2017; Sengupta et al., 2022). Household and small institutional consumers often prefer to dispose of their waste to informal waste collectors due to their door-to-door collection service along with nominal monetary incentives provided to disposers (i.e. purchase waste materials, including e-waste) (Borthakur and Govind, 2018). Informal e-waste collectors are very efficient, though their supply chains are often linked to informal e-waste recyclers.

Lack of awareness regarding the harmful impacts of uncontrolled e-waste recycling (Singh et al., 2020) and the costs of disposing of e-waste at formal collection centres makes e-waste disposal for formal recyclers an unpopular option (Turaga et al., 2019). Thus, a substantial fraction of the e-waste collected by informal recyclers would flow to the informal e-waste recyclers. The e-waste recycling operations in the informal sector are primitive, mostly manual, and lack consideration of environmental or occupational health and safety measures (Borthakur and Singh, 2012). Final waste disposal methods in this sector cause significant environmental pollution. In summary, it is of paramount importance to employ the services of the kabadiwalas as formal e-waste collectors, while the operation of informal e-waste recyclers (value recovery units) is not supported, and they must be encouraged to formalise their operations and abide by the regulations laid out by the government. In addition, transforming the informal e-waste collectors and recyclers into more formal value recovery operations will provide additional social, environmental, and economic benefits.

Aligning with these, Sengupta et al. (2022) proposed a modified extended producer responsibility (EPR) model integrating the kabadiwalas into the existing formal e-waste management framework and stated that this integration could provide a synergistic effect on the current e-waste industry in the country. The formal and informal sectors are expected to benefit from one another upon such integration. Even though the kabadiwalas in India are known to handle a significantly large fraction of the total generated e-waste in the country, their earnings are low, and they are often exposed to potential health and safety hazards (Chi et al., 2011). The proposed integration is expected to benefit the informal waste collectors by providing them with healthier working conditions (improved lifestyle), while the formal sector is expected to benefit from improved access to e-waste, ensuring that they can operate at their total capacity (Sengupta et al., 2022). However, to date, detailed research studies pertaining to informal waste collectors' solid waste collection activities, including e-waste, are very limited. To further investigate the applicability of the proposed EPR model in the Indian context, a case study has therefore been formulated to study the operational characteristics and working efficiency of the kabadiwalas as designated e-waste collectors in India. This case study has multiple aspects, and firstly 1000 Indian households will be surveyed to understand the likelihood of household consumers disposing of their e-waste to kabadiwalas compared to other e-waste disposal methods. Secondly, a kabadiwala cluster will be identified in the Delhi NCR (National Capital Region), India, and they will be interviewed by visiting their operational facilities (waste collection and storage area). In addition, the daily waste collection by each kabadiwala will be quantified. Thirdly, a GPS-based real-time waste collection route tracking method will be employed in this work to determine the distance kabadiwalas travelled each day to collect that waste. The findings of this case study could help justify the proposed EPR model (Sengupta et al., 2022) and quantify the e-waste collection volume in the informal sector.

2. Operational characteristics of kabadiwalas

In the first part of the work, Sengupta et al. (2022) introduced the operational characteristics of kabadiwalas, and thus, a summary is presented here (Fig. 1). Household waste collection by the kabadiwalas is an age-old belief/norm among the Indian community. Many people still prefer to dispose of their waste to kabadiwalas (section 3), enabling them to operate at vast scales nationwide (though the exact number is not reported). The majority of the e-waste disposed of by households, shops, and small industries is effectively collected by the kabadiwalas due to their significantly large workforce and efficient waste collection strategies. Fig. 2 indicates some of the e-waste items commonly collected by kabadiwalas in India.

Within the informal waste management sector, a middleman is responsible for the recruitment and management (both operational and financial) of the kabadiwalas and the operation of the waste storage site (Fig. 1). The number of kabadiwalas employed under each middleman varies based on the scale of business set up by the middleman. Some kabadiwalas operate independently, however, they are fewer in number. At the start of each day, each kabadiwala is given about 1000–2000 Indian Rupees (Rs.) or USD 12–25 by the middleman to be used as an incentive in exchange for the valuable waste collected from their designated locality. These incentives are awarded to the disposers to encourage them to discard their waste, and the amounts vary with the type of waste. For example, the kabadiwalas offer around Rs.10/kg (USD 0.12/kg) for newspapers, while they offer Rs. 50/kg (USD 0.60/kg) for any e-waste. Bills or receipts are not issued for waste transactions. The middleman also sets a fixed rate for different waste categories in each kabadiwala cluster.

Kabadiwalas are often required to be authorised (i.e. hold a work permit) for waste collection by the local resident welfare association (RWA), and the middleman is responsible for maintaining these work permits. Residents from most residential sectors or colonies get together to set up RWAs that cater to the general welfare of the residents. For localities with no functioning RWAs, kabadiwalas can enter and collect waste without any authorisation. For each residential sector or colony (spanning an area of approximately 0.8–2.5 km^2), around 5 kabadiwalas are allocated by the middleman.

Kabadiwalas use modified manual or motorised rickshaws (i.e. three-wheeler vehicles with an attached cart at the rear end) for waste collection within the designated area (Fig. 1). These modified vehicles do not have an overhead covering, exposing the rider to severe weather conditions.

