Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-023-30207-2

REVIEW ARTICLE

Challenges to implement and operationalize the WEEE reverse logistics system at the micro level

Suzana das Neves Silva[1] · Luciana Harue Yamane[1] · Renato Ribeiro Siman[1]

Received: 18 April 2023 / Accepted: 27 September 2023

Abstract
Waste electrical and electronic equipment (WEEE) possesses unique characteristics such as its growing production and the potential for resource extraction due to its composition. The implementation and operationalization of a reverse logistics system (RLS) for WEEE is a challenge, particularly concerning the micro level. The implementation of such systems often prioritizes urban centers and their higher population densities, generally overlooking the micro level. The latter refers to ward- or village-level divisions, which can be regarded as the smallest administrative divisions of both urban and rural areas. Furthermore, it encompasses any area facing logistical challenges regarding RLS operationalization due to factors such as geographical isolation, budgetary constraints, imbalances, social isolation, environmental aspects, and even geopolitical conflicts. This study is aimed at addressing this literature gap by discussing the challenges to implement and operationalize a WEEE RLS at the micro level. A systematic literature review was employed as our methodology. We found 13 challenges for developed and developing countries without distinction between macro and micro levels. An additional approach highlighted the significance of monitoring and controlling WEEE RLS. The challenge *The population and LRS entities' lack or insufficient training and awareness* received the most citations in the conducted search. These challenges were organized by operational phase and discussed from the perspective of the micro level to comprehend multifactorial local challenges involving all stakeholders in the reverse logistics of WEEE in emerging nations. This can assist local administrators and constitutes the primary contribution of this study.

Keywords E-waste · Reverse logistic · Small cities · Village level · Small municipalities

Introduction

The processes to produce waste electrical and electronic equipment (WEEE) have characteristics that make their reverse logistics system (RLS) complex from an operational point of view, such as its progressive and diffuse production, the heterogeneity of its composition, varying sizes (from cell phones to refrigerators), and their possibility of containing both valuable and dangerous components.

The most recent report available, the Global E-waste Monitor 2020, shows that approximately 53.6 million tons of WEEE were produced in 2019, averaging 7.3 kg per individual (Forti et al. 2020). Although the next report is scheduled for December 2023, estimates expect that this trend of increasing WEEE production will persist.

Developed countries such as Australia, China, Japan, the Republic of Korea, and those in the EU and in North America lead this production. The USA and Canada average per capita around 20 kg, whereas the EU, 17.7 kg (Forti

Responsible Editor: Philippe Garrigues

Highlights
- Implementing the WEEE reverse logistic at micro level is challenging
- Micro level (lower administrative divisions) is often overlooked
- Challenges were identified in all operational stages
- Most cited challenge is environmental awareness
- Future studies should focus on supervision and control challenges

✉ Renato Ribeiro Siman
renato.siman@ufes.br

[1] Environmental Engineering Department, Federal University of Espírito Santo, 514, Fernando Ferrari Avenue, Vitória, Espírito Santo 29075-910, Brazil

Published online: 13 October 2023

et al. 2020). In contrast, in developing nations such as those in the African continent (which has 1.2 billion inhabitants), the average production per person only totals 1.9 kg (Forti et al. 2020). Therefore, despite the significant production of WEEE, rates fluctuate depending on the country and population scale.

Regarding their composition, WEEE shows a notable economic incentive for recycling, encompassing a diverse range of resources and over 60 distinct metals, including copper, gold, silver, aluminum, and iron (Thakur and Kumar 2020). These metals are predominantly found in printed circuit boards (PCBs) and represent a potential source for resource even in developing nations. Brazil, for example, may channel these resources to waste picker associations, provided they integrate themselves into an RLS. PCBs have an attractive market value, which can stimulate local associations and companies to engage in this process.

Reverse logistics generally refers to a set of processes for managing the physical flow of products and their packaging from material extraction to end consumers (reversing traditional logistics) (Tibben-Lembke 1998). An operationally viable WEEE RLS must assign responsibilities to all members of the chain under the principle of shared responsibility. The chain begins with consumers, who must return WEEE to retailers or distributors. In turn, retailers and distributors must return them to manufacturers or importers. Finally, manufacturers and importers are responsible for the environmentally appropriate disposal of WEEE (European Union 2012; Brasil 2020; Gharib et al. 2022).

Faced with the rapid growth of the global production of WEEE (Khoshand et al. 2023), the advancement of environmental legislation, and the increase in consumer pressure for social responsibility, several LRS have been implemented in the world, mainly in developed countries. Switzerland was the first country to implement an organized WEEE collection and recycling system in 1995 (Sinha-Khetriwal et al. 2005), followed by Sweden, which became a global leader in WEEE collection as a result of a 2001 agreement between electrical and electronic equipment manufacturers and local authorities.

The European Union, a continental example, has guidelines that determine the implementation of public policies to manage WEEE, such as the WEEE Directive (2012/19/EU) and the Restriction of Hazardous Substances Directive (European Union 2012). However, in developing countries, WEEE LRSs remain at an early stage of implementation, whose specific models must be adjusted to local realities with special care for operationalization in villages and neighborhoods in which logistical challenges may be greater (Guarnieri et al. 2020; Shittu et al. 2021; Dutta and Goel 2021; Xavier et al. 2021). As one moves toward the grassroots level, management models drift further away from established systems, which is an undesirable circumstance. These issues can compound with each other due to the absence of collection mechanisms, resulting in challenges such as REEE accumulation and resource wastage.

WEEE management varies across developed and developing countries due to factors such as infrastructure, regulations, and available resources. Developed countries have a robust infrastructure, efficient collection, specialized recycling centers, and stringent regulations. In contrast, developing countries face challenges regarding infrastructure, waste separation and treatment, and inadequate regulations. This difference underscores the need for a coordinated global approach, including international cooperation, comprehensive regulations, the sharing of best practices, and awareness about WEEE recycling and proper disposal (Anandh et al. 2021).

The literature has the following categorization of the micro level: according to Koshta et al. (2021), and it refers to the division made at the ward or village level and can be considered as the smallest administrative divisions for urban and rural areas.

Countries usually have distinct levels of administrative divisions whose names and structure vary from country to country and even within the same country. For example, in the WEEE LRS in Brazil, municipalities with less than 80,000 inhabitants were not covered by Federal Decree No. 10.240, which estimates that, by 2025, the Brazilian WEEE LRS will have 5,000 collection points in 400 of its largest municipalities, reaching around 60% of its Brazilian population. However, although the program encompasses more than half of the Brazilian population, it fails to support 93% of the municipalities in the country (from a total of 5,570) (IBGE 2021).

However, the definition of the micro level goes beyond the administrative scope (Fig. 1). For a more comprehensive understanding, the micro level can be conceptualized as any area facing logistical challenges integrating itself into the RLS. This may happen for various reasons, such as geographical factors (e.g., islands), economic constraints (e.g., budget deficits), social isolation or imbalances (e.g., Indigenous peoples, impoverished communities, and “slums”), environmental aspects (e.g., areas close to environmental preservation zones), and geopolitical conflicts (e.g., war-involved regions).

Furthermore, this distinction between micro levels is applicable to both developed and developing countries. For instance, the Brazilian municipality of São Paulo represents a macro level, but only the municipality itself is considered at this level, whereas the surrounding neighborhoods fall under the micro level. A similar example is observed in Europe, in which an extensive rail network facilitates connectivity between rural or less populous areas. Consequently, establishing connections among these locations constitutes a macro level that encompasses regions that

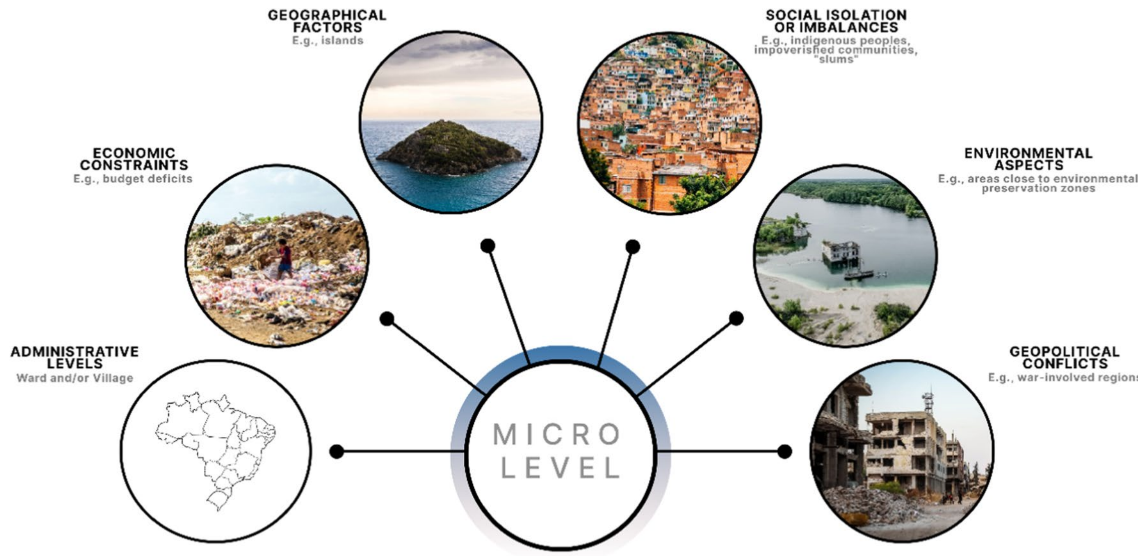


Fig. 1 Micro level under the perspective of RLS

can be easily integrated to an RLS. However, achieving these connections offers challenges. Hansen et al. (2022) highlight that transportation services can involve costs and bureaucratic hurdles. The authors also found that some sector stakeholders considered increasing waste availability for recycling by international waste transportation but strict regulations on cross-border waste transportation hindered such an approach.

In summary, the analysis of these diverse administrative layers gives rise to a realization: regardless of their origin, all types of waste fall under a universal principle: extended producer responsibility. This concept demands that manufacturers of goods (including WEEE) take responsibility for the proper management of these products at the end of their life cycle, which includes collection, recycling, and proper disposal (Leclerc and Badami 2020).

In other words, waste generated in the urban center of a developed country follows the same principle as waste generated in a rural area of a developing country. The producer's responsibility remains the focus, regardless of the geographical origin of the waste. Even waste with more isolated geographical origins still fall subject to this same principle, ensuring that collection takes place even at the micro level.

This context evinces that collection must remain a crucial element even in regions with lower waste production rates (such as Africa, see above) and in logistically remote areas uncovered by a RLS. Waste accumulates over time in these collection-deprived localities, differing from urban centers which, despite their significant production, benefit from RLS implementation and its corresponding collection. Therefore, collection proves imperative in scenarios of remote production, in which the threat of waste accumulation becomes considerably more pressing, fostering informal recycling, for instance.

The informal recycling sector is a problematic social and environmental obstacle (Ciocoiu et al. 2016; Orlins and Guan 2016; Liu et al. 2017; Tran et al. 2018; Yong et al. 2019; Tian et al. 2021; Mohammadi et al. 2021). The flow of WEEE through informal recyclers is greater than that of formal recyclers (Kumar and Dixit 2018a; Baidya et al. 2020; Okwu et al. 2022).

The complexities of the collection network and the deficiencies of the process have been reported as the main reasons for the failure of many formal initiatives (Pourhejazy et al. 2021). Formal WEEE recycling is generally seen as unprofitable since it requires expensive investments, dependence on government subsidies, and high labor costs to recover underperforming materials with low profits (Bakhiyi et al. 2018). Zhang et al. (2015) explain that, due to economic factors, informal recycling is profitable in China because informal collectors pay consumers for WEEE. Therefore, most consumers in China are willing to sell their discarded products to street vendors, rather than participating in collection systems, for which they must pay to dispose of their discarded electronic products.

Discussing the challenges to implement and operationalize LRS at the micro level is the main contribution of this study since reverse logistics in urban centers (which concentrate higher population densities) are usually elected for LRS implementation (although they also face challenges, especially in developing countries).

Thus, this research considered places with 80,000 inhabitants or less as the micro level. Locations that also face operational problems related to WEE collection, transportation, storage, and/or final disposal due to geographical isolation (such as islands or remote areas) can also be considered as the micro level.

