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Guidelines and strategies to implement and operationalize WEEE LRS in small Brazilian municipalities

Diretrizes e estratégias para implementação e operacionalização do sistema de logística reversa de resíduos eletroeletrônicos em municípios brasileiros de pequeno porte

Suzana das Neves Silva [a]
Serra, ES, Brasil
[a] Universidade Federal do Rio de Janeiro (UFRJ)

Renato Ribeiro Siman [b]
Vitória, ES, Brasil
[b] Universidade Federal do Espírito Santo (UFES)

Luciana Harue Yamane [b]
Vitória, ES, Brasil
[b] Universidade Federal do Espírito Santo (UFES)

SNS é doutoranda em Engenharia Ambiental pela Universidade Federal do Rio de Janeiro (UFRJ), Mestra em Engenharia e Desenvolvimento Sustentável pela Universidade Federal do Espírito Santo (UFES) - 2023, com graduação em Engenharia Ambiental também pela UFES - 2020, com atividades de atuação principalmente dentro da área de gerenciamento de resíduos sólidos, mais especificamente em resíduos eletroeletrônicos, e-mail: suzananevess@gmail.com

RRS é Engenheiro Químico pela UFRRJ (2000) com ênfase em meio ambiente (Secretaria de Meio Ambiente da PMRJ e CEDAE - Centro de Controle de Qualidade), mestrado (2003) e doutorado (2007) em Engenharia Hidráulica e Saneamento pela EESC/USP. Atua como professor dos Mestrados Acadêmico Engenharia Ambiental (PPGEA) e Profissional em Engenharia e Desenvolvimento Sustentável (PPGES), ambos do Centro Tecnológico da Universidade Federal do Espírito Santo (UFES), onde ministra aulas e orientações. Chefe do Laboratório de Gestão do Saneamento Ambiental (LAGESA) e Professor Associado do curso de Engenharia Ambiental da UFES, e-mail: renato.siman@ufes.br

HY é Mestre em Ciências em Engenharia Ambiental pela Universidade Federal do Espírito Santo (2007), doutorado em Ciências pela Universidade de São Paulo (2012) e pós-doutorado pela Universidade de São Paulo (2014). Tem experiência na área de gestão e gerenciamento de resíduos sólidos e microbiologia ambiental, e-mail: luciana.yamane@ufes.br

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Abstract

Although Brazilian Federal Decree no. 10.240/2020, in effect since February 2020, established mandatory reverse logistics service (RLS) for electronic waste (e-waste) in municipalities with a population exceeding 80,000 inhabitants in Brazil to reach 60% of the Brazilian population by 2025, the population threshold set fails to encompass 93% of all municipalities in Brazil. This study identified the need to understand the root causes of these challenges in these areas and proposed guidelines and strategies to facilitate the implementation of RLS for e-waste. Various approaches, such as questionnaires, focus groups, and document analyses, were employed to collect data and validate the identified challenges. Results underscored the significance of the identified challenges, with improper disposal of e-waste being a primary issue. The proposed guidelines and strategies can assist decision-makers in promoting the implementation of RLS for e-waste in small municipalities in Brazil.

***Keywords**: E-waste. Reverse logistics. Small Cities. Village Level. Small Municipalities.*

Resumo

Embora o Decreto Federal brasileiro nº 10.240/2020, em vigor desde fevereiro de 2020, tenha estabelecido atendimento para cidades com população superior à 80 mil habitantes para o Sistema de Logística Reversa Obrigatória (SLRO) de Resíduos Eletroeletrônicos (REEE) no Brasil, atendendo a 60% da população brasileira até 2025, o corte populacional firmado não engloba 93% do total de municípios no Brasil. Este estudo identificou a necessidade de compreender as causas raízes desses desafios nessas áreas e propôs diretrizes e estratégias para facilitar a implementação do SLR de REEE. Foram utilizadas várias abordagens, como questionários, grupos de foco e análises de documentos para coletar dados e validar os desafios identificados. Os resultados mostraram a importância dos desafios identificados, com o descarte inadequado de REEE sendo um problema principal. As diretrizes e estratégias propostas têm o potencial de apoiar os tomadores de decisão na promoção da implementação do SLR de REEE em municípios de pequeno porte no Brasil.

Palavras-chave: Resíduos Eletroeletrônicos. Logística Reversa. Cidades Pequenas. Nível de vilarejo. Municípios de pequeno porte.

Introdução

In 2020, Federal Decree 10.240 came into effect, mandating that by 2025, the WEEE RLS should cover 400 of Brazil's largest municipalities and reach 5,000 collection points, serving 60% of the population. However, this only covers municipalities with over 80,000 residents, representing about 7% of Brazil's total municipalities. While Article 8 of this decree states that no municipality should be excluded, smaller municipalities face challenges such as inadequate infrastructure, lack of technical staff, and limited information for managing solid waste.

Municipalities are responsible for integrated solid waste management and creating the Municipal Plan for Integrated Solid Waste Management (MPISWM), but the NSWP excludes urban cleaning services from direct responsibility in reverse logistics. Nonetheless, legislation encourages municipalities to participate in reverse logistics as co-managers. For example, state plans from Espírito Santo and Rio de Janeiro propose strategies to integrate all municipalities into the WEEE RLS through sectoral agreements.

Despite these legal frameworks, Brazil's reverse logistics system for WEEE still faces significant challenges, especially at the micro level. Studies highlight obstacles like lack of skilled labor, insufficient technology, and difficulties within the supply chain. Identifying the root causes of these challenges is crucial for developing effective strategies. This research addresses the need to establish guidelines and strategies to implement the WEEE RLS in smaller municipalities, those with fewer than 80,000 residents, which remain largely underserved.

Considering this context, there is a clear need to identify the root causes of the challenges faced by smaller municipalities in Brazil. This will allow for the proposal of guidelines and strategies that can facilitate the implementation and operationalization of the WEEE RLS, addressing a critical research gap.

2. Materials and methods

2.1 Case Study

In this research, municipalities with less than 80,000 inhabitants were classified as small, totaling 5,170 Brazilian municipalities. This case study included these small municipalities since Federal Decree no. 10.240/2020 establishes the mandatory implementation of the RLS for WEEE only in large municipalities (with more than 80,000 inhabitants as mentioned above).

2.2 Step 1 – Validation of challenges related to the implementation and operationalization of the WEEE RLS

The objective of this stage was to validate the micro challenges identified by Silva et al. (2023) (Table 1) and to identify new challenges in small Brazilian municipalities.