The working hours of the kabadiwalas are typically between 7 am and 5 pm, and their earnings depend on the waste collected. At the start of the day, the kabadiwalas are gathered at the storage site to collect their vehicles and weighing scales together with the incentives used for trading. After collecting enough waste, they return to the waste storage site to dump the collected waste. This implies that the kabadiwalas begin and end their work at the same location daily, at the middleman's waste storage site. They usually work seven days a week due to more waste disposal activities during the weekends.

The collected waste is segregated based on the type of waste and

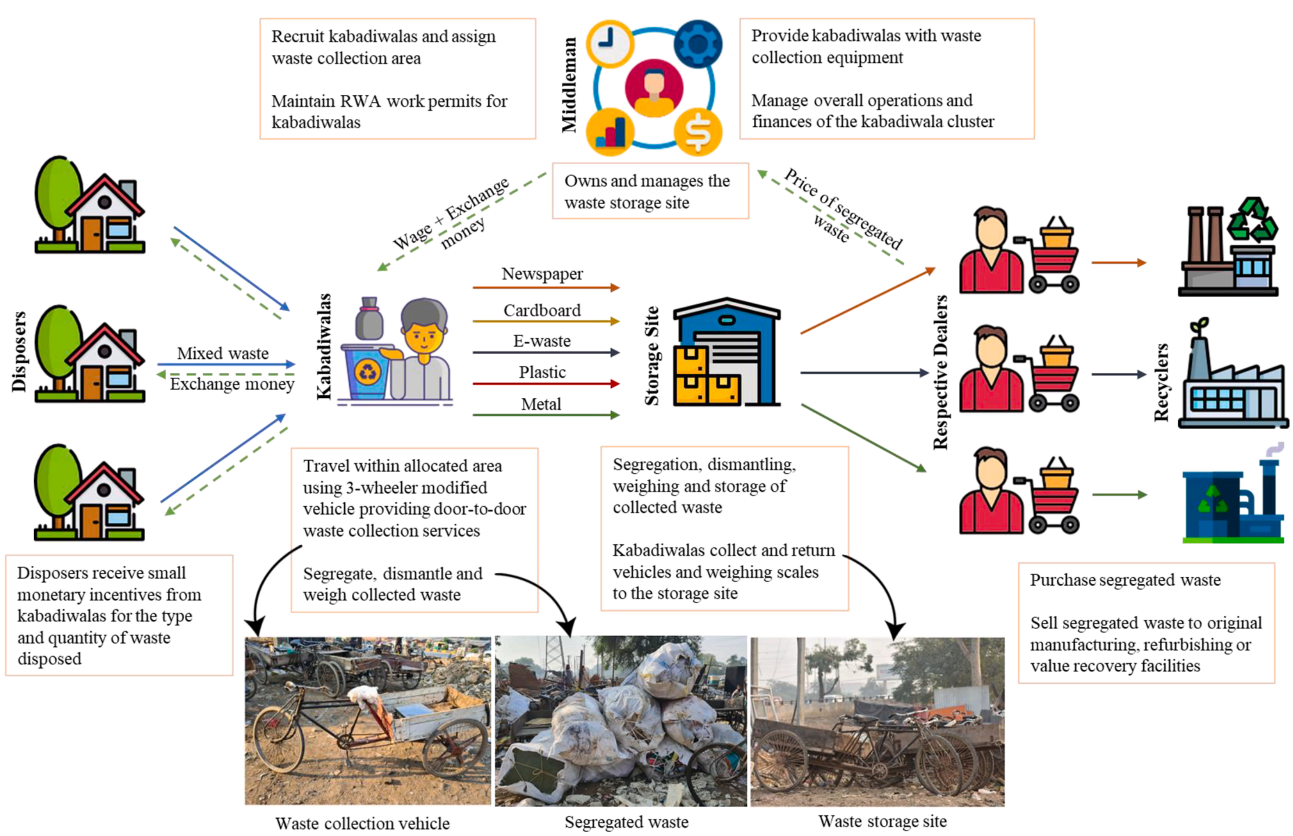

Fig. 1. Interactions between different stakeholders in the informal e-waste management sector in India.

Fig. 2. Types of household e-waste collected by kabadiwalas.

weighed, including e-waste (Fig. 1). The e-waste fraction is further segregated in terms of their working condition (Fig. 2). The kabadiwalas return the remaining exchange money to the middleman and then receive their wage based on the type and quantity of waste collected during that day, with the rate of Rs. 0.50–2 (USD 0.006–0.024) per kg of waste. Their average daily income varies between Rs. 100–500 (USD 1.20–6).

The middleman sells the segregated waste to different dealers. The e-waste dealer is responsible for picking up all the segregated e-waste, and the middleman sells the collected waste at slightly higher prices than what is paid to the waste disposers. For example, in the case of e-waste sold for refurbishing (no dismantling), if the kabadiwala pays the disposer Rs. 50/kg (USD 0.60/kg) of e-waste, the middleman sells it to the dealer at Rs. 55–70/kg (USD 0.65/kg–0.85/kg). The net profit margin will be the source of income for the middleman. The dealers then deliver the collected waste to their respective recyclers, including informal recyclers in India.