At the macro level, the studies carried out by Bouzon et al. (2018) and Sirisawat and Kiatcharoenpol (2018) point out the main barriers to WEEE LRS implementation: lack of skilled labor to handle this type of waste, lack of recycling technologies, disagreement among supply chain entities (lack of coordination and support in the supply chain to implement an LRS), limited planning of reverse logistics activities, absence of specific regulations, insufficient waste management practices (lack of unambiguous return policies or of fully regulated waste management), lack of financial resource prioritization, lack of a transportation infrastructure, and lack of a technical staff trained to manage solid waste in general.

Micro-level challenges increase due to vehicle routing, resource allocation, facility location, collected/treated waste capacity determination, among other factors, but no studies have shown how and what challenges impact a WEEE LRS.

In view of the above, our study aims to fill this gap in the literature by identifying the challenges to implement and operationalize reverse logistics systems of electronic waste at the micro level by a systematized literature review to aid local managers.

Methodology

The systematized review of the literature to be used in this research was divided into seven stages as illustrated in Fig. 2.

I. Definition of search terms
II. Definition of databases and period of publication
III. Search of articles on databases
IV. Application of filters to select articles (title, abstract, and full reading of articles)
V. Download of selected articles
VI. Identification and categorization of WEEE LRS challenges
VII. Analysis and systematization of secondary data

Based on an initial evaluation of the literature, the chosen research problem was "Challenges related to the implementation and operationalization of reverse logistics systems for electronic waste in locations classified as micro level." The main search terms related to the theme were identified, namely: "WEEE," "e-waste," "electronic waste," "electrical and electronic waste," "waste of electric and electronic equipment," "electro-electronic equipment," "implementation," "deployment," "reverse logistics system," "reverse logistic," "electronics logistic," "shared responsibility," "operational," "operationalization," "collection," "transport," "temporary storage," "final destination," "dysfunction," "problem," "difficulty," "barrier," "obstacle," "micro level," "village level," "ward village level," "municipal," "rural," "island," "small town," "small village," and "hamlet."

The search for articles was conducted on two platforms: Scopus and Web of Science. The latter creates a network of publications and researchers based on citations and the controlled indexing of content (Clarivate 2022). The platform was chosen due to its relevance as its collection encompasses more than 74.8 million academic data and datasets, 1.5 billion references, and 254 disciplines and enables the search for recognized authors in an area of interest (Clarivate 2022). The choice of Scopus was also based on its relevance. Updated in 2019, its content coverage guide indicates that the platform consists of about 23,452 active journal titles, 120,000 conferences, and 206,000 books from more than 5,000 international publishers (Elsevier 2020). Moreover, Scopus is considered as one of the largest curated databases of scientific journals, books, conference proceedings, etc., which are selected by a process that undergoes continuous reassessment (Singh et al. 2021).

The use of both platforms enables a more complete analysis. They were searched in July 2022 using only combinations of English keywords, including patents and citations. The search used the Boolean operators "AND" (which enables the combination of two or more words) and "OR" (which is used for similar terms or for those with the same meaning). Some points regarding the used platforms should be considered. The first refers to the difference in found results per platform. When searching for the aforementioned search terms, Scopus retrieved 376 articles and Web

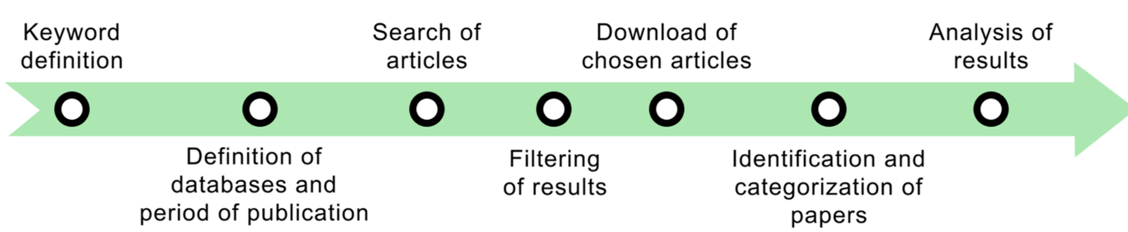


Fig. 2 Research steps

of Science, only six. This can be due to different policies on use of versions of publication dates (Liu et al. 2021).

After removing duplicates, the sample from both platforms totaled 378 original studies. From a preliminary analysis of study titles, keywords, and abstracts, 84 studies from Scopus and two from the Web of Science were selected, resulting in a final bibliographic portfolio with 86 original publications. After reading these publications, the studies that did failed to fit the objectives of this study were excluded.

In the next step, the studies were read to identify and categorize the challenges to WEEE LRSs. For this, according to the Brazilian Federal Decree No. 10.240/2020, challenges were identified by stages of LRS operation, i.e.: (I) disposal by consumers of WEEE at specialized or door-to-door points, (II) receipt and temporary storage of WEEE discarded at receiving points or received at consolidation points, (III) transportation of WEEE from receipt or consolidation points to environmentally appropriate final destinations, and (IV) destination and final disposal.

Results and discussion

Overview of WEEE LRS challenges at the macro level

Some of the found challenges point to the importance of monitoring and controlling WEEE LRSs due to their fundamental importance for the functioning of these systems. Generally, the rigidity of legislation is unaccompanied by the supervision and control of the destination and final disposal of waste, enabling informal recycling (Morganti et al. 2020). Although many countries have implemented several structures to properly manage WEEE, most electronic waste ends up in landfills, incinerated, or illegally exported to developing countries (Rajesh et al. 2022).

Tian et al. (2022) report that competition with formal channels for WEEE recycling is a challenge. Most developing countries (especially China) have profitable indirect initiatives due to the demand for secondary resources and the low wages of skilled workers. The well-established structure of the informal sector and its operational capacity, especially in developing countries, lead to the wide collection, accessibility, and flexibility of door-to-door services (Pourhejazy et al. 2021).

Informal WEEE recyclers face some limitations, such as the lack of essential facilities that can improve their efforts and activities (Maphosa and Maphosa 2020; Jangre et al. 2022; Okwu et al. 2022); of safety equipment to protect them from health-related risks usually associated with hazardous elements (Acquah et al. 2021); of essential training on how to protect themselves, handle WEEE, environmental issues, etc. (Salhofer et al. 2016) and of access to adequate guidance, training, health units, and first aid treatment in case of emergencies (Acquah et al. 2021; Okwu et al. 2022); as well as low wages (Salhofer et al. 2016; Imran et al. 2017; Andeobu et al. 2021).

Awasthi and Li (2017) and Borthakur and Sinha (2013) point out that another problem in the informal WEEE processing sector involves child labor (which is illegal under international law) and vulnerable women.

However, in some cases, even the law fails to offer adequate coverage. Loopholes in legislation cause substantial deficiencies in enforcement capabilities and require the development of a wider range of enforcement tools. Thus, amendments to legal and political structures should consider not only legal principles but also effects on markets, access to the data necessary to establish a response mechanism, and the economic effort necessary to monitor operations (Morganti et al. 2020).

Rautela et al. (2021) highlight that WEEE transportation is a challenge due to the unidentified/recorded amount produced and collected in cities. The WEEE of developed countries is transported to developing countries, in which they are often stored under precarious conditions. The sustainable transportation of WEEE can be achieved by establishing adequate collection channels and transfer stations similar to those used for municipal solid waste (Rautela et al. 2021).

The informal sector remains actively involved in the transportation of WEEE without the benefit of specified vehicles and regulatory protection. Manufacturers, recyclers, and consumers would play crucial roles in enabling the smooth and safe transportation of WEEE produced in a city by adopting regulations (Rautela et al. 2021).

Notably, cost of transportation configures one of the main factors that influence the efficiency of urban WEEE mining. Bouvier and Wagner (2011) have shown that the barriers associated with reverse logistics systems mainly include costs associated with transportation. Nowakowski (2017) points out that collection companies must prepare vehicles and containers to return discarded equipment. Transportation costs depend on the type and fleet of vehicles, the length of the route, and the number of employees. Moreover, another cost arises since the vehicles are packed with unusable (rather than profitable) equipment.

A considerable commitment has been currently devoted to the development of international and national legislation that will strengthen the regulatory structure of waste and surveillance capabilities. However, the general inability of applying and regulating structures to effectively combat the illegal export of WEEE has been reported. This results in a general sense of impunity since both the perception of the risk of being caught and the likelihood of criminal prosecution are extremely low for environmental crimes (Favarin and Aziani 2020).

Mohammadi et al. (2021) state that transporting WEEE across borders is one of the worrisome challenges of WEEE management in Asian countries.

Salmon et al. (2021) claim that the export of WEEE to developing countries is a widely studied issue and that some products can be recycled by unregulated and harmful methods. New examples of fraud or dishonest practices include lapses in the security of personal data when used electronics are resold, non-functional products included in cross-border shipment transactions under the guise of reuse, buyer or seller fraud during online resale or product auctions, and repair of electronics with counterfeit components.

Elia et al. (2019) point out that the illegal dumping and export of waste to developing countries occurs in part due to the lack of collection points and coordination between collection service providers and retailers/manufacturers.

According to Tran et al. (2018), about 65% of all precious metals, plastics, and glass in WEEE remained in the Vietnamese economy due to reuse. The remainder (about 30–34%) was illegally exported (in the case of precious metals and plastics) or disposed in landfills (in the case of glass).

In addition to illegal export, there is also legal export to countries that have the technology to recycle WEEE. Recyclers are dedicated to dismantling and separating WEEE, instead of following advanced activities, so the collected and separated materials are exported to international markets for final material recovery (Gunarathne et al. 2020). In Sri Lanka, WEEE recyclers export most of the basic materials. Because Sri Lankan recyclers export materials with lower added value, they receive unattractive export market prices, creating financial difficulties for recyclers to remain in the industry (Gunarathne et al. 2020).

Furthermore, Sharma et al. (2021) find a lack of standards to measure the recycling potential of WEEE, i.e., its recyclability, which refers to the theoretical probability of an item actually being recycled considering the difficulty of physically treating and chemically recovering recyclable metals, plastics, and glass. A comprehensive theoretical guide to recycling processes with a quantitative ecological design and recycling responsibility is essential to determine the authentic recyclability of WEEE. This study created mathematical models based on the physical and chemical characteristics of the materials contained in the WEEE to calculate the recyclability and difficulty of recycling various types of electronics (Zeng and Li 2016).

Therefore, the need for more efficient supervision and control is of international concern, along with an integrated management of industries with governments and the whole society to effectively achieve environmental sustainability.

WEEE LRS challenges at the micro level

Regarding this study, it is important to highlight that, after the research, most of the portfolio summarized in Table 1 focus on the macro level, evincing the gap in the literature regarding the micro level. Only a few studies addressed challenges related to the operationalization and implementation of a WEEE LRS as part of the elaboration of their research problem (rather than as their main focus), applying it at lower levels (whether at the state, city, or neighborhood level), comparing urban and rural environment, or even evaluating case study on islands.

Notably, several studies on the portfolio focused on the challenge *The population and LRS entities' lack or insufficient training and awareness*. Although a social challenge, the operational scope of this study considered this a challenge since lack of awareness is directly related to inadequate disposal, the first step of reverse logistics systems.

Table 1 summarizes the bibliographic landscape of challenges listed in each operational phase. This table includes a diverse array of studies originating from the extensive literature concerning WEEE RLS. However, this study discusses the micro level, for which information availability in the literature is limited. Thus, while challenges have been identified at the macro level for both developed and developing countries, a gap remains to be filled in investigating the micro context, especially in developing countries. As a result, the classification of challenges followed the operational phases of the RLS as these very phases must be fulfilled for both the micro and macro levels, constituting a universal categorization that encompasses all spheres.

The following sections discuss how the identified challenges (Table 1) impact WEEE LRSs at the micro level according to operational stages.

Step (I): disposal

1A The population and LRS entities' lack or insufficient training and awareness Although disposal behavior and consumer awareness are central to successful WEEE management interventions, few consumers are aware of the importance of WEEE recycling, the hazards related to these products, and available disposal options. Thus, they often erroneously dispose of WEEE with other household waste (Araujo et al. 2017; Imran et al. 2017; Kumar 2019; Andeobu et al. 2021; Jangre et al. 2022; Okwu et al. 2022; Santos and Ogunseitan 2022), regardless of whether they reside in dense urban centers or in remote villages.