Table 1 - Summary of the challenges for the operationalization and implementation of the WEEE RLS

Operational stage	Challenges
1 – Disposal	1A – The population and LRS entities' lack or insufficient training and awareness

Operational stage	Challenges
	1B – Inadequate disposal of WEEE
	1C – Difficulty classifying and segregating WEEE
	1D – Inadequate distribution of WEEE disposal points
2 – Collection and Receipt	2A – Collection rate and WEEE collection/disposal points
	2B – Insufficient WEEE receiving and sorting plants
	2C – Intelligent WEEE collection systems not applied
3 – Transportation	3A – Deficient WEEE transport infrastructure
	3B – Long and costly distances
4 – Final Destination	4A – Lack of technical training to work in the WEEE recycling sector
	4B – Research and development shortage of WEEE recycling technologies
	4C – Absence or insufficient number of WEEE recycling companies
	4D – Heterogeneous composition hinders treatment

Source: Authors (2022).

A survey was conducted using a questionnaire with open and closed questions. In this case, an online questionnaire was prepared through the electronic platform of the Federal University of Espírito Santo, which allows the creation of surveys for both university members and the external community.

The first section provided basic information about the research and ensured confidentiality, with data used only for academic purposes. Participants were required to consent via an informed consent form. This research was ethically approved by Certificado de Apresentação para Apreciação Ética (CAAE) n° 6.008.765.

The questionnaire then collected information about participants represented sector and municipality/state. The sectors were divided into categories: academic, community, business, institutional, rural, and others. This division ensured diverse perspectives, helping to identify trends and discrepancies among different groups, enhancing the overall analysis.

For each challenge presented, participants could respond with "Agree," "Disagree," or "I don't know how to give an opinion." Open-ended questions were included at the end of each section to allow participants to comment on the challenges, providing space for both quantitative and qualitative insights.

2.3 Step 2 – Identification of root causes related to the implementation and operationalization of the WEEE RLS by a Focus Group and preparation of a CRT

To explore the root causes of challenges in implementing and operationalizing the WEEE RLS in small municipalities, a focus group was conducted, and the Current Reality Tree (CRT) tool was used to hierarchize these causes. The meeting took place on July 11, 2023, via Google Meet, with 10 participants from academic, business, institutional sectors, and organizations involved in recyclable materials.

The focus group followed a structured agenda, starting with a 10-minute presentation of the research objectives and the CRT tool, followed by participant introductions. Then, participants worked for 45 minutes using Figma software to construct the CRT collaboratively. The CRT helps identify undesirable effects (problems) and their root causes by mapping the cause-effect relationships in a hierarchical manner.

During the focus group, 13 challenges were listed and categorized. The challenges were then logically organized in a cause-effect sequence, with the root causes positioned at the base of the tree, highlighting points of greatest risk to system performance. The main undesirable effect was identified at the top of the tree. After considering all contributions, the meeting concluded, finalizing the CRT analysis.

2.4 Stage 3 – Proposition of guidelines and strategies to implement and operationalize the WEEE RLS in small Brazilian municipalities

To propose guidelines and strategies to implement and operationalize the WEEE RLS in small Brazilian municipalities, documentary research was carried out to support and analyze the cognitive map of the CRT.

Regarding the documentary research, Table 2 describes the databases that were searched and the terms that were used.

Table 2 - Details of documentary research

Tool	Database	Keywords	Time lapse
Documentary research	Municipal plans for integrated solid waste management, state solid waste plans, national solid waste plan, international plans related to solid waste, laws, policies, terms of reference, decrees, resolutions and publications from government bodies, banks data from city halls and research institutes, government transparency portals, annual reports, trade associations and public administration bodies	“electronic waste”, “e-waste”, “waste electronic equipment”, “electronic equipment”, “implementation”, “reverse logistics”, “reverse logistics system”, “reverse logistics of electronic waste”, “shared responsibility”	1990-2022

Source: Authors (2022).

The sources included municipal, state and national solid waste management plans, as well as international plans related to the topic. Legislation, public policies, terms of reference, decrees, resolutions and publications from government agencies, databases from city halls and research institutes, government transparency portals, annual reports, sector associations and public administration agencies were also analyzed. The documents were selected based on their relevance to the research, prioritizing official and institutional sources with updated information on the implementation of WEEE reverse logistics. The databases and websites consulted include the National Information System on Solid Waste Management (SINIR), Brazilian Institute of Geography and Statistics (IBGE), Ministry of the Environment and Climate Change (MMA), government transparency portals, city hall websites, research institutes, reports from sector associations and public administration bodies.

The documents collected were analyzed using the qualitative content analysis technique, which allowed the identification of patterns, gaps and key elements for structuring the reverse logistics system. The extraction and categorization of information were guided by the challenges and aspirations identified in the previous stages of the research, such as the systematic literature review, the survey research, the focus group and the CRT.

It is noteworthy that the guidelines and strategies focus on the challenges and aspirations pointed out throughout all the previous stages: systematized literature review, Survey, the focus group, and the CRT. Thus, rather than being constituted as a general set of guidelines, this set focused on those identified challenges, considering all the pointed out aspirations.

Moreover, it is emphasized that, given the guidelines incorporated in several spheres, especially at the federal level, this research aims to propose new guidelines and adjust existing ones, consolidating them for application in small municipalities.

3 Results and discussion

3.1 Step 1 – Validation of challenges related to the implementation and operationalization of the WEEE RLS

Figure 1 shows the distribution of the sectors represented by questionnaire participants. It should be noted that the label of the partitions shows the number of participants and the percentage represented by each one, respectively.