3. Case study methodology

3.1. Household e-waste generation and disposal survey: Do people dispose of e-waste to kabadiwalas?

Many people in India tend to hoard e-waste items at home as they are concerned about data security issues and value perception relating to the disposal of personal consumer electronics. This hoarding behaviour could also be attributed to the lack of awareness among people regarding formal e-waste recycling institutions and their operations in the country. Some common e-waste disposal methods in India include throwing e-waste with other household waste into garbage bins, selling to kabadiwalas, stripping for spare parts and selling the spare parts to informal e-waste refurbishers or repair shops.

To further study the household e-waste disposal habits among people in India and understand the likelihood of household consumers disposing of their e-waste to kabadiwalas as compared to other e-waste disposal methods (i.e. formal e-waste collection centres, disposal in garbage bins), an online survey was conducted with a sample size of 1000 respondents residing in over 85 cities and towns in India (Supplementary Document 1). The sample size for the survey was calculated based on Andrew Fisher's formula. The formula suggests a sample size of 385 participants for a population size greater than 10,000 with a confidence level of 95% and an error margin of 5%. However, with the available time and resources, 1000 surveys were conducted to reduce the error margin further to approximately 3%. The survey was created using Google Forms. The common methods of e-waste disposal currently used in India were first targeted, and these methods were included as options in the survey questions. Separate questions were asked about functional EEE no longer in use and their disposal (Supplementary Document 1).

A shareable link to the survey was circulated through different online messaging platforms, including shared messaging groups created by residents in the residential complexes in India. Such outreach was helpful in gathering responses from people mainly in the age range of 25–80 years. Some survey responses were also collected physically by visiting a private university in India to gather responses from young individuals (18–25 years). Respondents from different age groups and locations were targeted for a more realistic picture since they are EEE consumers and WEEE generators and disposers in the country.

3.2. Case study of kabadiwalas: Identification of middleman and kabadiwalas

To gain a comprehensive understanding of kabadiwalas' operation as informal waste collectors in India, a case study was conducted within the Delhi NCR (National Capital Region), which comprises some major cities (Delhi, Faridabad, Gurugram, Ghaziabad, Noida, Greater Noida, Baghpat, Alwar, Sonepat) and some small towns (World Population Review, 2023). This region was chosen as it comprises some of the prominent metropolitan cities of India, wherein the e-waste generation and disposal rates are expected to be high due to their large population and increased contribution to the Indian gross domestic product (GDP) (World Population Review, 2023). The case study includes interviews conducted with kabadiwalas, the middleman and a dealer who particularly purchases e-waste from the middleman working within one kabadiwala cluster (Fig. 1). The kabadiwala cluster being surveyed comprised 20 kabadiwalas. During the initial interviews, they were informed that the types and quantities of waste collected by them would be monitored for a period of 7 days (section 3.3). A 7-day period was chosen based on the available resources and human ethics clearances. Out of 20, 6 kabadiwalas (named as Person A-F) volunteered to participate in the case study. Their waste collection routes would also be tracked in real-time during working hours during this period, to which they consented (section 3.4).

3.3. Analysis of the daily waste collection of kabadiwalas

During the 7 days case study period, the images of the waste collected by the 6 kabadiwalas, including the dismantling methods performed, were captured using a digital single-lens reflex (DSLR) camera. Weights of segregated waste categories, such as paper, cardboard, e-waste, plastics, scrap iron, scrap tin, tires, and glass bottles, were individually identified. In addition, the waste collected in each category was weighed daily (Supplementary Document 1). This would provide the average e-waste collection percentage by kabadiwalas compared to other solid waste categories.

3.4. Real-time waste collection route tracking of kabadiwalas

A real-time location tracking method was employed to ascertain the daily waste collection of kabadiwalas for a period of 7 days. A GPS tracking device was installed with their consent (6 kabadiwalas in total). Considering that the kabadiwalas start and end their waste collection at the waste storage site, the distance travelled by vehicles between the time they collect and park their vehicles provides an estimate of the distance traversed by each kabadiwala for waste collection in a day. The tracking methodology employed in this work identified and recorded the GPS locations of the kabadiwalas' vehicles during their working hours in terms of latitude and longitude. Since the kabadiwalas do not have fixed working hours and sometimes return to the middleman's waste storage site (i.e. the starting and ending point of their workplace) multiple times a day to drop off the collected waste (when the cart is full), their last visit to the storage site was recorded to calculate the total distance travelled by kabadiwalas in a day to collect a particular waste quantity, including e-waste.

4. Results

4.1. Household e-waste generation and management survey results

From the analysis of survey results, it was found that the majority of the respondents tend to either exchange the functional but obsolete EEE for new ones (~26%) or keep these in storage as spare EEE (~25%) (Fig. 3a). Considering the reusability of these EEE, a significant number of respondents give such devices to their friends or family (~19%) or even sell them as second-hand products (~14%). Only one respondent (0.1%) mentioned that they dispose of all EEE that they no longer use to an e-waste recycling facility set up at their residential colony.