For Salhofer et al. (2016), the disposal of small WEEE, such as mobile phones, also offers a challenge precisely because of their size since they "fit" in the disposal of household waste, being discarded in a "practical" way.

Table 1 Summary of the challenges to operationalize and implement a WEEE RLS

Operational stage	Challenges	References
1 Disposal	1A The population and LRS entities' lack or insufficient training and awareness	(Nnorom et al. 2011; Borthakur and Sinha 2013; Sirisawat et al. 2015; Ylä-Mella et al. 2015; Nowakowski 2017, Nowakowski 2019; Dixit and Badgaiyan 2016; Jafari et al. 2017; Borthakur and Govind 2017; Pérez-Belis et al. 2017; Imran et al. 2017; Bakhiyi et al. 2018; Fan et al. 2018; Kumar and Dixit 2018b, Kumar and Dixit 2018a; Dagiliūtė et al. 2019; Chen et al. 2020; De Aquino et al. 2020; Gunarathne et al. 2020; Arya and Kumar 2020; Salmon et al. 2021; Islam et al. 2021; Shahrasbi et al. 2021; Andeobu et al. 2021; Gharib et al. 2022; Jangre et al. 2022; Siddiqua et al. 2022; Yadav et al. 2022; Almulhim 2022; Santos and Ogunseitan 2022)
	1B Inadequate disposal of WEEE	(Borthakur and Sinha 2013; Salhofer et al. 2016; Fan et al. 2018; Marczuk et al. 2019; Baidya et al. 2020; Gollakota et al. 2020; Mohammadi et al. 2021; Okwu et al. 2022; Rajesh et al. 2022; Almulhim 2022; Santos and Ogunseitan 2022)
	1C Difficulty classifying and segregating WEEE	(Cole et al. 2016, Cole et al. 2019; Tansel 2017; Kazancoglu et al. 2020; Okwu et al. 2022)
	1D Inadequate distribution of WEEE disposal points	(De Aquino et al. 2020; Sari et al. 2021)
2 Collection and receipt	2A Collection rate and WEEE collection/disposal points	(Bouvier and Wagner 2011; Mmereki et al. 2015; Zhang et al. 2015; Bakhiyi et al. 2018; Marczuk et al. 2019; Elia et al. 2019; Chen et al. 2020; Gunarathne et al. 2020; Gollakota et al. 2020; Arya and Kumar 2020; Andeobu et al. 2021; Okwu et al. 2022)
	2B Insufficient WEEE receiving and sorting plants	(Yao et al. 2013; Ciocoiu et al. 2016; Tansel 2017, Tansel 2020; Gunarathne et al. 2020; Vieira et al. 2020; Okwu et al. 2022; Singh et al. 2022)
	2C Intelligent WEEE collection systems not applied	(Yao et al. 2013; Elia et al. 2019; Nowakowski and Pamuła 2020; Kazancoglu et al. 2020)
3 Transportation	3A Deficient WEEE transportation infrastructure	(Nowakowski 2017; Hansen et al. 2022)
	3B Long and costly distances	(Nowakowski and Mrówczyńska 2018; Hansen et al. 2022)
4 Final destination	4A Lack of technical training to work in the WEEE recycling sector	(Mmereki et al. 2015; Araujo et al. 2017; Tansel 2017; Imran et al. 2017; Kumar and Dixit 2018a; Masud et al. 2019; Gollakota et al. 2020; Kazançoglu et al. 2020; Arya and Kumar 2020; Sharma et al. 2021)
	4B Research and development shortage of WEEE recycling technologies	(Zhang et al. 2015; Song et al. 2017; Awasthi and Li 2017; Bakhiyi et al. 2018; Kumar and Dixit 2018a; Yong et al. 2019; Vieira et al. 2020; Tansel 2020; Sharma et al. 2021; Salmon et al. 2021; Jangre et al. 2022)
	4C Absence or insufficient number of WEEE recycling companies	(Nnorom et al. 2011; Mmereki et al. 2015; Sirisawat et al. 2015; Song et al. 2017; Kumar and Dixit 2018a; Afonso 2018; Neto et al. 2019; Chen et al. 2020; Gollakota et al. 2020; Acquah et al. 2021; Sharma et al. 2021; Berežni et al. 2021; Andeobu et al. 2021; Okwu et al. 2022; Almulhim 2022)
	4D Heterogeneous composition hinders treatment	(Shahabuddin et al. 2022; Rajesh et al. 2022)

Dagiliūtė et al. (2019) shows that consumers who had less knowledge about collection points more often discarded WEEE along with household waste or stored them at home, being more prone to irregular disposal. Factors such as age, educational level, and income also correlate with these WEEE disposal behaviors.

Regarding the population's educational level, a highlight refers to rural communities lacking even more awareness about the management of WEEE (Sirisawat et al. 2015). It is also worth mentioning that this is the reality of many developing countries (Gunarathne et al. 2020), even in the urban environment.

Regarding the micro level, the financial scope can intensify the challenge of the population's lack of awareness. The difficulty in promoting environmental education campaigns, for example, can be due to a lean budget. Small municipalities have more restricted budgets and lesser capacity for collection, generating dependence on Federal and State intergovernmental transfers, making them financially dependent on the State and the Union and restricting their autonomy. When faced with financial difficulties, adopting a planning strategy (considered as a necessity in the face of resource scarcity) becomes essential to obtain the best possible results with the use of limited available resources.

In addition to consumers, other members in reverse logistics chains also lack awareness/information, especially local retailers since they lie outside commercial networks with vertical marketing strategies (as is common at the micro level). However, lack of awareness occurs on a global level.

Arya and Kumar (2020) report the lagging public awareness of the health hazards of informally recycling WEEE in India. The scavengers, manufacturers, and refurbishers involved in repairing obsolete appliances are unaware of the potential risk of these products to their health and the environment.

Similarly, Gunarathne et al. (2020) warn of the lack of awareness of all links in the WEEE LR chain in Sri Lanka, not just consumers. Pakistan also has a need to educate recyclers, scavengers, manufacturers, and consumers about the handling, collection, disposal, and impacts of WEEE (Imran et al. 2017).

Almulhim (2022) states that ignorance about the proper management of WEEE has configured a significant challenge for the population of Saudi Arabia. They state that awareness among chain members enables informed choices about management strategies to reduce the environmental impact of WEEE.

Consumer behavior has been studied to improve WEEE disposal patterns. Shahrasbi et al. (2021) point out that it is essential to obtain the necessary information about consumer attitudes and behaviors to design a structured WEEE management system. They also claim that increasing the amount of collected WEEE and ensuring that they are properly processed are two of the main objectives of Directive 2012/19/EU, both of which highly depend on consumer behavior and WEEE disposal.

Siddiqua et al. (2022) agree that understanding the buying and discarding behavior of consumers of electronic products would suggest to policymakers the development of strategies aimed at WEEE RLSs. They also show that the attitude and awareness of consumers is a key factor that directly influences the recycling of WEEE. Findings on the ignorance of WEEE disposal mechanisms practically imply that this can lead to the failure of the pro-environmental WEEE disposal programs implemented by the UAE government.

In addition to lack of awareness, authors have addressed lack of will. Gharib et al. (2022) state that the unwillingness of the population or local authorities to cooperate in the management of WEEE is a critical problem and that the perceptions of internal stakeholders (including manufacturers, suppliers, distributors, retailers, consumers, and government consumers) should be assessed and integrated.

Kumar (2019) comments that one of the biggest threats to the success of reverse supply chain management is the reluctance of consumers to participate in the recycling process. They also state that, since the starting point of any reverse supply chain is the will and active participation of consumers in the recycling process, it is necessary to understand the factors that influence this behavior that is dynamic and is influenced by consumer ideology, familiarity/convenience of recycling activities and demographics.

Some authors point out ways to promote this awareness. Almulhim (2022) points out that one of the pillars of WEEE management is raising awareness by programs and events. Disseminating information, promoting discussions, and involving government authorities and relevant stakeholders to raise awareness are the first step for the proper disposal of WEEE. Research by Ylä-mella, Keiski, and Pongrácz suggests an explicit need for more information and publicity about the recovery of mobile phones in Finland (especially up-to-date information on retrieval services by retailers) to change consumers' current storage habits.

This impact on consumers' storage, repair, reuse, and disposal behavior can be generated by the development of communication tools to improve people's awareness, such as implementing WEEE training programs, investing in more diverse strategies involving social media, providing information in physical locations, and promoting awareness campaigns (Islam et al. 2021; Almulhim 2022). The education of individuals is one of the most important factors to improve WEEE collection rates. Depending on their behavior, waste can go through official systems of waste collection, informal recycling, improper disposal, or be stored in a residence (Nowakowski 2019).

Compared to the macro level, the micro level has fewer inhabitants, which facilitates social mobilization by events and programs. Community representatives are more centralized, and people in the community generally know each other, spreading information more quickly among themselves. Despite the possibility of distant properties (such as in rural areas), government authorities must commit themselves to an exclusive transportation for social mobilization events.

In contrast, Islam et al. (2021) show that consumers are demanding a substantial change in existing WEEE management systems. Issues that require the attention of researchers and policymakers around product and service innovation include formal WEEE collection and service options (online, door-to-door, sidewalk pickup, and proximity to permanent recycling centers).

1B Inadequate disposal of WEEE Due to the lack of public awareness, most individuals seem to ignore the toxicity or hazard of WEEE, and few consumers know the dangers of WEEE. Thus, WEEE is generally discarded along with other waste contaminating urban solid waste—or even recyclable waste in selective collection (Borthakur and Sinha 2013; Okwu et al. 2022; Santos and Ogunseitan 2022). The main limitations in the European Union are related to small WEEE as they can easily be discarded with urban solid waste (Salhofer et al. 2016).

Gollakota et al. (2020) point out that unregulated disposal and illegal WEEE landfills in developing nations are the main concerns of WEEE management.

This impact on the environment due to the inadequate disposal of WEEE is worsened at the micro level. The mismanagement of solid waste is reported as one of the more immediate and acute challenges for islands (or small island developing states) than in other land masses. Inadequate disposal of WEEE and lack of end-of-life management systems cause coastal pollution, loss of biodiversity, and decreased natural population (Mohammadi et al. 2021).

A more realistic analysis must highlight that this challenge manifests itself both at macro levels in developed countries and at micro levels in developing nations as even developed countries with RLS in place face difficulties addressing this issue. An example of this is evident in the study conducted by Marczuk et al. (2019), which concluded that WEEE accounts for 0.02% of the total weight of common waste collected throughout the year in Lublin, indicating the imperfections in the WEEE collection system and the need for improvement. Thus, even after over 10 years as part of the European Union, the presence of WEEE in mixed municipal waste evinces it as an issue not only with WEEE collection but also with selective collection in general.

Challenges are inherent to RLS regardless of the level to which they are applied but they are further exacerbated at the micro level when in synergy with other factors.

1C Difficulty classifying and segregating WEEE Consumers are known to have difficulty in differentiating electrical and electronic equipment (Okwu et al. 2022) from WEEE because they neither know their concepts nor can identify types of WEEE, regardless of macro or micro levels. However, the solution (which stems from environmental education) is mostly lacking at the micro level due to the rarity of awareness campaigns.

According to Kazancoglu et al. (2020), the most significant problem in WEEE management stems from the lack of WEEE classification in emerging economies. The authors point out that, unlike in developed countries, emerging economies collect and recycle WEEE (when sent for treatment) without classifying them, thus incinerating or disposing their useful and valuable parts and components (and even products that could be reused) in landfills.

Furthermore, the absent or incorrect classification of WEEE directly affects their possible reuse and should thus be prioritized. Cole et al. (2019) claim that reuse is limited when discarded products need repairs, especially in the case of lower-value items. The authors state that discarded WEEE is usually intended for recycling due to incorrect handling during collection. Recycling targets also discourage the reuse of components since items are classified as "waste," for which recycling seems to be the easiest option (Cole et al. 2019).

WEEE requires manual sorting to produce adequate recycled products. Tansel (2017) considers the difficulty of separating the components as a challenge since they are screwed, embedded, glued, or welded to each other. For elements with similar physical, chemical, and thermodynamic properties, this difficulty can be reduced by pre-selecting the pieces that enter this process to release the materials by physical force. These processes may include grinding (by crushing, grinding, or shearing), which typically provide partial releases (Tansel 2017).