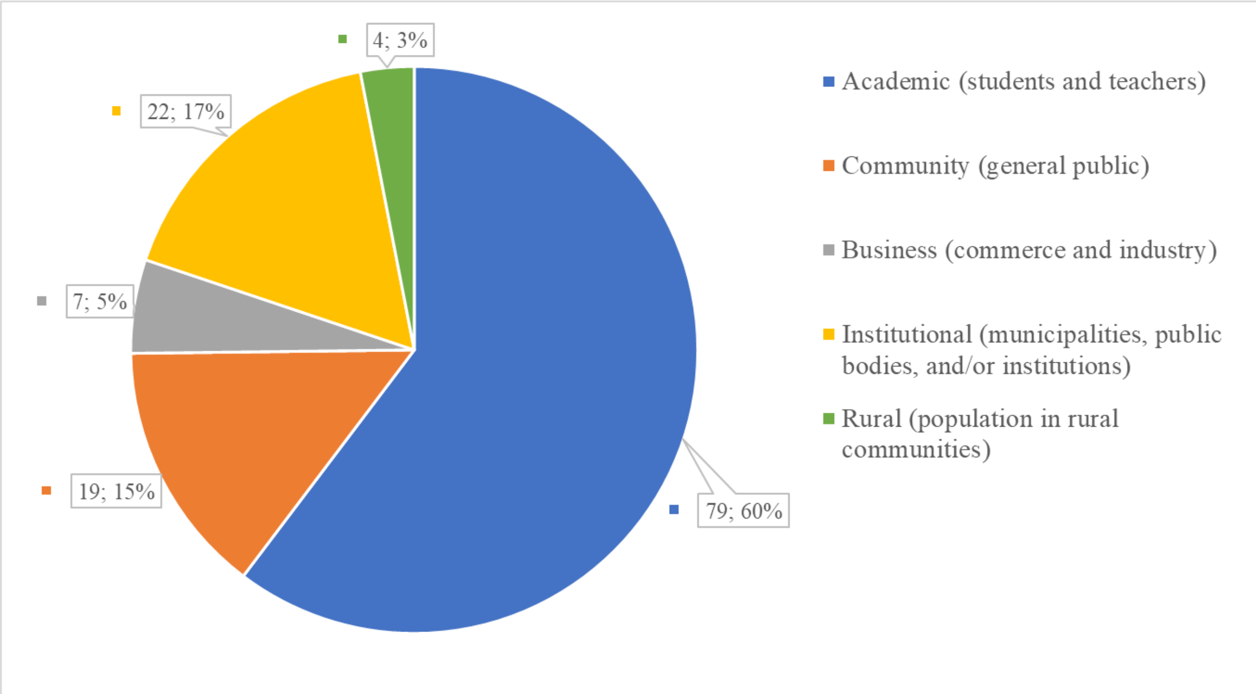

Figure 1 – Distribution of the sectors represented by questionnaire participants. Source: The Authors (2022).

Figure 1 shows that the academic sector was the most represented in the study, making up 60% of participants. This is explained by the research being conducted within a university, where both teachers and students contributed valuable perspectives. Despite this academic bias, responses were received from other sectors as well: community (15%), business (5%), institutional (17%), and rural (3%).

In terms of geographic distribution, responses came from 55 municipalities across seven Brazilian states, with most coming from the South and Southeast regions, adding geographical diversity to the research.

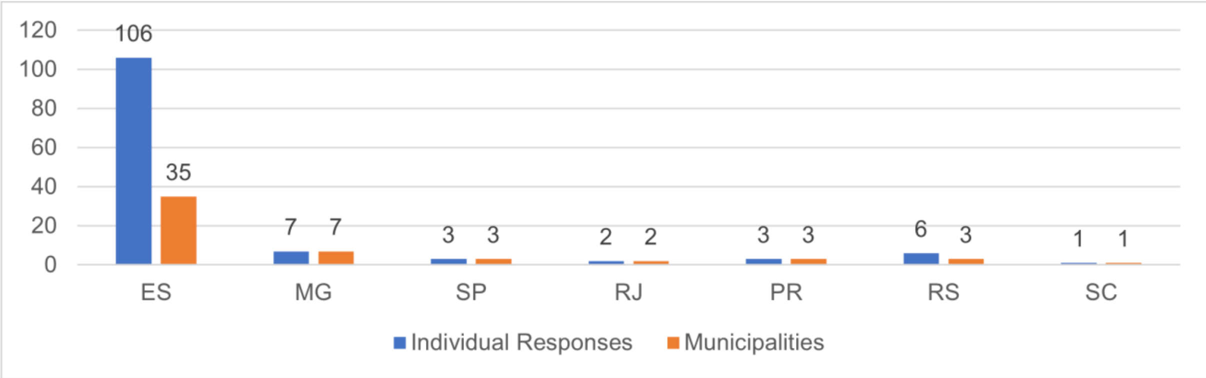

Figure 2 – Distribution of municipalities represented by questionnaire participants. Source: The Authors (2022).

The inclusion of 26 small Brazilian municipalities in the sample is noteworthy, validating the proposed guidelines and strategies that address their unique challenges. Figure 2 also shows a high concentration of responses from Espírito Santo, due to the research group's origins and strong dissemination efforts in that state.

Technically, Figures 3, 4, 5 and 6 illustrate the number and distribution of answers for each question by operational stage. Participants could select "Agree," "Disagree," "I don't know how to give an opinion," or leave the question blank ("No Answer"), as none of the questions were mandatory.