However, the e-waste disposal practices vary among the respondents. Most respondents (~45%) prefer to give away these WEEE to their local kabadiwalas (Fig. 3b). Comparatively, a smaller fraction of people (~7%) preferred to dispose of their e-waste at formal recycling centres. Many people (~22%) dispose of their e-waste directly into the garbage bins with other solid waste due to the perception that malfunctioning EEE are no longer valuable and lack of awareness about the harmful effects of improper disposal of e-waste (Ravindra and Mor, 2019). This is highly concerning as most of the solid waste collected from households either ends up at landfills or is incinerated in the open atmosphere. The presence of toxic and hazardous chemicals in e-waste could cause severe damage to health and the environment in such cases (Ilankoon et al., 2018; Manish and Chakraborty, 2019). The survey results also show that people tend to hoard WEEE in storage or strip it open for spare parts for personal use and selling. Five respondents (0.5%) mentioned that they dispose of all their WEEE in the e-waste collection bins at their workplaces or residential colonies. This indicates that awareness regarding the importance of proper e-waste recycling is on the rise among people in India. However, the initiatives to ensure appropriate household e-waste collection are still on a very small scale.

The survey results provide a better insight into e-waste disposal practices in the Indian community. It clearly indicates that many household consumers still prefer to dispose of their e-waste to kabadiwalas. Households and other smaller institutions in India do not still dispose of their e-waste at formal recycling facilities due to a lack of awareness and the costs associated with the disposal process. The door-to-door collection service provided by the kabadiwalas, along with the monetary incentives, make waste disposal to them a favourable option compared to the formal e-waste collection mechanisms in India (Borthakur and Govind, 2018; Sengupta et al., 2022). In summary, the survey results in this work solidify the necessity of investigations to assess the roles of kabadiwalas in e-waste management in India, which is one of the key objectives of this work.

4.2. Analysis of the daily waste collection of kabadiwalas

The kabadiwalas being surveyed were found to collect several kinds of solid waste, such as paper, cardboard, plastics, tires, glass bottles, scrap iron, tins and e-waste during the survey period of 7 days, whereby 10% (Supplementary Document 1) of the total waste collected are e-waste (Fig. 4).

Out of the 6 kabadiwalas employed during the survey period, only 4

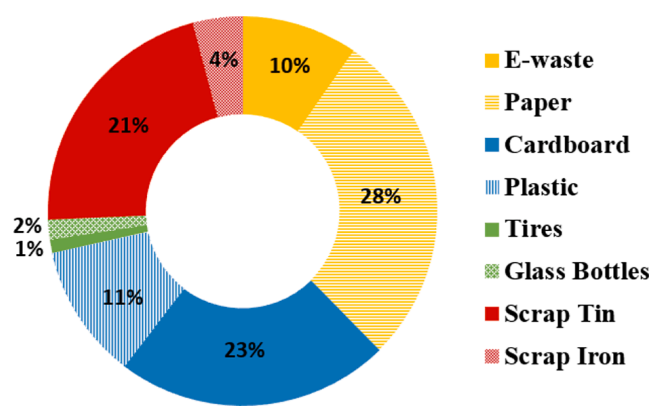

Fig. 4. Types of solid waste collected by 6 kabadiwalas in this case study of 7 days.

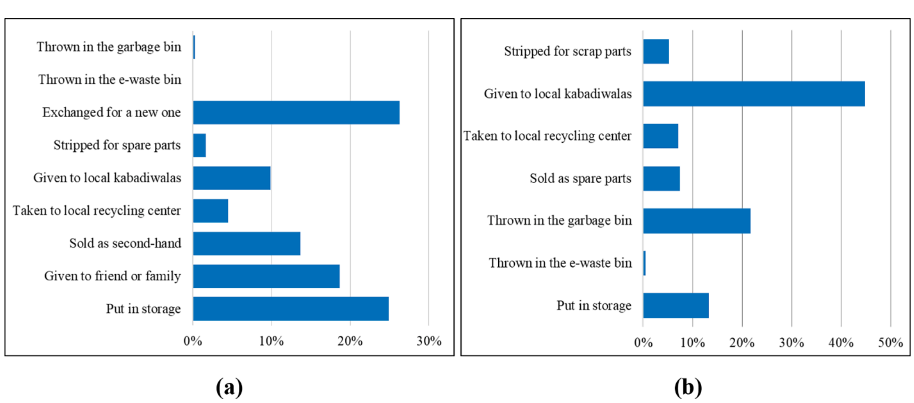

Fig. 3. Household e-waste disposal survey results: a) disposal of functional EEE not in use, and b) e-waste disposal methods.

kabadiwalas (Persons B, C, D and E) could collect e-waste (Fig. 5). However, they were not able to collect e-waste on all 7 days. The e-waste collection is lower because people tend to discard e-waste less frequently than other solid waste items, such as newspapers, cardboard, and plastics, generated daily. WEEE collected by the kabadiwalas during the survey period included video cassette recorders (VCRs), televisions, printers, fluorescent lamps, coolers, refrigerators, blenders, and desktop computers.