Classification can separate WEEE in lots with different prices according to their composition, valuing residues, and separating those that have contaminants. However, it is worth mentioning that this activity implies the existence of a structure than can receive and sort this waste when carried out after consumers' disposal stage.

Xavier et al. (2020) find two types of WEEE disassembly: the destructive, which neither preserves parts and components nor separates materials; and the non-destructive, which considers disassembly to preserve materials and components. In Brazil, NBR 16156:2013 establishes requirements to protect the environment and manage occupational safety and health risks during WEEE disassembly.

These criteria and requirements mentioned above are important but unattainable at the micro level since estimating the cost of disassembling WEEE is complex due to the different materials contained in them.

Additionally, safe and non-destructive WEEE disassembly requires the provision of spaces to receive and package post-consumer products, accommodate workstations and tools, and to allocate the different obtained materials; parameters which are hardly found at the micro level due to a lack of facilities or small installations (Xavier et al. 2020).

1D Inadequate distribution of WEEE disposal points An appropriate amount of disposal points arranged in strategic locations are essential to ensure coverage of the largest possible area (Sari et al. 2021).

WEEE disposal points must receive and store electronic products consumers discard without mischaracterizing these products until their transfer to their final environmentally appropriate disposal. Therefore, the appropriate location configures a point installed in a dry, clean, and safe place against theft, loss, and breakdown of collector containers with coverage and signage (Brasil 2020). Moreover, one should consider the population's easy access.

The inadequate location of disposal points impacts the difficulty of consumers' disposal. Retail is a very important part of the WEEE LRS since it is the closest stage to consumers. Thus, retailers become mediators between the industry and consumers. As consumers acquire electronic products at these commercial establishments, they configure easy points for disposal after use. Management entities should think of these points strategically, prioritizing places that receive great circulation of people and are easily accessible to consumers, such as shopping malls, supermarkets, and large popular stores.

Moreover, the inadequate location of disposal points also impacts collection routes. Studies propose appropriate locations or criteria for this by simulating transportation routes. De Aquino et al. (2020) highlight that the increase in WEEE maximized this problem due to the lack of adequate disposal sites (both in number and location). The authors proposed a mathematical model to allocate WEEE collection points to minimize the costs of opportunity, transportation, installation, and distance between demand and collection points. Sari et al. (2021) conducted a study that aimed to design a collection system determining the number and location of disposal point facilities and the site of a transportation route from a collection center to a final disposal location. They concluded that a disposal point should have a maximum range of 11.2 km and that, although a challenge, it can also offer an opportunity for the head of LRS management to design a collection system.

The micro level offers two aspects for consideration. In cities considered small (with less than 80,000 inhabitants), the problem involving inadequate localization of disposal points can be minimized since urban areas are smaller and commercial establishments are usually concentrated in these areas, facilitating the distribution of points. Moreover, it may be feasible to consult with the population to select an efficient location.

However, the problem of distributing the number and strategic location of disposal points in rural areas is maximized depending on the distance between residences and city centers/municipalities. If the aforementioned study was to be considered, for example, a 11.2-km maximum range of a disposal point would likely amount to one point for each residence in a rural area, resulting in an unfeasible system. Therefore, consumers may also opt for residential collection. However, if retail and/or managing entities provide this service, they should also provide adequate transportation, especially for large WEEE, such as refrigerators and stoves.

Step (II): collection and receipt

2A Collection rate and WEEE collection/disposal points The rate of WEEE collection/disposal is related to the behavior of consumers in relation to disposal, the degree of awareness of the population, legal issues, the fulfillment of goals, among other factors.

Most developing countries lack a WEEE legislation. In 2019, 78 countries had their WEEE legislation covering 71% of the world's population (Shahabuddin et al. 2022). Although some countries have the necessary legislation in place to collect and recycle WEEE, some goals imposed on the volume of WEEE collected and/or treated are minimal, requiring no effort from the LRS chain to comply with it.

Regarding consumer behavior, it is observed that the storage of obsolete or damaged WEEE in homes is common either due to emotional attachment, misinformation, or unwillingness, hindering the recycling and circularization of materials (Arya and Kumar 2020; Okwu et al. 2022; Santos and Ogunseitan 2022).

Gunarathne et al. (2020) claim that a challenge Sri Lankan families face in managing WEEE is their reluctance to dispose of televisions, refrigerators, rice cookers, and other old household equipment. This situation resembles that of some other developing countries and arises mainly due to lack of awareness.

However, at the micro level, the return rate of WEEE may suffer from the lower consumption link, which is directly related to local per capita production.

Zhang et al. (2015) showed that China—a country with more than 50% of the population living in rural areas and a wide difference in income and living standards between rural and urban areas—has a penetration rate of electronic products below 50%. Most electronic devices, such as computers and air conditioners, often still work, despite their obsolescence. Moreover, its disposal rate of WEEE is non-existent or much lower than that offered by companies. Thus, according to this study, China may be a country that has a lower WEEE production rate and a higher rate of reuse. However, its WEEE is still not discarded either due to the absence of this practice or of a local WEEE LRS.

For Andeobu et al. (2021), one of the challenges affecting WEEE management in South Africa includes home and business WEEE return rates. The authors conclude that access to sufficient volumes of WEEE is the most significant challenge for the growth of the South African WEEE recycling industry and for companies to move from their current manual decommissioning and limited preprocessing to further processing.

Therefore, micro WEEE return rates and collection/disposal points economically hinder the operationalization of reverse logistics systems due to the lack of scale. Possibly, the managing body of these locations will need to create a reverse logistics network that collects/receives WEEE from various locations in the vicinity to obtain a minimum WEEE weight. An example consists of intermunicipal municipal solid waste public consortia that, due to their formation and consolidation, require investments and support from the Union and the States. According to Ventura et al. (2019), small municipalities demand the most attention due to the increase in the deficient provision of collection services as these municipalities lack financial resources the most and qualified technical personnel to manage municipal solid waste.

Directly linked to return rates, the insufficient amount collection points is a reality in many countries (Elia et al. 2019; Gollakota et al. 2020).

The lack of WEEE collection points incentivized informal collectors due to their accessibility, which expanded the informal WEEE sector (Bakhiyi et al. 2018; Chen et al. 2020). Chen et al. (2020) also highlight the sub-barriers of this challenge: the lack of effective and acceptable collection models, site rental and employee recruitment costs, and the fear of competitive advantages from indirect collectors.

Bouvier and Wagner (2011) concluded that a barrier associated with WEEE collection systems (whether by voluntary delivery sites, private companies, and/or non-profit donation centers) is the lack or restricted access to a conveniently located facility.

According to Marczuk et al. (2019), reverse logistics systems require constant adaptation to changes in transportation structure and the amount of generated waste. The increasing amount of WEEE discarded at certain times of the year would require a greater number of collection points, more frequent emptying during these periods, and additional information campaigns. This challenge must be solved by selecting and continuously cooperating with entities that will be responsible for monitoring the filling these points.

Marczuk et al. (2019) report that this challenge is faced mainly in urban centers. The micro level shows a smaller fluctuation in disposal behavior and thus in the collection of WEEE discarded during the year. Generally, the reality shows low return rates because of the longer life of obsolete devices, i.e., a lower purchase rate of electronic products.

Mmereki et al. (2015) highlight that developed countries offer a variety of options for WEEE collection points (including sidewalk points, permanent delivery centers, and special delivery events) and points of purchase to facilitate WEEE collection. On the other hand, the lack of collection points impacts the micro level even more. Research by Gunarathne et al. (2020) shows that the absence of WEEE collection points in less populous areas leaves most of the WEEE generated in these areas without formal collection. Thus, WEEE recyclers have the burden of establishing their own collection channels.

One of the causes of this challenge at the micro level may be the financial issue discussed earlier. WEEE collection points have considerable cost as, in addition to involving various types of waste containers, they also require storage and transportation to consolidation points until they are forwarded for recycling.

Another issue that influences is the legislative sphere. The WEEE LRS in Brazil (still in its implementation phase), for example, fails to provide collection/disposal points for small municipalities, i.e., the country lacks even a legal requirement by the decree that establishes the system in the country, inhibiting the establishment of points at the micro level.

Moreover, micro-level trading is also an influence factor. The micro level generally shows a predominance of local retailers and merchants (rather than commercial networks) who neither have the necessary information nor are charged for the availability of collection/disposal points. Therefore, note that retailers are a fundamental part of the LRS because they are the closest contact with consumers.

2B Insufficient WEEE receiving and sorting plants Chen et al. (2020) point out that the availability of an infrastructure system plays a significant role in stimulating management practices in the WEEE industry.

The need for these locations is, according to Tansel (2020), due to advances in product design for increasingly compact and efficient systems, which, in turn, have created challenges for recycling and recovering materials as they involve a lack of infrastructure, adequate collection mechanisms, and proper material recovery mechanisms and processes.

According to Vieira et al. (2020), the lack of a collection service routine reflects the absence of a structure to receive the collected WEEE. The limited planning of waste management and the lack of reverse logistics organization represent the absence of the organization that would enable the reuse, recycling, and remanufacturing of products. For Gunarathne et al. (2020) and Okwu et al. (2022), the absence of well-established plants to receive and sort WEEE creates challenges (such as mixing WEEE with other types of waste), creating another problem not only for the collection but also for the treatment of WEEE.

The successful implementation of WEEE collection and its operation are of paramount importance to a developing country such as India, which has a considerable rate of WEEE production but an inadequate infrastructure. In addition to infrastructure, the distribution of collection points across geographical regions should be considered (Singh et al. 2022). Romania, as other Central and Eastern European countries, is far behind Western Europe in implementing reforms in the WEEE sector, and one of the main reasons for this gap is the lack of infrastructure to collect and recycle WEEE (Ciocoiu et al. 2016).

According to Yao et al. (2013), the planning and optimization of a formal collection network are fundamental for the recovery of WEEE in China. The authors focused on the weaknesses of the WEEE recycling system and the precarious municipal WEEE collection facilities in Shanghai.

At the micro level, self-employed recyclers and informal sector companies may resist delivering WEEE to organized and equipped receiving and sorting plants. The establishment of these plants would generate opportunities for cooperatives of more advanced waste pickers, for example, toward verticalizing the production chain.

Singh et al. (2022) provide significant information: the reported literature mostly covers the collection of WEEE in urban areas and almost no study has evaluated rural areas. Different parts of India have measures to collect WEEE from urban and rural users but their volume of collection is far from the expected value despite various stakeholders' efforts, such as the government and manufacturers, to improve it.

2C Intelligent WEEE collection systems not applied Smart systems play a crucial role in optimizing all stages of WEEE management, encompassing operations, tracking, collection, recycling, and overall management. These technological solutions leverage automation, data analysis, and connectivity to enhance the efficiency and sustainability of management. These systems encompass monitoring and tracking, data analysis, and online platforms.

Their advantages are notable: optimization of collection, sorting, and recycling operations with reduced costs and required resources; enhancement of traceability, facilitating the tracking of product lifecycles and thus reinforcing accountability; and production of crucial data to support decisions, including consumption patterns, product types, and waste flows (Shevchenko et al. 2021).

The Internet of Things and smart systems have a close and highly synergistic relation. The Internet of Things is a network of physical objects embedded in sensors, software, and technologies that aims to connect and exchange data with other devices and systems over the Internet. These devices and systems range from common household objects to sophisticated industrial tools, which can be applied to waste management (Haque et al. 2020). When applied to WEEE management systems, IoT plays a pivotal role in creating more efficient and responsive smart systems. Consequently, smart technologies can drive the transformation of waste management practices toward a more circular economic model.

According to Favot et al. (2022), European extended producer responsibility models to manage WEEE have been introduced, reflecting variations in market concentration and player responsibilities across countries. These models include the State Fund (eco-tax) Model, in which producers contribute to a waste management fund (potentially coordinated by a government agency); the Single Organization Model, characterized by industry-controlled compliance organizations and environmental agreements; the Competing Organization Model, in which compliance organizations handle take-back duties and compete based on fees; and miscellaneous producer-funded models. These models, although developed for the macro level, can also be adapted for the micro level if modified appropriately.