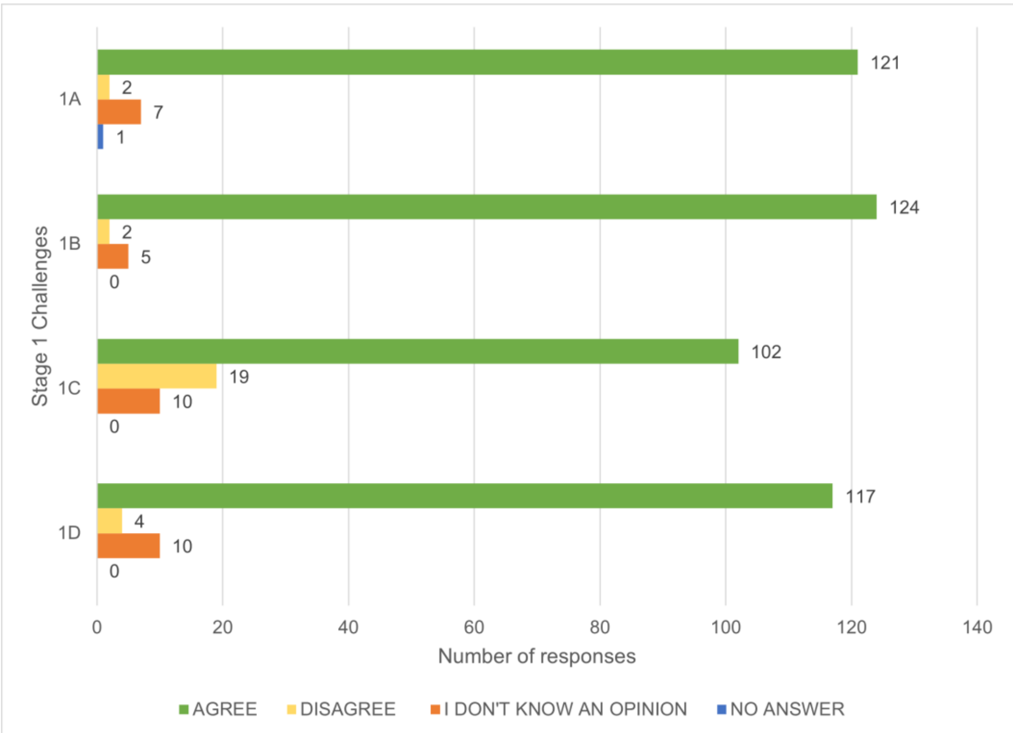

Figure 3 – Number and distribution of questionnaire responses for disposal stage challenges. Source: The Authors (2022). Legend: 1A The population and LRS entities' lack or insufficient training and awareness, 1B Inadequate disposal of WEEE, 1C Difficulty classifying and segregating WEEE and 1D Inadequate distribution of WEEE disposal points.

The results in Figure 3 show a strong consensus (92.1%) among participants regarding key challenges in WEEE management, including the lack of training and awareness (1A), inadequate disposal of

WEEE (1B), and insufficient WEEE disposal points (1D). Only 2% disagreed, while 5.6% expressed no opinion. These results underscore the relevance of these challenges, particularly regarding public awareness. Research by Shahabuddin et al. (2022) emphasizes that public awareness, alongside efforts from national and international bodies, is crucial for effective WEEE management and supports a circular economy. Moreover, Dagiliūtė et al. (2019) highlighted the lack of awareness, not only among consumers but also among small local merchants, especially those not integrated into verticalized marketing networks, which is common in small municipalities.

In rural areas, limited communication infrastructure further complicates the dissemination of environmental education, as highlighted by Bucur (2020) and Zhang et al. (2023). This emphasizes the need for tailored awareness strategies, such as local community lectures and mobile information campaigns. Similarly, Calıs & Ergul (2015) pointed out that training educators and incorporating environmental topics into school curriculums can help raise future generations' awareness about proper waste management.

A notable point of divergence was the challenge 1C, "Difficulty classifying and segregating WEEE," where 14.5% of participants expressed disagreement. Despite 77.9% agreement, this challenge appears less pronounced in smaller municipalities. Research by Guarnieri et al. (2020) suggests that basic knowledge of electronic products is widely distributed, and the issue is more about access to specific disposal guidelines. However, limited information in smaller municipalities may hinder the proper management of different WEEE types.

Figure 4 further emphasizes significant agreement (81.9%) on the challenges of insufficient WEEE receiving and sorting plants (2B) and the absence of intelligent collection systems (2C). This reflects the findings of Sari et al. (2021), who pointed out that such logistical challenges represent major barriers to the effective implementation of WEEE management systems.

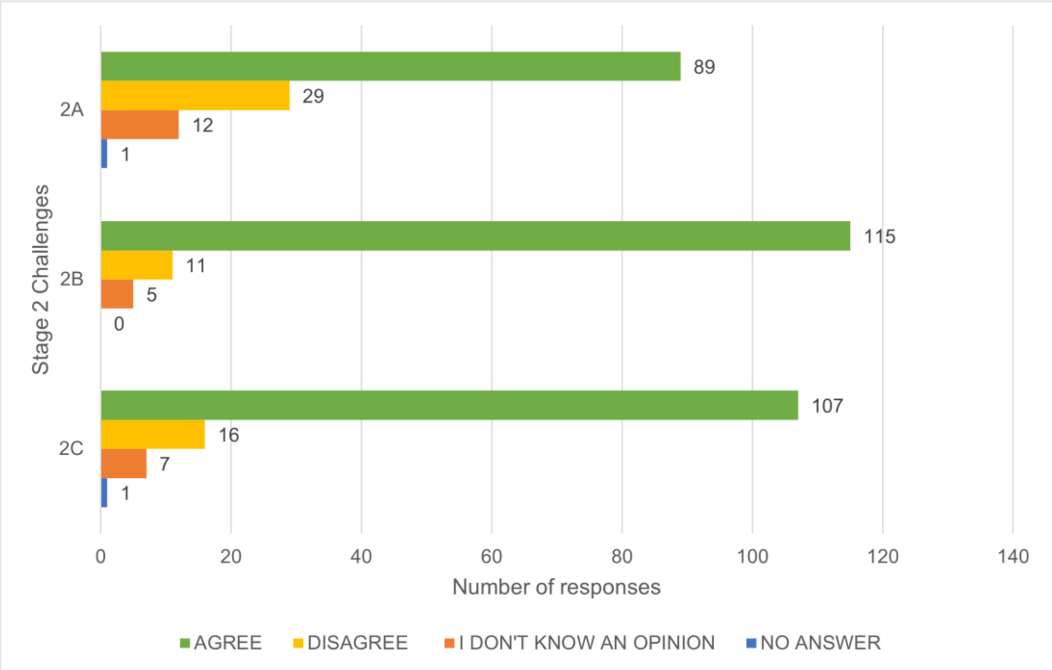

Figure 4 – Number and distribution of questionnaire responses for collection and receipt stage challenges. Source: The Authors (2022). Legend: 2A Collection rate and WEEE collection/disposal points, 2B Insufficient WEEE receiving and sorting plants and 2C Intelligent WEEE collection systems not applied.

The deficiencies in WEEE receiving and sorting centers, along with the challenges of implementing intelligent collection systems, are significant obstacles in the Brazilian context. These gaps lead to issues such as the contamination of WEEE with other types of waste, complicating both the collection and treatment processes. Gunarathne et al. (2020) and Okwu et al. (2022) highlight that without proper facilities, the efficient management of WEEE becomes nearly impossible. Furthermore, the absence of intelligent systems, like tracking technologies, creates inefficiencies in WEEE reverse logistics (Kazancoglu et al., 2020).

The lack of digitalization in WEEE management impacts social, economic, and environmental aspects, as observed by Kazancoglu et al. (2020), who advocate for integrating new technologies to reduce pollution, enhance working conditions, and minimize waste. However, small municipalities face additional challenges due to limited financial resources and infrastructure, making it harder to establish screening facilities and adopt advanced information technologies.