During the case study, it was observed that the kabadiwalas do not consider relevant environmental and occupational health and safety (OHS) measures during their waste collection and segregation activities. The collected waste is brought back to the waste storage site and dumped on open land (Fig. 6a) without considering the mobilisation of toxic substances from e-waste into soil and water (e.g. a broken fluorescent lamp could mobilise mercury). The kabadiwalas also fail to use appropriate personal protective equipment (PPE) while performing manual e-waste dismantling activities (Fig. 6b). They typically use small dismantling tools, such as hammers, chisels and small drills, to break open electronic devices and extract their components.

4.3. Real-time waste collection route tracking of kabadiwalas

Due to the informal nature of their work, there are no fixed work schedules for the kabadiwalas. As their daily income directly depends on the quantity of the waste collected, their primary objective is to work until they have collected enough waste to earn their living for the day. However, their work schedules are affected by several social factors such as age, health condition and festive seasons in India. Their flexible work schedule also impacts the distance they travel daily to collect waste and the waste collection activities in a week (Fig. 7a). Each kabadiwala is allocated to a specific region for waste collection, due to which the average distance they traverse differs (Fig. 7b).

The average distance travelled by the kabadiwalas per working day was found to be in the range of 18 km (for Person D) to 30.75 km (for Person F) (Fig. 7b). However, some kabadiwalas (e.g. Person B, C, D and E) travelled all 7 days of the week, while Person F only travelled for 4 days (Fig. 7a), indicating their flexible work schedule.

The distances travelled by the kabadiwalas were estimated (Fig. 7) by plotting their locations in terms of latitudes and longitudes and then tracing a path on Google My Maps (Figs. 8 and 9).

Person A and Person F were the eldest (>60 years) and were found unable to work on all days of the week (Fig. 7a) due to their poor health conditions. In comparison, Persons B and E were the youngest (25 and 27 years, respectively) and worked for maximum hours on all days of the week, covering the longest distances (Fig. 7a). This indicates that age and health condition are two significant factors that affect the working ability of the kabadiwalas.

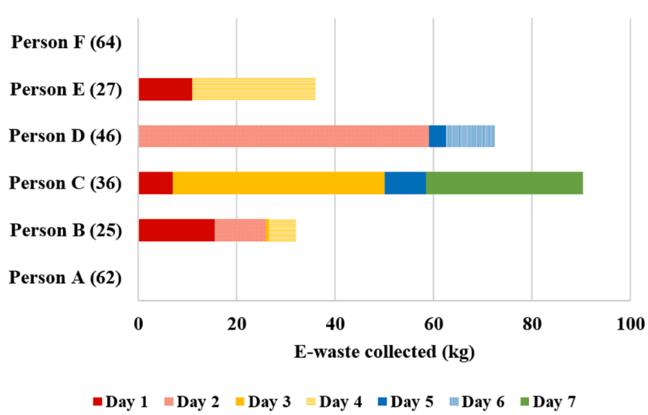

Fig. 5. Quantities of e-waste collected by kabadiwalas (their ages are indicated in the brackets) in the 7 days case study.

Since these kabadiwalas travel around their allocated area multiple times in a day, their stops are frequent and concentrated over a small area. They can also be found to make multiple stops at the same location throughout the day (i.e. locations F, G, and H in Fig. 8 and locations D, J, and K in Fig. 9). The maps indicating the path traversed were therefore plotted in separate layers for a clearer representation. Location A (Figs. 8 and 9) indicates the waste storage site where each kabadiwala collects and returns their vehicle at the start and end of each working day.

Among the 4 kabadiwalas (Persons B, C, D and E) who collected e-waste during the study period, Person C was found to collect the maximum quantities. Out of the 7 days, Person C collected e-waste on 4 days (Fig. 5).

On Day 2, Person C travelled a total distance of 20 km for waste collection but did not collect any e-waste (Figs. 5 and 8) while, on Day 3, Person C travelled a smaller distance (17 km) and collected 43 kg of e-waste (Figs. 5 and 9). This indicates no direct correlation between the quantities of e-waste collected and the distance these informal waste collectors travelled. This variation can be due to multiple factors, such as e-waste disposal rates, the waste collection area on a particular day (compare Figs. 8 and 9) and the number of households visited.

The findings of this case study indicate that the kabadiwalas travel significantly large distances each day for solid waste collection, including e-waste, using their manual vehicles. Considering their vehicles do not have an overhead covering, they are often exposed to severe weather conditions, which makes their work extremely challenging. However, they work under such conditions as their daily income, even though very low, relies on the quantity of waste they collect daily. Due to their widespread reach, they can effectively collect e-waste not only from every part of big cities but also from small towns and rural areas where formal e-waste collection services may not be available. In summary, the household waste collection strategies of kabadiwalas are efficient, and their services can be obtained for formal waste management in India, including e-waste. Moreover, they do not charge any disposal fee, unlike some formal collection mechanisms, which often require the disposers to pay a fee for disposing of their waste. Instead, the kabadiwalas offer monetary incentives to household waste disposers, making them the preferred option. The large distances travelled by the kabadiwalas are primarily due to the multiple rounds they make within their allocated waste collection areas throughout the day. This makes waste disposal more convenient and enables disposers to dispose of their waste constantly, thereby reducing hoarding practices.