Kazancoglu et al. (2020) highlight the gap, especially in WEEE collection processes, based on tracking technologies and intelligent collection systems. The authors report that collection process digitization should be designed to leverage support and provide social, economic, and environmental benefits, such as reducing air pollution, improving working patterns, and reducing waste by using new technologies such as smart vehicles. Therefore, the implementation of digital technologies in WEEE collection processes provides process traceability and cost and time recovery per collection point.

Nowakowski and Pamuła (2020) investigated a system to facilitate the planning of WEEE collection and facilitate communication between individuals who request the collection of waste and collection companies. The authors claim that the mobile applications that currently support waste collection are relatively limited and primarily used to find waste collection points or set reminders related to the collection schedule. Additional features, such as vehicle route planning, could improve these applications.

Elia et al. (2019) find that the adoption of dynamic approaches to WEEE collection based on variable (rather than fixed) collection frequencies could help improve the overall efficiency of collection processes. Moreover, the demand for sustainable, low-carbon urban logistics is also increasing due to urban pollution and congestion. The authors described different models of WEEE collection, comparing them by simulation modeling, which enabled them to evaluate a set of key integrated performance indicators, evincing the benefits and limits of different logistic scenarios.

Yao et al. (2013) claim that the project of the WEEE collection network is a typical reverse logistics issue characterized by a convergent structure, in which end-of-life products are collected from many users and transported to a reduced number of recyclers by vehicle routing.

In the research by Yao et al. (2013), the WEEE collection and transportation network in Shanghai take place in an integrated solution approach. Collection and transit locations are identified by quadratic optimization models, and a well-organized collection scheme is then offered as a comprehensive scheduling guidance. The vehicle routing problem consists of locating the best route to a destination from a starting point with numerous variations and solutions.

Routes can be facilitated at the micro level due to the few collection points and smaller local centers (if centralized), unlike rural areas. Another point is financial resource scarcity. In fact, digital transformation projects require high investments to acquire technologies that remain expensive for management and the cost of information technology professionals, who are increasingly disputed in the market. Finally, a data infrastructure is needed, in view of the difficulties of storing public data and the need to integrate the systems used in city halls.

Stage (III): transportation

Regarding transportation challenges, to provide a more realistic analysis, it is crucial to emphasize that issues related to the inadequate transportation infrastructure for WEEE and extensive costly distances are not only confined to micro levels and developing countries (Wilker et al. 2022; Hansen et al. 2022; Nowakowski and Mrówczyńska 2018; Feitosa 2020; Kazancoglu et al. 2020; Da Costa et al. 2020) but also extend to macro levels and developed nations (Nowakowski and Mrówczyńska 2018; Hong et al. 2011). Even in developed countries with implemented RLSs, transportation demands careful locally adapted approaches.

The complexity stems from transportation challenges significantly differing between developed and developing countries due to disparities in their realities. Of all process stages, transportation shows the greatest discrepancy in reality between these two types of nations. A transportation challenge faced by a developing country can be exponentially more arduous than that faced by developed nations. While the nature of the problem remains the same, its magnitude varies according to context.

Lastly, the literature has significant limitations substantiating the discussion on transportation-associated challenges, constituting a substantial gap in this field of study. It is essential that more in-depth studies are conducted to explore this intricate transportation issue. The substantial discrepancies in transportation realities between developed and developing countries and micro and macro perspectives underscore the urgent need to fill this research gap, which this study has clearly identified.

3A Deficient WEEE transportation infrastructure The main transportation modes are divided into five categories: rail, road, waterway, air, and pipeline. Since infrastructure is the set of fundamental services for the socioeconomic development of a location, the transportation infrastructure refers to roads, highways, bridges, tunnels, railways, airports, ports, waterways, among others (Araújo et al. 2019).

A system that makes infrastructure impossible or in some way disrupts the flow of transportation of a region regardless of the type of transportation is considered inadequate. Some examples include problems with signage, plate readability and visibility, lack of protective devices, road obstacles and disturbances, insufficient and poor breakdown lanes, curves with small rays and low visibility, very narrow roads, and worn pavement (Wilker et al. 2022).

Hansen et al. (2022) point out that a potential barrier to the inclusion of WEEE management in investment decisions is the lack of waste transportation and recycling infrastructure. While the authors conclude that many developing countries lack such infrastructure (especially in rural areas), they fail to specify the type of structure but it is understood as referring to routes, bridges, tunnels, airports, ports, etc.

Nowakowski and Mrówczyńska (2018) report that restrictions such as lack of parking should be considered in city centers, busy streets, narrow sidewalks, etc. depending on the collection model. These factors can prevent the successful implementation of mobile collection in these areas, unlike rural areas, for example.

According to Feitosa (2020), the management responsible for treating waste in small municipalities has few employees and a minimum truck fleet, which hinders the process of collection and transportation to a final destination. Moreover, it is important to highlight that the responsibility for collecting and transporting WEEE lies in the companies or entities managing the LRS, who are also expected to hire trained professionals.

Another important point is the need to comply with current legislation on the transportation of certain types of WEEE classified as hazardous waste. This procedure may involve criteria such as handling with diligent care to avoid breakage; appropriate packaging or storage to minimize risks of breakage; no tilting of collectors containing fragile products; no crushing, pressing, or compacting WEEE during transportation; transportation vehicle with a closed or covered chassis; etc.

3B Long and costly distances The results of the Nowakowski and Mrówczyńska (2018) research indicate that the extension of the route in the transportation of waste is the main factor on emissions and the sustainability of collection methods. The authors conclude that mobile collection has some limitations in densely populated urban areas and that the collection of WEEE at the time of delivery of new equipment is the most efficient method since it avoids additional expenses and emissions.

Hansen et al. (2022) point out the need for waste transportation and recycling services in Kenya—and East Africa in general despite differences between countries and provinces. They also highlight that the transportation of waste is particularly complicated due to the distances between users, making it difficult to collect devices, including economically.

Transportation costs directly impact economic viability. For Kazancoglu et al. (2020), the shipping cost is considered the most important criterion for difficulties locating sorting centers. In the transportation of hazardous waste, two key objectives considered are cost and risk, with the shortest route equaling the fastest route for carrier companies (Liang et al. 2020).

Therefore, according to its structure, the improvement of accessibility to transportation reduces travel time and cost, increases traffic volume, and spatially redistributes economic activities (Hong et al. 2011).

This challenge has no relevant impact in small and localized centers as they only have small-scale routes, but long routes negatively affect the rural micro level. According to Da Costa et al. (2020), in most Brazilian municipalities, waste transportation and final disposal are carried out at random, without deep analysis to reduce route extensions, thus using a larger amount of fuel and increasing process costs and impacting air quality.

Step (IV): final destination

An environmentally appropriate final destination involves reuse, recycling, resource recovery, energy use, or other destinations. Most of the challenges found refer to recycling.

4A Lack of technical training to work in the WEEE recycling sector The WEEE recycling workforce is unqualified (Mmereki et al. 2015; Kumar and Dixit 2018a; Sharma et al. 2021). Among the main challenges for WEEE management is the lack of training to safely handle and process products during the recovery of materials in uncontrolled recycling operations (Tansel 2017).

Arya and Kumar (2020) reported that the biggest challenge in the WEEE management system in India is lack of technical knowledge. The authors also warn of inadequate disposal, after which the waste is sent to landfills or incinerators of municipal solid waste with limited chance of separation before its final destination, leading to environmental and health risks.

For Kazançoglu et al. (2020), the barrier with the second highest impact is the lack of qualification and education of workers and that urban recovery operations require certain technical skills (unlike other sectors). Gollakota et al. (2020) found that most recycling operations are manual, especially in developing countries. The authors point out that the sophisticated technologies installed are at suboptimal operational scale due to workers' lack of training for operations.

Moreover, Imran et al. (2017) attest that technical knowledge and awareness of the problem go hand in hand. Due to the lack of awareness of the general public and WEEE stakeholders, very few have experience in WEEE management.

This challenge is intensified at the micro level. Masud et al. (2019) point out that the implementation of WEEE management technology in remote areas is another challenging task; the resolution of problems associated with operation and maintenance becomes difficult due to the lack of adequate knowledge and information.

Islands exemplify the micro level, in which the lack of technical assistance is an intense challenge. Araujo et al. (2017) considered the application of their study on an island and, due to the lack of professionals to repair electronic devices, new equipment was favored to quickly replace damaged equipment, thus increasing the problems of WEEE management on site. WEEE can accumulate on the island for about three months before being sent to their final destination: municipal sorting and recycling units in Pernambuco, Brazil (Araujo et al. 2017).

4B Research and development shortage of WEEE recycling technologies Arya and Kumar (2020) report that the environmentally correct management of electronic waste in developing countries is either limited or completely absent. WEEE management is more complex than municipal solid waste management due to the higher toxic concentration in electronic devices, thus requiring special techniques to treat WEEE and prevent leakage and dissipation of toxins into the environment.

Kumar and Dixit (2018b) point out that the sustainability of WEEE management practices depends on available technologies and recycling techniques and that one of the main problems related to WEEE management is the lack of advanced technologies. There is a gap in the Research and Development of WEEE recycling technologies (Song et al. 2017; Vieira et al. 2020) as well as in the communication between industries that recycle waste and end users of electronic items, hindering the development of technologies that can manage waste (Jangre et al. 2022).

The application of advanced technologies in integrated recycling plants significantly increases material recovery and reduces impacts on the environment and humans (Zhang et al. 2015). However, in the best circumstances, current recycling methods are imperfect and lead to the loss of critical materials in small concentrations (Salmon et al. 2021).

Sharma et al. (2021) claim that a huge amount of metals remain untapped due to inefficient treatments, and Bakhiyi et al. (2018) conclude that metal recovery technologies still perform poorly (e.g., difficulties recycling valuable metals) and are still immature and/or polluting.

Some WEEE components, such as PCB, CRT monitors, and LCD screens, also remain extremely difficult to recycle, mainly due to their complexity, dangerous nature, and inefficient recycling technologies, so much so that many recyclers simply refuse to process them (Liu et al. 2017; Afonso 2018).

Santos and Ogunseitan (2022) report that the variability of WEEE requires advanced technologies to recover critical materials and rare earth elements. Due to the lack of technologies and investments, Brazil only undertakes the dismantling process. Recycling processes that recover critical metals and/or rare-earth elements (which are requested worldwide) should be evaluated as an economic opportunity (Santos and Ogunseitan 2022).

The lack of advanced WEEE recycling technologies is even more visible at the micro level. These technologies have a high cost and are applied in power plants, a distant reality for rural localities. Although the level of investment required for different technologies in the circular economy varies significantly, certain technologies and innovations often require prohibitive financial investment for many companies, especially small and medium-sized enterprises (Rizos and Bryhn 2022).

Yong et al. (2019) claim that WEEE value recovery operations in Malaysia have suboptimal metal recovery and energy efficiency. The authors conclude that this calls for the continuous technical improvement of these semi-formal businesses recovering the value of electronic waste in Malaysia.

In addition to composition, advances in product design toward increasingly compact and efficient systems have created challenges for recycling and recovering WEEE materials due to the lack of appropriate material recovery mechanisms and processes and of adequate infrastructure and collection mechanisms (Tansel 2020).

4C Absence or an insufficient number of WEEE recycling companies Management could efficiently handle WEEE collection, transportation, recycling, and disposal by an effective infrastructure (Kumar and Dixit 2018a). Chen et al. (2020) highlight that the availability of an adequate infrastructure system plays a significant role in stimulating appropriate management practices in the WEEE industry. A proper on-premises infrastructure improves the process of implementing formal WEEE management practices.

Kumar and Dixit (2018b) and Sharma et al. (2021) found the great incidence of formal WEEE treatment facilities facing infrastructure barriers. These include lack of facilities (storage, transportation, treatment, and disposal) and limited planning of WEEE production.

Nnorom et al. (2011) conclude that one of the main restrictions to good WEEE management in developing countries is the unavailability of formal recycling infrastructure. WEEE management is a considerably more difficult challenge in developing countries due to the lack of sufficient and safe facilities to recycle WEEE, which entails the accumulation of waste at home and/or inadequate disposal (Mmereki et al. 2015; Song et al. 2017; Gollakota et al. 2020; Kazançoglu et al. 2020; Acquah et al. 2021; Berežni et al. 2021; Andeobu et al. 2021; Almulhim 2022).