In smaller municipalities, the absence of WEEE sorting centers results in greater contamination risks and higher costs. The inadequate infrastructure exacerbates the difficulty of applying intelligent systems, as local governments may lack the technological capabilities to support such systems (Gunarathne et al., 2020).

One challenge that stands out is 2A, "Collection rate and WEEE collection/disposal points," which had a higher level of disagreement at 22.1%, compared to an agreement of 67.9%. This disagreement may stem from a mismatch between international models and the Brazilian reality, especially in smaller municipalities. Ventura et al. (2019) noted that small municipalities often lack the financial and technical resources necessary to implement comprehensive WEEE collection systems, leading to a lower collection rate and fewer disposal points.

Moreover, the higher level of disagreement could also stem from a misunderstanding of the term "collection/disposal fee." In this context, it refers to the rate of WEEE collection in relation to the total waste generated, rather than a monetary fee. This misunderstanding highlights the need for clear communication and education to foster a better-informed discussion on WEEE management in Brazil.

In the Transport stage (Figure 5), which addresses challenges 3A "Deficient WEEE transport infrastructure" and 3B "Long and costly distances," 19.9% of participants refrained from expressing an opinion, while 10.3% disagreed, and 69.5% agreed. The significant proportion of respondents who opted not to provide a concrete opinion highlights a gap in understanding regarding this challenge. As noted by Hansen et al. (2022), the lack of transport and recycling infrastructure is a common issue in many developing countries, especially in rural areas where the benefits of economies of scale are more pronounced. However, these studies often fail to specify the type of infrastructure in question, which may have contributed to the uncertainty among participants (Hansen et al., 2022).

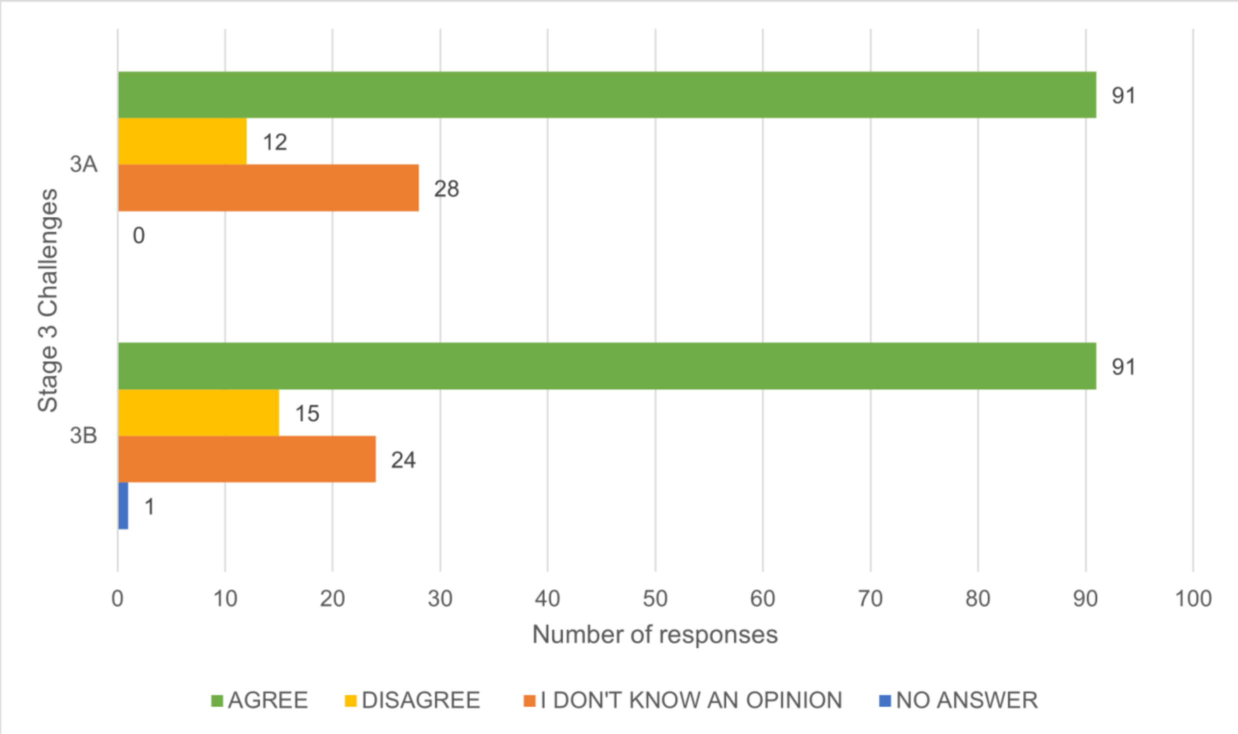

Figure 5 – Number and distribution of questionnaire responses for transport stage challenges. Source: The Authors (2022). Legend: 3A Deficient WEEE transport infrastructure and 3B Long and costly distances

This gap in research concerning transport-related challenges can result in participants being less informed, thereby making it difficult for them to take a clear stance on the issue. The lack of a solid foundation in literature may lead some respondents to hesitate in forming strong opinions, emphasizing the need for more in-depth studies that address the logistical complexities of transporting WEEE. This is critical for enhancing understanding and providing clearer information for more informed decisions and policies.

The scenario reflected in Figure 5 demonstrates a notable level of misinformation and disagreement concerning transportation issues, underlining the challenges posed by the need for economies of scale in WEEE reverse logistics. Further exploration of this issue is necessary to develop more accessible and practical approaches to transportation challenges in this sector.

In Figure 6, challenges 4A "Lack of technical training to work in the WEEE recycling sector" and 4C "Absence or insufficient number of WEEE recycling companies" received an agreement rate of 79.4%, while 8.0% expressed disagreement, and 12.2% chose not to provide a definitive opinion. These numbers indicate substantial recognition of these challenges by the participants. This consensus highlights the need for investment in technical training and the development of more recycling facilities, especially in regions where WEEE management infrastructure is insufficient (Gunarathne et al., 2020).