5. Discussion and Conclusion: Moving forward with kabadiwalas' services as e-waste collectors in India

Even though India's e-waste generation is growing alarmingly, the country's documented collection and recycling rates remain appallingly low. The current e-waste management system in India suffers from several shortcomings. Lack of proper inventorisation in the informal e-waste management sector, unsafe and unhealthy working conditions of informal e-waste collectors and recyclers, insufficient formal e-waste recycling organisations with limited operating capacities, and lack of general awareness about the harmful impacts of unregulated e-waste recycling are some common factors contributing towards having an ineffective e-waste management system in India even after the continuous efforts by the government.

Considering that over 90% of the total e-waste generated in India is currently processed by the informal sector (Biswas and Singh, 2020), kabadiwalas being the primary informal waste collectors, play a critical role in the e-waste management supply chain in the country. Even though their e-waste collection, segregation and pre-treatment methods have often been criticised for being crude and unsafe, the case study results indicated that many people in India still prefer to dispose of their waste to the kabadiwalas. With a significantly large workforce, these informal waste collectors can effectively collect most of the household waste generated within the country due to their widespread reach. The

Fig. 6. a) collected mixed waste dumped at the storage site, and b) manual dismantling of weee without the use of any ppe.

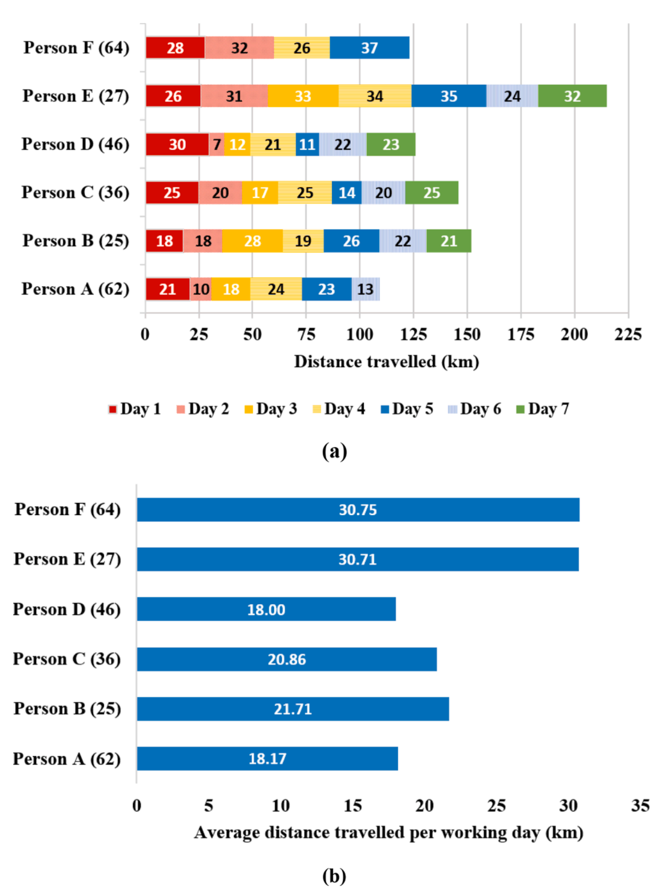

Fig. 7. a) distance travelled by 6 kabadiwalas on each of the 7 days, and b) average distance travelled per working day by 6 kabadiwalas.

collected waste inventorisation results indicated that approximately 10% of the total waste collected by the 6 kabadiwalas during the 7 days case study period comprised e-waste, while the GPS tracking results indicated that they travelled significantly large distances of about 20–30 km each day for waste collection using their manual vehicles. Considering the large scale at which these kabadiwalas operate in India, these informal waste collectors are expected to collect substantial quantities of e-waste generated in households and small businesses (Supplementary Document 1). The results indicated that kabadiwalas are a critical part of the waste management industry in developing countries like India. Even though they collect large quantities of household waste generated in the country, they are often found to be living impoverished lives with very low income, limited supply of food, proper sanitation, and sometimes accommodation. They are also often exposed to hazardous environments due to the unregulated nature of their work (i.e. waste segregation and pre-treatment using small tools). Therefore, it is necessary to make their operations more efficient and devise methods to provide a better lifestyle to these informal waste collectors in India.

Sengupta et al. (2022) suggested that formalising the operations of kabadiwalas (through their registration under State Pollution Control Boards or SPCBs) and incorporating them into the existing formal e-waste management system in the country can help make the current system more efficient, wherein both the formal e-waste recycling industry and the kabadiwalas can mutually benefit from each other's co-existence. This integration can be achieved through certain modifications to the existing EPR schemes (Fig. 6 of Sengupta et al., 2022) and legislative frameworks in India. The integration will help the informal waste collectors by providing them with healthier working conditions (upon registration under the respective SPCBs, they will be required to abide by the operating regulations and safety standards laid out by the government) and improved lifestyles. It is also expected to improve the overall collection, distribution, and recycling rates of e-waste in the country, thereby supporting and contributing towards the Indian government's target of achieving an e-waste recycling rate of 80% from the financial year 2024 onwards as per the E-Waste (Management) Rules, 2022 (effective from 1st April 2023) (Ministry of Environment, Forest and Climate Change, 2022).