In emerging countries, most companies only collect WEEE, reverse manufacturing and mischaracterizing them, and destining their waste to landfills. Once separated, value-added materials such as PCB are sold to recycling plants in developed countries due to the absence of recycling companies to extract precious metals in most emerging countries (Muniz et al. 2017).

Andeobu et al. (2021) claim that the infrastructure to manage and recycle WEEE in most of Nigeria is limited or non-existent. Nigeria faces several challenges, such as the lack of standardized recycling sites and lack of adequate infrastructure for WEEE management (Okwu et al. 2022). Sirisawat et al. (2015) found a general lack of efficiency within the reverse logistics system in Thailand and no suitable place to consolidate WEEE in communities. Neto et al. (2019) stated that the main barriers to reverse logistics is the lack of adequate facilities to extract precious metals in Brazil, which represents the final treatment phase of WEEE.

The absence of a formal recycler is a persistent challenge at the micro level. Yao et al. (2013) showed the precarious municipal WEEE collection facilities in Shanghai. Afonso (2018) points out that the management of WEEE in Brazil is still in its infancy as it lacks an infrastructure that considers regional differences and territorial extension. Finally, Rautela et al. (2021) conclude that WEEE recycling and treatment facilities require advanced capital investments, but only a few countries allocate budgets for WEEE management.

4D Heterogeneous composition hinders treatment In general, WEEE comprises 40% metal, 30% plastic polymers, and 30% oxides of varied materials. However, these quantities can vary significantly from country to country due to uneven mixtures of electrical and electronic equipment in WEEE (Shahabuddin et al. 2022). Some components receive specific treatment due to their toxicity such as batteries (which undergo a separate recycling process) and cathode ray tube monitors (since they contain lead).

These products may also have unrecyclable materials, such as paper (adhesives, labels, carbon paper, and metallized, paraffinized, and laminated papers), plastics (adhesives, foam, and polystyrene), glass (mirrors and ceramics), rubber, and even wood (TV cabinets and old stereos), which compose part of the packaging for transportation and thus have a low participation in the composition of these products (Ribeiro 2019).

Many developed countries face the problem of separating WEEE due to their complex composition (Rajesh et al. 2022). Shahabuddin et al. (2022) report that handling and processing WEEE still offer a challenge due to their complex mix of hazardous, precious, basic, and other materials.

In general, mechanical separation processes are used as pre-treatment, including methods such as grinding, electrostatic and magnetic separation, and particle size classification. Generally, this pre-process is the only treatment that occurs at the micro level due to its technical ease and low cost. However, the lack of technical training in the WEEE recycling sector (as mentioned above) can make it a complex process.

Final considerations

Figure 3 shows the density of bibliographic citations related to the identified challenges per operational stage of the WEEE LRS discussed in this review.

Figure 3 shows that, of the stages of the WEEE LRS, disposal (48 studies) has the most bibliographic citations, followed by final destination (37 studies), collection and receipt (24 studies), and, finally, transportation (4 studies). The number of bibliographic citations for each stage shows discrepancies, and the figure shows the importance future studies on WEEE management should give to transportation.

Therefore, after combining all the challenges encountered, WEEE LRSs in developed countries can serve as an example for developing countries, which often lack such system. Many developed countries already have WEEE recycling policies and facilities, but the problem lies in developing countries with higher population densities, in which it is difficult to collect, sort, and recycle WEEE (Tembhare et al. 2022).

Moreover, it is necessary to consider that each site has particularities and that the micro level demands attention and adjustment to them. Thus, Marinello and Gamberini (2021) claim the need to better disseminate WEEE management approaches, optimize current practices, or design specific solutions according to the needs and characteristics of different territories. The authors state that no single solution will suffice for all countries and that each should be addressed according to their own social, political, and economic circumstances (Shahrasbi et al. 2021).

Andeobu et al. (2021) conclude that local government councils are the main stakeholders in the management and recycling process, thus incurring expenses to deal with WEEE and requiring policymakers to understand the determinants, motivations, and costs associated with collecting and disposing of WEEE. Gunarathne et al. (2020) claim that since waste management in developing countries is highly contextual viable and sustainable solutions must be designed to meet specific local circumstances.

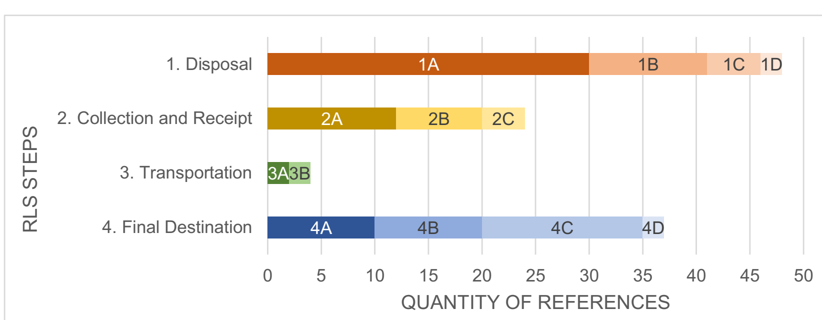
Koshta et al. (2021) argue that a national WEEE estimate provides a more comprehensive view of what is generated in a country but that these estimates are of limited use to an LRS since they fail to consider the effect of economic and social variables at the local level, critical to the efficient operation of such system. Thus, a micro-level strategy is essential to operationalize WEEE LRSs.

Study limitations

A pertinent observation is that the examined literature addresses the challenges of WEEE RLS in a general manner, without delving into discussions at both macro and micro levels. The employed methodology, a systematic literature review, in turn reflects this gap, as the absence of specific focus on these levels translates into an inherent limitation of the study.

Furthermore, it is important to highlight that the analysis is predominantly theoretical, lacking empirical data or local diagnoses. The absence of practical examples limits the tangibility of conclusions and the applicability of the discussed ideas. This scenario is particularly noticeable when considering developing countries in the initial phase of RLS implementation. In these contexts, not only is the discussion at the micro level scarce but also the very inclusion of the micro level in the early stages of system implementation is incipient.

Fig. 3 Density of references per step



In summary, the study provides valuable insights; however, it is crucial to acknowledge and address these limitations to properly contextualize its findings. Future investigations should consider more comprehensive approaches that encompass discussions at both macro and micro scales and seek ways to enrich theoretical analysis with practical examples, especially in the contexts of developing countries.

Conclusions

In all, 13 challenges were identified according to their operational stage (disposal: 4; collection and receipt: 3; transportation: 2; and final destination: 4).

Some of the found challenges were also discussed, addressing the importance of supervising and controlling WEEE LRSs. These challenges involve informal recycling, amounts not legally registered, lack of recycling measurement systems, illegal export to developing countries, and lack of knowledge sharing between the formal and informal WEEE sectors. Several studies have reported informal recycling as a challenge, configuring a concern at the micro level. However, this level produces an irrelevant amount of WEEE compared to developed countries, making informal recycling an easier challenge to circumvent.

The challenge *The population and LRS entities' lack or insufficient training and awareness* have a greater number of results in our search, this configuring a challenge thoroughly addressed in the literature. At the micro level, the rural communities lack even more awareness about WEEE management, for example. However, because such communities are smaller, they enjoy the advantage of covering their entire population (or almost) with an awareness campaign.

In addition to this challenge, at the micro level, the challenges identified with the greatest impact are *Absence or insufficient number of WEEE recycling companies*; *Return rate and WEEE collection/disposal points*; *Insufficient WEEE receiving and sorting plants*; *Deficient WEEE transportation infrastructure*; *Long and costly distances*; and *Inadequate distribution of WEEE disposal points*.

Return rates and WEEE collection/disposal points can be a difficult challenge to address because the function of any system requires a minimum amount of waste, which a single collection point may fail to achieve. The general lack of collection or transportation structure, the use of WEEE recycling companies, and insufficient collection points (given their cost) are difficult to overcome by the restrictions and financial dependence of these places. The inadequate location of receiving/collecting points is an easy challenge to circumvent at the micro level since it has only a few points available, and a mathematical study could find the optimal location. Long and costly distances are a worrying challenge in rural localities, configuring an inevitable difficult as collection points generally lie far from centers.

The identified challenges with less impact refer to *Difficulty classifying and segregating WEEE*; *Intelligent WEEE collection systems not applied*; *Research and Development shortage of WEEE recycling technologies*; *Heterogeneous composition hinders treatment*; *Inadequate disposal of WEEE*; and *Lack of technical training to work in the WEEE recycling sector*.

Some challenges cause less impact because they already require some development in the implementation of an LRS that may be absent at the micro level. Although very important, intelligent collection systems and advanced technologies require implementation basics, constituting a future investment claim for the micro level. Other challenges are more impactful when related to a relevant amount of WEEE, such as inadequate disposal, classification and segregation difficulties, and the heterogeneous composition of WEEE (only relevant for the macro level).

Although the legal point of view evinces the mandatory implementation of WEEE LRS, it is essential that these directions be ratified at the state and municipal level given the particularities that occur mainly at the municipal level such as those addressed in this study. Finally, the challenges emerging countries faced in managing WEEE offer a complex process due to the number of stakeholders involved and the complexities of the macro environment, thus requiring a systematic approach to understand the multifaceted and multi-stakeholder challenges of WEEE recycling in these countries.

In conclusion, the impact of this study is to shed light on the discussion surrounding the challenges of WEEE RLS in a micro perspective, encompassing both developing and developed countries. In developing countries, the emphasis lies in the meticulous consideration of the micro sphere when implementing or strengthening RLS. This implies a shift from the traditionally focused approach on urban centers and regions with higher WEEE generation. Instead, it is imperative to recognize the importance of incorporating areas with economic limitations, geographical isolation, inequalities, environmental challenges, and even geopolitical issues. In developed countries, the desired impact is the expansion of RLS coverage, aiming to encompass as much waste as possible. Even countries that have implemented such systems must extend its reach. Special attention should be directed toward micro-level areas that may have been overlooked regarding coverage. Therefore, this study not only seeks to emphasize the importance of RLS but also to foster a comprehensive approach that considers the nuances of different contexts, promoting a more equitable and efficient treatment of WEEE.

Acknowledgements This research was supported by the Espírito Santo Research and Innovation Support Foundation (FAPES), Espírito Santo, Brazil (Process no. 83757392/2018).

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by S.d.N.S. The first draft of this manuscript was written by S.d.N.S., and all authors commented on previous versions of this manuscript. All authors read and approved this final manuscript.

Data availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent to participate We consented.

Consent for publication We consented.

Competing interests The authors declare no competing interests.