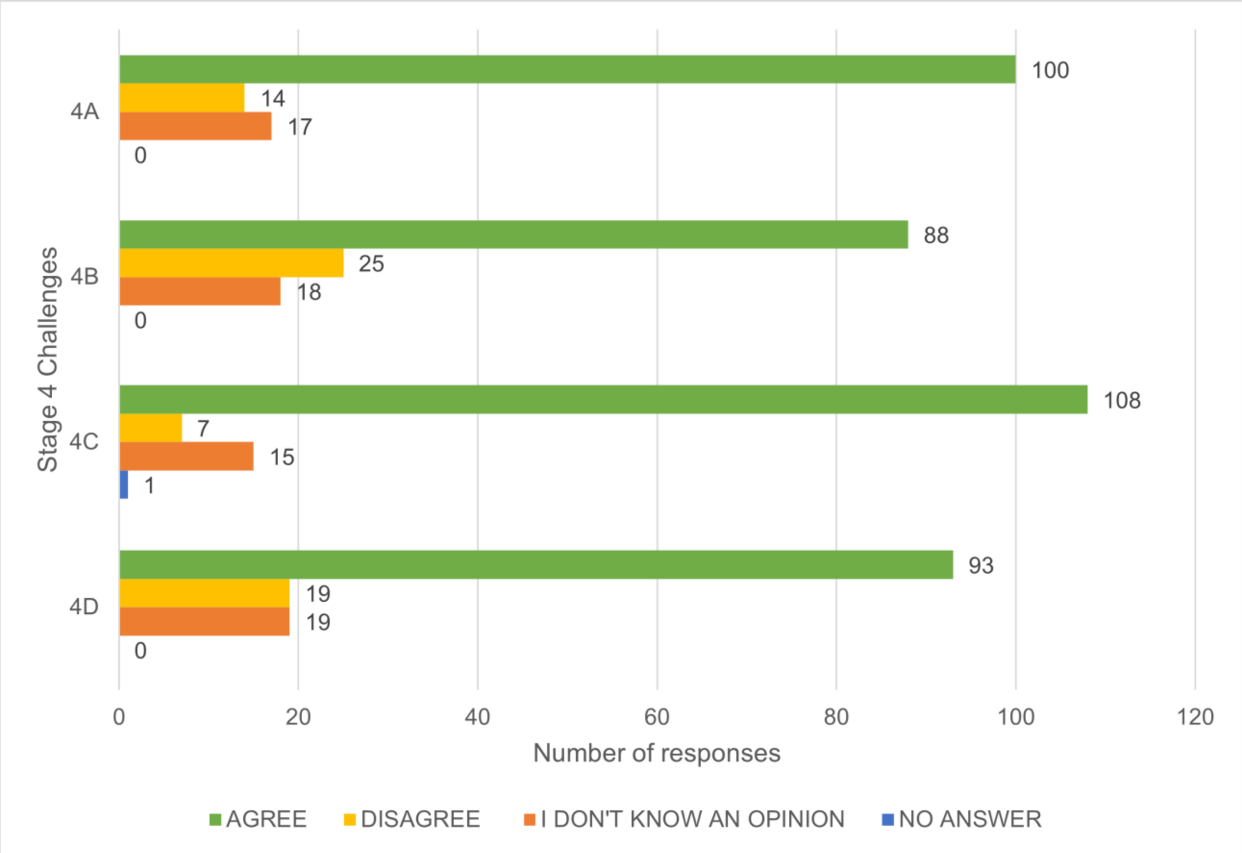

Figure 6 – Number and distribution of questionnaire responses for final destination stage challenges. Source: The Authors (2022).

Legend: 4A Lack of technical training to work in the WEEE recycling sector, 4B Research and development shortage of WEEE recycling technologies, 4C Absence or insufficient number of WEEE recycling companies and 4D Heterogeneous composition hinders treatment.

However, the challenges *4B Research and development shortage of WEEE recycling technologies* and *4D Heterogeneous composition hinders treatment* showed a 69.1% agreement, 16.8% disagreement, and 14.1% "*I don't know how to give an opinion*" rates. This scenario denotes a more complex disposition of opinions toward these challenges.

The high rate of agreement in challenges 4A and 4C can be interpreted in the light of the national reality. The lack of technical training to work in the WEEE recycling sector and the insufficiency of recycling companies are challenges that have persisted for a long time in the Brazilian scenario, having been frequently highlighted as obstacles to the advancement of reverse logistics, even in large municipalities. This may explain participants' positive and agreeing responses as they recognize the pertinence and relevance of these questions.

Regarding challenges 4B and 4D, the divergence and the "*I don't know how to give an opinion*" answers may be related to the complexity and technical specificity of these issues. The lack of research and development of WEEE recycling technologies and the difficulty associated with the heterogeneous composition of these residues are areas that demand specialized technical knowledge, which is difficult to explore in small municipalities since they are generally concentrated in urban centers and more industrialized regions.

The disagreement may reflect the uncertainties regarding the technical and economic feasibility of these solutions, whereas the "*I don't know how to give an opinion*" answers can be attributed to some participants' lack in-depth understanding of these challenges.

Santos & Ogunseitan (2022) highlights that the variability of WEEE requires the use of advanced technologies to recover critical materials and rare earth elements. In Brazil, due to the lack of technologies and investments, the process currently employed is limited to dismantling. Recycling processes that can recover critical metals and rare earth elements, which are in increasing global demand, should be evaluated as economic opportunities (Santos & Ogunseitan, 2022).

Finally, a general summary of the stages shows that, in the disposal stage, a significant percentage of 88.55% in agreement with the proposals stands out, showing a remarkable adherence. On the other hand, 5.15% disagreed with the statements, whereas 6.11% were unable to give an opinion and a small portion of 0.19% offered no answer. The collection and receipt stage showed an agreement of 76.34%, suggesting solid support for the proposed approaches. However, the 16.41% disagreement and 6.87% uncertainty evidence nuance of opinions and knowledge among participants.

In the transportation stage, 69.47% agreed with each other, with 10.31% disagreeing and 19.85% showing being unable to give an opinion. This result highlights the complexity and heterogeneity of perspectives about transportation in WEEE reverse logistics. Finally, in the waste disposal stage, the percentage of agreement was 74.24%, with 12.40% disagreement and 13.17% of indecision, indicating a more notable divergence in this context.

It is notable that, despite some divergences, all challenges can be considered validated for the next stage, a clear sign of their relevance and pertinence. Although disagreement peaked at 22.1%, it is important to note that most respondents agreed with all challenges. The overall average disagreement, which was 10.1% for the 13 challenges, suggests that, on average, participants found a solid basis for agreeing to the proposals. Overall agreement reached 77.6%, reflecting comprehensive support for the identified challenges.