Sengupta et al. (2022) have proposed the use of an incentive-based EPR model to provide improved income to informal waste collectors in India, while the formal e-waste recyclers are expected to benefit from an improved supply of household e-waste generated within the country, enabling them to run their operations smoothly and continuously. With approximately 1% of the country's population involved in the informal waste recycling industry (Arya and Kumar, 2020; Sengupta et al., 2022), the complete eradication of informal waste collectors and their practices can lead to extensive unemployment. Thus, the formalisation and incorporation of kabadiwalas into the formal e-waste management system can contribute towards both environmental and economic sustainability. It is paramount to perform large-scale studies to estimate and identify kabadiwalas in India, which determines the feasibility of incorporating informal waste collectors into formal supply chains via modified EPR frameworks. Estimating the number of kabadiwalas in different cities was not the objective of this study and thus identified as a limitation of this work.

However, informal value recovery operations are not supported as these cause severe impacts on human health and the environment due to the toxic substances present in e-waste (Chakraborty et al., 2018). It is believed that the existing informal value recovery operations can also become a part of the formal e-waste management industry by upgrading their e-waste handling systems (to use safe and upgraded technology)

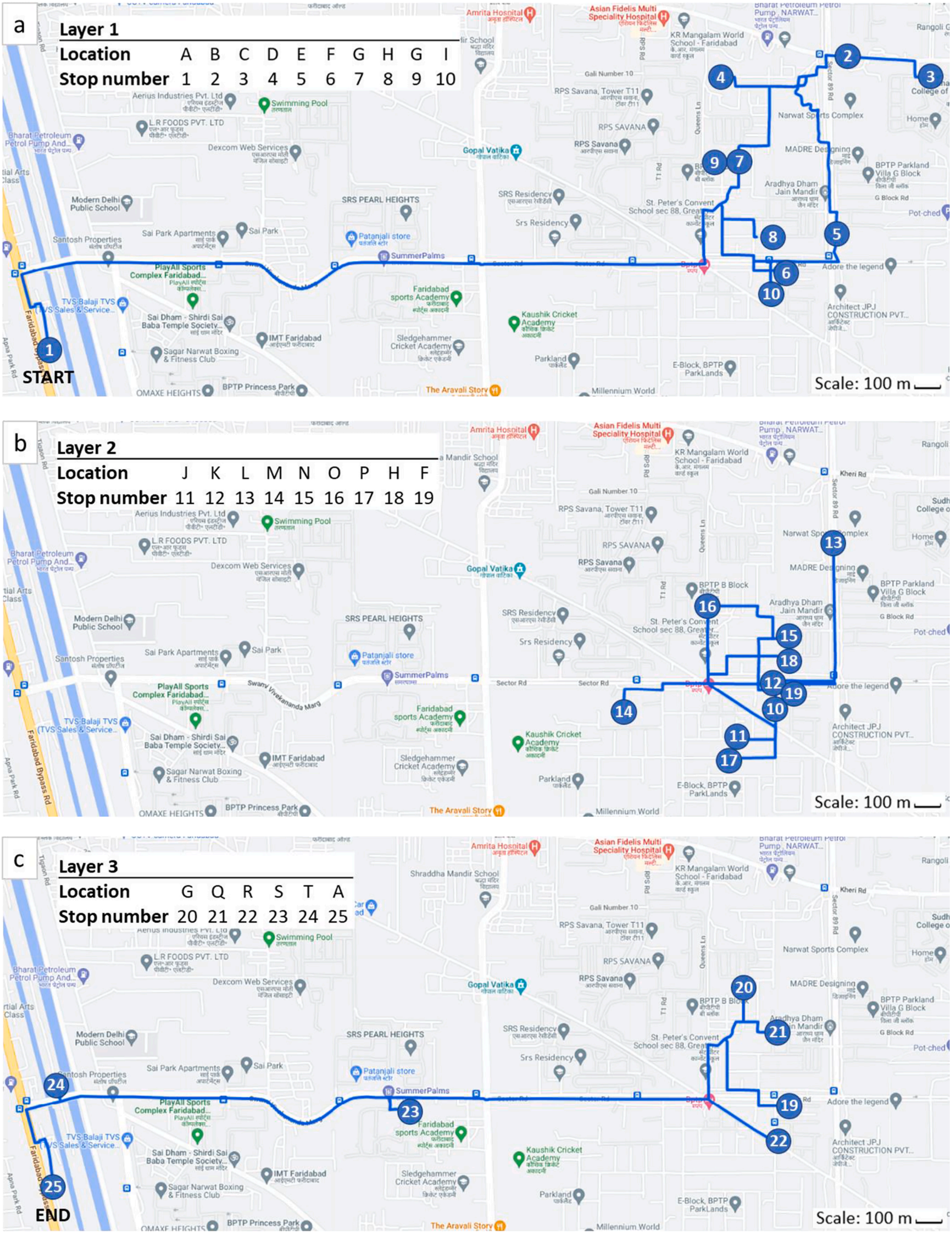

Fig. 8. Layers 1 (a), 2 (b) and 3 (c) of the paths travelled by Person C on Day 2 (covered 20 km, collected no e-waste). Source: Google My Maps.