References

Acquah AA, D'Souza C, Martin BJ et al (2021) A preliminary assessment of physical work exposures among electronic waste workers at Agbogbloshie, Accra Ghana. Int J Ind Ergon 82:103096. https://doi.org/10.1016/J.ERGON.2021.103096

Afonso JC (2018) Resíduos de Equipamentos Eletroeletrônicos: O Antropoceno Bate à Nossa Porta. Revista Virtual de Química 10:1849–1897. https://doi.org/10.21577/1984-6835.20180121

Almulhim AI (2022) Household's awareness and participation in sustainable electronic waste management practices in Saudi Arabia. Ain Shams Eng J 13:101729. https://doi.org/10.1016/J.ASEJ.2022.101729

Anandh G, PrasannaVenkatesan S, Goh M, Mathiyazhagan K (2021) Reuse assessment of WEEE: systematic review of emerging themes and research directions. J Environ Manag 287:112335

Andeobu L, Wibowo S, Grandhi S (2021) An assessment of e-waste generation and environmental management of selected countries in Africa, Europe and North America: a systematic review. Sci Total Environ 792. https://doi.org/10.1016/j.scitotenv.2021.148078

Araújo A d S, da Cruz CM d S, Barreto J d M et al (2019) Modais de transporte no Brasil. Pesquisa e Ação 5 http://editorarevistas.mackenzie.br/index.php/LOGS/article/view/14420

Araujo RRD, De Oliveira JD, Fragoso Selva V et al (2017) Generation of domestic waste electrical and electronic equipment on Fernando de Noronha Island: qualitative and quantitative aspects. Environ Sci Pollut Res 24:19703–19713. https://doi.org/10.1007/s11356-017-9648-3

Arya S, Kumar S (2020) E-waste in India at a glance: current trends, regulations, challenges and management strategies. J Clean Prod 271:122707. https://doi.org/10.1016/J.JCLEPRO.2020.122707

Awasthi AK, Li J (2017) Management of electrical and electronic waste: a comparative evaluation of China and India. Renew Sust Energ Rev 76:434–447. https://doi.org/10.1016/J.RSER.2017.02.067

Baidya R, Debnath B, Ghosh SK, Rhee SW (2020) Supply chain analysis of e-waste processing plants in developing countries. Waste Manag Res 38:173–183. https://doi.org/10.1177/0734242X19886633

Bakhiyi B, Gravel S, Ceballos D et al (2018) Has the question of e-waste opened a Pandora's box? An overview of unpredictable issues and challenges. Environ Int 110:173–192. https://doi.org/10.1016/J.ENVINT.2017.10.021

Berežni I, Castro FD, Batinić B et al (2021) WEEE treatment and system management in Italy and Serbia: a comparison. Waste Manag Res 39:1302–1316. https://doi.org/10.1177/0734242X211050195

Borthakur A, Sinha K (2013) Electronic waste management in India: a stakeholder's perspective. Electron Green J 1. https://doi.org/10.5070/G313618041

Borthakur A, Govind M (2017) Emerging trends in consumers' E-waste disposal behaviour and awareness: A worldwide overview with special focus on India. Resources, Conservation and Recycling 117:102–113. https://doi.org/10.1016/j.resconrec.2016.11.011

Bouvier R, Wagner T (2011) The influence of collection facility attributes on household collection rates of electronic waste: the case of televisions and computer monitors. Resour Conserv Recycl 55:1051–1059. https://doi.org/10.1016/J.RESCONREC.2011.05.019

Bouzon M, Govindan K, Rodriguez CMT (2018) Evaluating barriers for reverse logistics implementation under a multiple stakeholders' perspective analysis using grey decision making approach. Resour Conserv Recycl 128:315–335. https://doi.org/10.1016/J.RESCONREC.2016.11.022

Brasil (2020) DECRETO No 10.240, DE 12 DE FEVEREIRO DE 2020. http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/decreto/D10240.htm. Accessed 31 Aug 2022

Chen D, Faibil D, Agyemang M (2020) Evaluating critical barriers and pathways to implementation of e-waste formalization management systems in Ghana: a hybrid BWM and fuzzy TOPSIS approach. https://doi.org/10.1007/s11356-020-10360-8/Published

Ciocoiu CN, Colesca SE, Rudəreanu C, Popescu ML (2016) Management of waste electrical and electronic equipment in Romania: a mini-review. Waste Manag Res 34:96–106. https://doi.org/10.1177/0734242X15615422

Clarivate (2022) Journal citation reports - Clarivate. https://clarivate.com/products/scientific-and-academic-research/research-analytics-evaluation-and-management-solutions/journal-citation-reports/. Accessed 30 Mar 2023

Cole C, Cooper T, Gnanapragasam A (2016) Extending product lifetimes through WEEE reuse and repair: opportunities and challenges in the UK. 2016 Electronics Goes Green 2016+(EGG):1–9. https://doi.org/10.1109/EGG.2016.7829857

Cole C, Gnanapragasam A, Cooper T, Singh J (2019) An assessment of achievements of the WEEE Directive in promoting movement up the waste hierarchy: experiences in the UK. Waste Manag 87:417–427. https://doi.org/10.1016/J.WASMAN.2019.01.046

Da Costa NRM, Nascimento VF, Ometto JPHB (2020) Vista do A história da coleta de resíduos em Novo Hamburgo, RS e uma proposta de uma nova roteirização utilizando sistema de informações geográficas. Oficina Do Historiador 13. https://doi.org/10.15448/2178-3748.2020.2.38033

Dagiliūtė R, Deividas Zabulionis D, Sujetovienė G, Žaltauskaitė J (2019) Waste of electrical and electronic equipment: trends and awareness among youths in Lithuania. Waste Manag Res 37:95–101. https://doi.org/10.1177/0734242X18806999

De Aquino ÍRB, Ferreira da Silva Junior J, Guarnieri P, Camara e Silva L (2020) The proposition of a mathematical model for the location of electrical and electronic waste collection points. Sustainability 13:224. https://doi.org/10.3390/SU13010224

Dixit S, Badgaiyan AJ (2016) Towards improved understanding of reverse logistics–Examining mediating role of return intention. Resources, Conservation and Recycling 107:115–128. https://doi.org/10.1016/j.resconrec.2015.11.021

Dutta D, Goel S (2021) Understanding the gap between formal and informal e-waste recycling facilities in India. Waste Manag 125:163–171. https://doi.org/10.1016/J.WASMAN.2021.02.045

Elia V, Gnoni MG, Tornese F (2019) Designing a sustainable dynamic collection service for WEEE: an economic and environmental analysis through simulation. Waste Manag Res 37:402–411. https://doi.org/10.1177/0734242X19828121/FORMAT/EPUB

Elsevier (2020) Content coverage guide | Elsevier solutions. https://www.elsevier.com/solutions/scopus/how-scopus-works/content. Accessed 30 Mar 2023

European Union (2012) Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Off J Eur Communities 2012, L197/38

Fan C, Fan SKS, Wang CS, Tsai WP (2018) Modeling computer recycling in Taiwan using system dynamics. Resour Conserv Recycl 128:167–175. https://doi.org/10.1016/J.RESCONREC.2016.09.006

Favarin S, Aziani A (2020) The global waste trafficking and its correlates. J Contemp Crim Justice 36:351–383. https://doi.org/10.1177/1043986220939701

Favot M, Grassetti L, Massarutto A, Veit R (2022) Regulation and competition in the extended producer responsibility models: results in the WEEE sector in Europe. Waste Manag 145:60–71

Feitosa MMDS (2020) Políticas de Gestão e Gerenciamento Integrados dos Resíduos Sólidos Urbanos no Município de Água Branca-AL. Universidade Federal De Alagoas https://www.repositorio.ufal.br/handle/123456789/8753 Accessed 23 Nov 2022

Forti V, Balde CP, Kuehr R, Bel G (2020) The Global E-waste Monitor 2020: quantities, flows and the circular economy potential. United Nations University (UNU)/United Nations Institute for Training and Research (UNITAR) – co-hosted SCYCLE Programme. International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam, p 120

Gharib B, Alblooshi KM, Syed, et al (2022) Sustainable management of electronic waste: empirical evidences from a stakeholders' perspective. https://doi.org/10.1002/bse.2987

Gollakota ARK, Gautam S, Shu CM (2020) Inconsistencies of e-waste management in developing nations – facts and plausible solutions. J Environ Manag 261:110234. https://doi.org/10.1016/J.JENVMAN.2020.110234

Guarnieri P, Cerqueira-Streit JA, Batista LC (2020) Reverse logistics and the sectoral agreement of packaging industry in Brazil towards a transition to circular economy. Resour Conserv Recycl 153:104541. https://doi.org/10.1016/J.RESCONREC.2019.104541

Gunarathne N, de Alwis A, Alahakoon Y (2020) Challenges facing sustainable urban mining in the e-waste recycling industry in Sri Lanka. J Clean Prod 251:119641. https://doi.org/10.1016/J.JCLEPRO.2019.119641

Hansen UE, Reinauer T, Kamau P, Wamalwa HN (2022) Managing e-waste from off-grid solar systems in Kenya: do investors have a role to play? Energy Sustain Dev 69:31–40. https://doi.org/10.1016/J.ESD.2022.05.010

Haque KF, Zabin R, Yelamarthi K et al (2020) An IoT based efficient waste collection system with smart bins. Institute of Electrical and Electronics Engineers

Hong J, Chu Z, Wang Q (2011) Transport infrastructure and regional economic growth: evidence from China. Transportation (Amst) 38:737–752. https://doi.org/10.1007/s11116-011-9349-6

IBGE (2021) Panorama geral do Brasil. https://cidades.ibge.gov.br/brasil/panorama. Accessed 02 Dec 2022

Imran M, Haydar S, Kim J et al (2017) E-waste flows, resource recovery and improvement of legal framework in Pakistan. Resour Conserv Recycl 125:131–138. https://doi.org/10.1016/J.RESCONREC.2017.06.015

Islam MT, Huda N, Baumber A et al (2021) A global review of consumer behavior towards e-waste and implications for the circular economy. J Clean Prod 316:128297. https://doi.org/10.1016/J.JCLEPRO.2021.128297

Jafari A, Heydari J, Keramati A (2017) Factors affecting incentive dependency of residents to participate in ewaste recycling: a case study on adoption of e-waste reverse supply chain in Iran. Environment, Development and Sustainability 19:325–338. https://doi.org/10.1007/s10668-015-9737-8

Jangre J, Prasad K, Patel D (2022) Environmental Science and Pollution Research Analysis of barriers in e-waste management in developing economy: an integrated multiple-criteria decision-making approach. Environ Sci Pollut Res:1–115. https://doi.org/10.1007/s11356-022-21363-y

Kazançoglu Y, Ada E, Ozturkoglu Y, Ozbiltekin M (2020) Analysis of the barriers to urban mining for resource melioration in emerging economies. Res Policy 68:101768. https://doi.org/10.1016/J.RESOURPOL.2020.101768

Kazancoglu Y, Ozbiltekin M, Ozkan Ozen YD, Sagnak M (2020) A proposed sustainable and digital collection and classification center model to manage e-waste in emerging economies. J Enterp Inf Manag 34:267–291. https://doi.org/10.1108/JEIM-02-2020-0043

Khoshand A, Karami A, Rostami G, Emaminejad N (2023) Prediction of e-waste generation: application of modified adaptive neuro-fuzzy inference system (MANFIS). Waste Manag Res 41:389–400. https://doi.org/10.1177/0734242X221122598

Koshta N, Patra S, Singh SP (2021) Estimation of E-waste at micro level for reverse logistics: a case of Delhi. J Clean Prod 314:128063. https://doi.org/10.1016/J.JCLEPRO.2021.128063

Kumar A (2019) Exploring young adults' e-waste recycling behaviour using an extended theory of planned behaviour model: a cross-cultural study. Resour Conserv Recycl 141:378–389. https://doi.org/10.1016/J.RESCONREC.2018.10.013

Kumar A, Dixit G (2018a) Evaluating critical barriers to implementation of WEEE management using DEMATEL approach. Resour Conserv Recycl 131:101–121. https://doi.org/10.1016/J.RESCONREC.2017.12.024

Kumar A, Dixit G (2018b) An analysis of barriers affecting the implementation of e-waste management practices in India: a novel ISM-DEMATEL approach. Sustain Prod Consum 14:36–52. https://doi.org/10.1016/j.spc.2018.01.002

Leclerc SH, Badami MG (2020) Extended producer responsibility for E-waste management: policy drivers and challenges. J Clean Prod 251:119657

Liang S, Pi H, Hsu CH, Kadry SN (2020) Sustainable transportation system for electronic waste recycling from a social perspective. IET Intell Transp Syst 14:1378–1387. https://doi.org/10.1049/IET-ITS.2019.0824

Liu L, Liang Y, Song Q, Li J (2017) A review of waste prevention through 3R under the concept of circular economy in China. J Mater Cycles Waste Manag 19:1314–1323. https://doi.org/10.1007/s10163-017-0606-4

Liu W, Huang M, Haifeng W (2021) Same journal but different numbers of published records indexed in Scopus and Web of Science Core Collection: causes, consequences, and solutions. Scientometrics 126:4541–4550. https://doi.org/10.1007/s11192-021-03934-x

Maphosa V, Maphosa M (2020) E-waste management in Sub-Saharan Africa: a systematic literature review. Cogent Bus Manag 7. https://doi.org/10.1080/23311975.2020.1814503

Marczuk A, Misztal W, Jóźwiakowski K et al (2019) The research on effectiveness of the electronic and electrical waste selective collection system in Lublin city, Poland. Arch Environ Prot 45:55–63. https://doi.org/10.24425/AEP.2019.128641

Marinello S, Gamberini R (2021) Toxics Multi-criteria decision making approaches applied to waste electrical and electronic equipment (WEEE): a comprehensive literature review. https://doi.org/10.3390/toxics9010013

Masud MH, Akram W, Ahmed A et al (2019) Towards the effective E-waste management in Bangladesh: a review. Environ Sci Pollut Res 6:1250–1276. https://doi.org/10.1007/s11356-018-3626-2