The unanimous validation reflects the remarkable similarity of the Brazilian reality in this context, transcending geographical barriers and highlighting the relevance of the challenges at hand. This unanimity of validation strengthens the basis to address the identified challenges and develop effective strategies for WEEE management in Brazil.

3.2 Step 2 – Identification of root causes related to the implementation and operationalization of the WEEE RLS according to the focus group and CRT

Figure 7 shows the CRT developed in collaboration with the focus group, graphically composed of the 13 operational dysfunctions validated in the previous stage, which are interconnected by arrows in a structure to be read from the bottom to the top, evincing the main undesirable effect identified: challenge *1B Inadequate disposal of WEEE.*

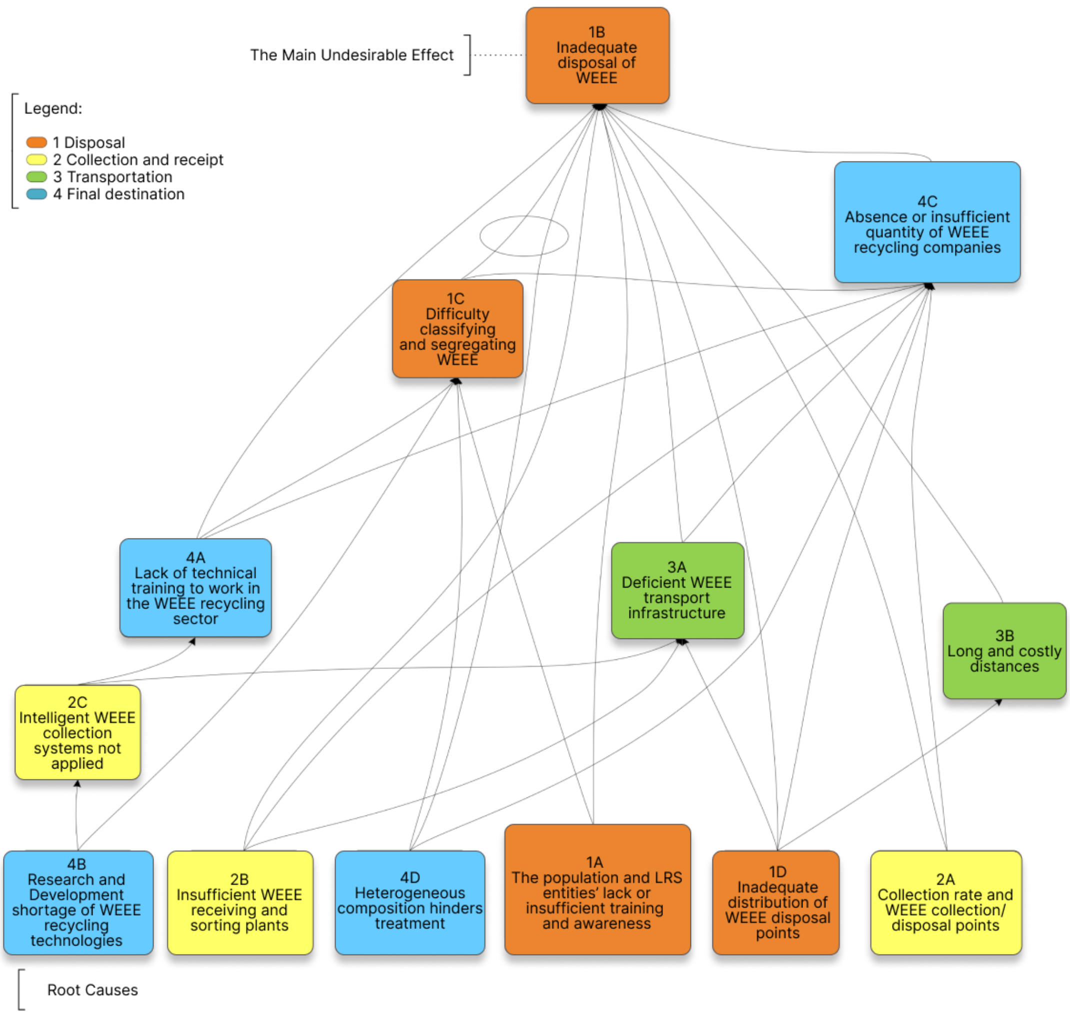

Figure 7 – Current Reality Tree developed in collaboration with the focus group. Source: The Authors (2022).

As seen in Figure 7**Erro! Fonte de referência não encontrada.**, the main identified undesirable effect refers to challenge *1B*, which is directly related to another 10 out of 12 remaining challenges. The interconnection of the main undesirable effect with so many other challenges highlight how solving this core problem can have a ripple effect on solving many other related problems.

First, the relation with challenge 1A shows that the absence of training and awareness programs directly contributes to the problem of improper disposal. The absence of adequate educational programs to inform the population and the entities involved in the RLS about the risks and consequences of the improper disposal of WEEE causes the inadequate disposal of WEEE either due to ignorance or lack of incentives for correct disposal.

Moreover, the lack of ongoing awareness programs may result in a lack of stimulus to separate and appropriately collect WEEE, directly connecting to challenge *1C Difficulty classifying and segregating WEEE*. The complexity in distinguishing and separating the various electronic components of WEEE can inadequately mix materials, making treatment even more challenging. This scenario, in turn, can discourage people from adopting proper disposal practices, exacerbating the problem of improper WEEE disposal.

The relation between the main undesirable effect and challenge 1D is highlighted with the fact that the inadequate distribution of disposal points for WEEE makes it more difficult for the population to access appropriate places to dispose of their used electronic equipment, which is worsened in small municipalities with a predominance of rural areas in relation to urban ones. This lack of convenient disposal points can lead people to dispose of them in inappropriate places, such as common garbage bins or even in public spaces and increases the risk of environmental contamination due to the improper disposal of WEEE since electronic materials contain substances that harm the environment and human health.

The relation between the main undesirable effect and challenge 2A shows that, the WEEE collection rate is incipient, i.e., when only a limited amount of this waste is properly collected, results in insufficient availability of materials for recycling or appropriate treatment either due to the lack of consolidated volume for sale or to the lack of stimulus to install decentralized sorting and receiving units. As a result, many choose to improperly dispose of these items, contributing to the problem of improper WEEE disposal.