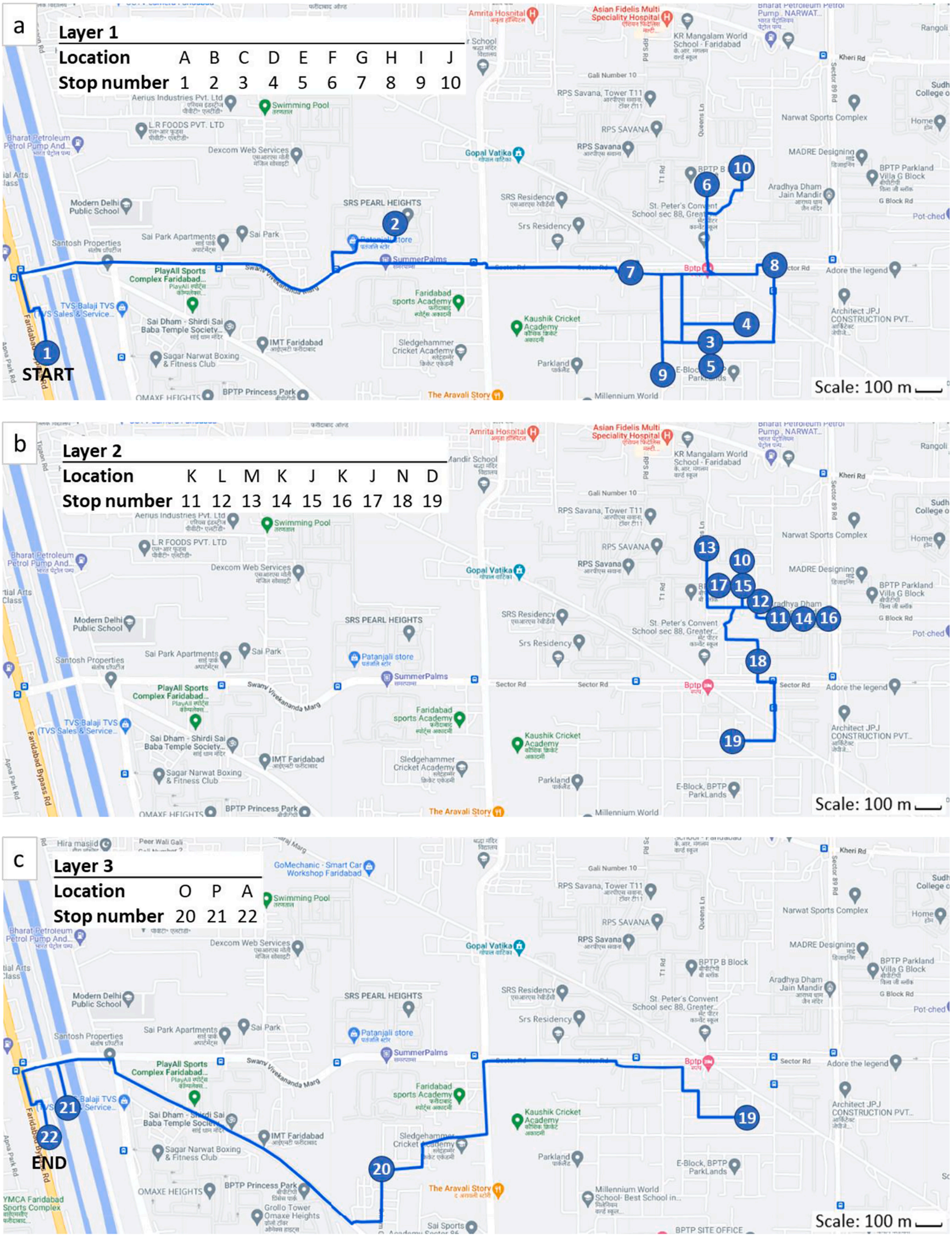

Fig. 9. Layers 1 (a), 2 (b) and 3 (c) of the paths travelled by Person C on Day 3 (covered 17 km, collected 43 kg of e-waste). Source: Google My Maps.

according to the prescribed regulations and converting themselves to formal recyclers through registration under respective regulatory bodies, such as the SPCBs as suggested in Sengupta et al. (2022).

The overall outcomes of the work could help achieve the United Nations sustainable goals (SDGs) in the country (SDG 11: sustainable cities and communities, SDG 12: responsible consumption and production). In addition, this work also supports the overall objective of the "Mission LiFE" announced by the prime minister of India (Niti Aayog, 2023) by promoting sustainability and cultivating the circular economy concept within the existing e-waste industry in India.

CRediT authorship contribution statement

Diyasha Sengupta: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft. **I.M.S.K. Ilankoon:** Conceptualization, Validation, Writing – review & editing, Resources, Funding acquisition, Supervision. **Kai Dean Kang:** Conceptualization, Writing – review & editing. **Meng Nan Chong:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supplementary document containing raw data has been added.

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Appendix A. Supplementary data

Supplementary data (Supplementary Document 1) to this article can be found online at https://doi.org/10.1016/j.mineng.2023.108154.

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