Mmereki D, Li B, Li'ao W (2015) Waste electrical and electronic equipment management in Botswana: prospects and challenges. J Air Waste Manage Assoc 65:11–26. https://doi.org/10.1080/10962247.2014.892544

Mohammadi E, Singh SJ, Habib K (2021) How big is circular economy potential on Caribbean islands considering e-waste? J Clean Prod 317:128457. https://doi.org/10.1016/J.JCLEPRO.2021.128457

Morganti M, Favarin S, Andreatta D (2020) Illicit waste trafficking and loopholes in the European and Italian legislation. Eur J Crim Policy Res 26:105–133. https://doi.org/10.1007/s10610-018-9405-2

Muniz FA, Da Silva WH, Junior FG, Simas R (2017) Valorização de resíduos: recuperação de metais de placas de circuitos eletrônicos. Revista Engenho 9:65–79 https://revistas.anchieta.br/index.php/RevistaEngenho/article/download/858/750

Neto JFO, Silva M, Santos SM (2019) A mini-review of E-waste management in Brazil: perspectives and challenges. https://doi.org/10.1002/clen.201900152

Nnorom IC, Osibanjo O, Ogwuegbu MOC (2011) Global disposal strategies for waste cathode ray tubes. Resour Conserv Recycl 55:275–290. https://doi.org/10.1016/J.RESCONREC.2010.10.007

Nowakowski P (2017) A proposal to improve e-waste collection efficiency in urban mining: container loading and vehicle routing problems – a case study of Poland. Waste Manag 60:494–504. https://doi.org/10.1016/J.WASMAN.2016.10.016

Nowakowski P (2019) Investigating the reasons for storage of WEEE by residents – a potential for removal from households. Waste Manag 87:192–203. https://doi.org/10.1016/J.WASMAN.2019.02.008

Nowakowski P, Mrówczyńska B (2018) Towards sustainable WEEE collection and transportation methods in circular economy - comparative study for rural and urban settlements. Resour Conserv Recycl 135:93–107. https://doi.org/10.1016/J.RESCONREC.2017.12.016

Nowakowski P, Pamuła T (2020) Application of deep learning object classifier to improve e-waste collection planning. Waste Manag 109:1–9. https://doi.org/10.1016/J.WASMAN.2020.04.041

Okwu O, Hursthouse A, Viza E, Idoko L (2022) New models to reduce the health risks of informal WEEE recyclers in MTN phone village, Rumukurushi, Port Harcourt, Nigeria. https://doi.org/10.3390/toxics10020084

Orlins S, Guan D (2016) China's toxic informal e-waste recycling: local approaches to a global environmental problem. J Clean Prod 114:71–80. https://doi.org/10.1016/J.JCLEPRO.2015.05.090

Pérez-Belis V, Braulio-Gonzalo M, Juan P, Bovea MD (2017) Consumer attitude towards the repair and the second-hand purchase of small household electrical and electronic equipment. A Spanish case study. Journal of cleaner production 158:261–275. https://doi.org/10.1016/j.jclepro.2017.04.143

Pourhejazy P, Zhang D, Zhu Q et al (2021) Integrated E-waste transportation using capacitated general routing problem with time-window. Transp Res E Logist Transp Rev 145:102169. https://doi.org/10.1016/J.TRE.2020.102169

Rajesh R, Kanakadhurga D, Prabaharan N (2022) Electronic waste: a critical assessment on the unimaginable growing pollutant, legislations and environmental impacts. Environ Chall 7:100507. https://doi.org/10.1016/J.ENVC.2022.100507

Rautela R, Arya S, Vishwakarma S et al (2021) E-waste management and its effects on the environment and human health. Sci Total Environ 773:145623. https://doi.org/10.1016/J.SCITOTENV.2021.145623

Ribeiro ÁA (2019) A coleta seletiva: recapturando valores de materiais recicláveis e reduzindo o descarte de rejeitos no meio ambiente de uma cidade mineira. Universidade Federal De Ouro Preto http://monografias.ufop.br/handle/35400000/1956. Accessed 21 Oct 2022

Rizos V, Bryhn J (2022) Implementation of circular economy approaches in the electrical and electronic equipment (EEE) sector: barriers, enablers and policy insights. J Clean Prod 338:130617. https://doi.org/10.1016/J.JCLEPRO.2022.130617

Salhofer S, Steuer B, Ramusch R, Beigl P (2016) WEEE management in Europe and China – a comparison. Waste Manag 57:27–35. https://doi.org/10.1016/J.WASMAN.2015.11.014

Salmon D, Babbitt CW, Babbitt GA, Wilmer CE (2021) A framework for modeling fraud in E-waste management. Resour Conserv Recycl 171:105613. https://doi.org/10.1016/J.RESCONREC.2021.105613

Santos SM, Ogunseitan OA (2022) E-waste management in Brazil: challenges and opportunities of a reverse logistics model. Environ Technol Innov 28:102671. https://doi.org/10.1016/J.ETI.2022.102671

Sari DP, Masruroh NA, Asih AMS (2021) Extended maximal covering location and vehicle routing problems in designing smartphone waste collection channels: a case study of Yogyakarta province, Indonesia. Sustainability 13:8896. https://doi.org/10.3390/SU13168896

Shahabuddin M, Nur Uddin M, Chowdhury JI et al (2022) A review of the recent development, challenges, and opportunities of electronic waste (e-waste). Int J Environ Sci Technol. https://doi.org/10.1007/s13762-022-04274-w

Shahrasbi A, Shokouhyar S, Zeidyahyaee N (2021) Consumers' behavior towards electronic wastes from a sustainable development point of view: an exploration of differences between developed and developing countries. Sustain Prod Consum 28:1736–1756. https://doi.org/10.1016/J.SPC.2021.09.016

Sharma M, Joshi S, Govindan K (2021) Issues and solutions of electronic waste urban mining for circular economy transition: an Indian context. J Environ Manag 290:112373. https://doi.org/10.1016/J.JENVMAN.2021.112373

Shevchenko T, Saidani M, Danko Y, Golysheva I, Chovancová J, Vavrek R (2021) Towards a smart E-waste system utilizing supply chain participants and interactive online maps. Recycling 6(1):8

Shittu OS, Williams ID, Shaw PJ (2021) Global E-waste management: can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Manag 120:549–563. https://doi.org/10.1016/J.WASMAN.2020.10.016

Siddiqua A, El Gamal M, Abdul K, et al (2022) Citation: E-device purchase and disposal behaviours in the UAE: an exploratory study. https://doi.org/10.3390/su14084805

Singh S, Dasgupta MS, Routroy S (2022) Evaluation of sustainable e-waste collection method for urban and rural region of India. Waste Manag Res 40:545–555. https://doi.org/10.1177/0734242X211018512

Singh VK, Singh P, Karmakar M et al (2021) The journal coverage of Web of Science, Scopus and dimensions: a comparative analysis. Scientometrics 126:5113–5142. https://doi.org/10.1007/S11192-021-03948-5

Sinha-Khetriwal D, Kraeuchi P, Schwaninger M (2005) A comparison of electronic waste recycling in Switzerland and in India. Environ Impact Assess Rev 25:492–504. https://doi.org/10.1016/j.eiar.2005.04.006

Sirisawat P, Kiatcharoenpol T (2018) Fuzzy AHP-TOPSIS approaches to prioritizing solutions for reverse logistics barriers. Comput Ind Eng 117:303–318. https://doi.org/10.1016/J.CIE.2018.01.015

Sirisawat P, Kiatcharoenpol T, Choomrit N, Wangphanich P (2015) A study of reverse logistics practices: a case study of the computer parts industry in Thailand. https://doi.org/10.1109/IEEM.2015.7385668

Song X, Wang J, Yang J, Lu B (2017) An updated review and conceptual model for optimizing WEEE management in China from a life cycle perspective. Front Environ Sci Eng 11(5):1–12. https://doi.org/10.1007/S11783-017-0985-8

Tansel B (2017) From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. Environ Int 98:35–45. https://doi.org/10.1016/J.ENVINT.2016.10.002

Tansel B (2020) Increasing gaps between materials demand and materials recycling rates: A historical perspective for evolution of consumer products and waste quantities. Journal of Environmental Management 276:111196. https://doi.org/10.1016/j.jenvman.2020.111196

Tembhare SP, Bhanvase BA, Divya et al (2022) E-waste recycling practices: a review on environmental concerns, remediation and technological developments with a focus on printed circuit boards. Dev Sustain 24:8965–9047. https://doi.org/10.1007/s10668-021-01819-w

Thakur P, Kumar S (2020) Metallurgical processes unveil the unexplored “sleeping mines” e-waste: a review. Environ Sci Pollut Res 27(26):32359–32370

Tian T, Liu G, Yasemi H, Liu Y (2022) Managing e-waste from a closed-loop lifecycle perspective: China’s challenges and fund policy redesign. Environ Sci Pollut Res 1:1–12. https://doi.org/10.1007/S11356-022-19227-6/FIGURES/6

Tian X, Xiao H, Liu Y, Ding W (2021) Design and simulation of a secondary resource recycling system: a case study of lead-acid batteries. Waste Manag 126:78–88. https://doi.org/10.1016/J.WASMAN.2020.12.038

Tibben-Lembke RS (1998) The impact of reverse logistics on the total cost of ownership. Journal of Marketing Theory and Practice 6(4):51–60. https://doi.org/10.1080/10696679.1998.11501810

Tran HP, Schaubroeck T, Nguyen DQ et al (2018) Material flow analysis for management of waste TVs from households in urban areas of Vietnam. Resour Conserv Recycl 139:78–89. https://doi.org/10.1016/J.RESCONREC.2018.07.031

Ventura KS, Beatriz A, Suquisaqui V (2019) Aplicação de ferramentas SWOT e 5W2H para análise de consórcios intermunicipais de resíduos sólidos urbanos. Ambiente Construído 20:333–349. https://doi.org/10.1590/S1678-86212020000100378

Vieira BD, Guarnieri P, Camara e Silva L, Alfinito S (2020) Prioritizing barriers to be solved to the implementation of reverse logistics of e-waste in Brazil under a multicriteria decision aid approach. Sustainability (Switzerland) 12. https://doi.org/10.3390/su12104337

Wilker W, Morais C, Martins De Oliveira T et al (2022) Rapid protocol proposal for visual inspection of wooden bridges. Adv For Sci 9:1761–1771. https://doi.org/10.34062/AFS.V9I2.13532

Xavier LH, Ottoni M, Lepawsky J (2021) Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks. J Clean Prod 297. https://doi.org/10.1016/j.jclepro.2021.126570

Xavier LH da SM, Ottoni M de SO, Gomes CF, et al (2020) Resíduos de Equipamentos Eletroeletrônicos Guia de Desmontagem. http://mineralis.cetem.gov.br/handle/cetem/2380. Accessed 04 Oct 2022

Yadav S, Patel S, Killedar DJ, Kumar S, Kumar R (2022) Eco-innovations and sustainability in solid waste management: An indian upfront in technological, organizational, start-ups and financial framework. Journal of Environmental Management 302:113953. https://doi.org/10.1016/j.jenvman.2021.113953

Yao L, He W, Li G, Huang J (2013) The integrated design and optimization of a WEEE collection network in Shanghai, China. Waste Manag Res 31:910–919. https://doi.org/10.1177/0734242X13487583

Ylä-Mella J, Keiski RL, Pongrácz E (2015) Electronic waste recovery in Finland: Consumers’ perceptions towards recycling and re-use of mobile phones. Waste management 45:374–384. https://doi.org/10.1016/j.wasman.2015.02.031

Yong YS, Lim YA, Ilankoon IMSK (2019) An analysis of electronic waste management strategies and recycling operations in Malaysia: challenges and future prospects. J Clean Prod 224:151–166. https://doi.org/10.1016/J.JCLEPRO.2019.03.205

Zeng X, Li J (2016) Measuring the recyclability of e-waste: an innovative method and its implications. J Clean Prod 131:156–162. https://doi.org/10.1016/J.JCLEPRO.2016.05.055

Zhang S, Ding Y, Liu B et al (2015) Challenges in legislation, recycling system and technical system of waste electrical and electronic equipment in China. Waste Manag 45:361–373. https://doi.org/10.1016/J.WASMAN.2015.05.015