Regarding challenge 2B, the insufficient reception and sorting centers may hinder people's access to appropriate places to dispose of their used electronic equipment, consolidate volumes, and integrate waste pickers' organizations into the RLS, contributing to the problem of inadequate disposal of WEEE. Moreover, the lack of adequate infrastructure to receive and process WEEE hinders the efficient recovery of valuable materials, increasing pressure on natural ecosystems due to mining.

Finally, inadequate transport infrastructure for WEEE makes it difficult to intelligently collect this waste, especially in areas with no dedicated transport systems for this purpose. A lack of suitable vehicles and an efficient logistics network can delay collection, improperly store these items and, ultimately, inadequately dispose of WEEE.

Moreover, extensive and costly distances between collection sites and processing points increase the costs associated with WEEE transportation and logistics. These additional costs can discourage the adoption of responsible WEEE management practices, leading to cheaper alternatives, such as improper disposal.

Intermediate undesirable effects include *1C Difficulty classifying and segregating WEEE, 2C Intelligent WEEE collection systems not applied, 3A Deficient WEEE transport infrastructure, 3B Long and costly distances, 4A Lack of technical training to work in the WEEE recycling sector* and *4C Absence or insufficient number of WEEE recycling companies*. It should be noted that all stages of the RLS are represented in these effects.

In the end, the main undesirable effect, *Inadequate disposal of WEEE*, has six root causes. These dysfunctions are primary roots that affect the challenges validated during the development of this study and described in the CRT, being distributed among Stages I, II, and IV of the WEEE RLS.

The challenge *The population and LRS entities' lack or insufficient training and awareness* is a root cause as the absence of awareness among the population about the importance of separating and properly collecting WEEE can lead to citizens' inappropriate disposal behavior. As explained, without a clear understanding of environmental risks and the need to correctly recycle or dispose of WEEE, people may choose to inappropriately dispose of it, directly contributing to challenge 1B.

Moreover, the lack of training programmers can result in difficulties classifying and segregating WEEE (challenge link 1A-1C). Despite the widespread recognition that disposal behavior and consumer awareness play a key role in successful WEEE management interventions, a relevant finding is that few consumers are aware of the importance of WEEE recycling, the risks associated with this waste, and the available disposal sites. As a result, many consumers often dispose of their WEEE incorrectly along with household waste, regardless of whether they reside in dense urban centers or remote villages (Araujo et al., 2017; Imran et al., 2017; Kumar, 2019; Andeobu et al., 2021; Jangre et al., 2022; Okwu et al., 2022; Santos & Ogunseitan, 2022).

The challenge *Inadequate distribution of WEEE disposal points* is a root cause that is intrinsically related to the challenges of transport infrastructure and the involved distances. Challenge 3A, which concerns *deficient WEEE transport infrastructure,* highlights the importance of effective logistics systems for transporting WEEE from collection points to treatment or recycling plants. Unevenly distributed disposal points make transportation infrastructure inefficient and costly, rendering it even more challenging to properly manage this waste.

Similarly, challenge 3B, which deals with *Long and costly distances*, emphasizes how distances between collection, treatment, and recycling points can increase the costs and complexity of transporting WEEE. As argued by Kazancoglu et al. (2020), transportation cost is a crucial criterion to determine the location of sorting centers. The context of hazardous waste transport considers two key objectives: cost and risk. In this context, the shortest is also the fastest route for transport companies (Liang et al., 2020).

According to Costa et al. (2020), many Brazilian municipalities often carry out the transport and final disposal of waste randomly without an in-depth analysis to reduce route length. This results in excessive fuel consumption, driving up the costs associated with the process. Therefore, the inadequate distribution of WEEE disposal points, along with the challenges related to transport infrastructure and the involved distances, form an interconnected set of obstacles that requires addressal to improve WEEE management in Brazil.

Finally, the inadequate distribution of WEEE disposal points is also related to challenge *4C Absence or insufficient number of WEEE recycling companies.* When disposal points are concentrated in areas with few recycling companies, there may be an imbalance between the supply and demand of recycling services, which makes it difficult to properly treat WEEE.

It is important to note that the lack of formal WEEE treatment facilities has been identified as an infrastructure challenge by both Kumar & Dixit (2018) as well as Sharma et al. (2021). These infrastructure challenges encompass a shortage of facilities for storing, transporting, treating, and disposing of WEEE, as well as limitations in planning and forecasting WEEE generation.

The *Collection Rate and Incipient WEEE Collection/Disposal Points* challenge is root cause as it directly impacts the viability and development of WEEE recycling companies. Insufficient WEEE collection rates and scarce available collection/disposal points significantly decrease the amount of WEEE materials available for recycling. This creates a challenging landscape for WEEE recycling companies as they have no access to a sufficient amount of raw material to justify their investments in infrastructure and technology. As a result, many companies may be hesitant to enter the WEEE recycling market, which contributes to the *absence or insufficient amount of WEEE recycling companies* (4.3).

Moreover, as highlighted by Bouvier & Wagner (2011), a challenge associated with the WEEE collection system, whether by voluntary drop-off sites, private companies, and/or non-profit donation centers, refers to the lack of access to conveniently located facilities. This hinders the proper disposal of WEEE by consumers and consequently contributes to *the incipient WEEE Collection Rate and the lack of adequate WEEE collection/disposal points*.

The challenge *of insufficient WEEE receiving and sorting plants* is a root cause as their inadequacy directly compromises the effectiveness of the entire WEEE management process. Without an adequate infrastructure to process and sort WEEE, recycling companies face significant difficulties in sourcing quality materials for their recycling processes. This can discourage new investments in the WEEE recycling sector and limit the expansion of existing businesses. A study highlights that the availability of an infrastructure system plays a significant role in stimulating management practices in the WEEE industry (Chen et al., 2020).

Moreover, the lack of receiving and sorting infrastructure is also intertwined with challenge *3A Deficient WEEE transport infrastructures*. The inadequacy of the receiving and sorting centers hinders the process of transporting WEEE to these facilities. This can result in longer distances and higher transportation costs, which, in turn, negatively impacts the WEEE management system.

Xavier et al. (2020) point out that the safe non-destructive dismantling of WEEE requires the following: provision of spaces to receive and package WEEE, accommodation of workstations and tools, and a location to allocate the different materials obtained during disassembly, parameters that are difficult to find in small municipalities due to the lack of facilities or their small size.

On the other hand, the challenge *Research and development shortage of WEEE recycling technologies* is a root cause as it limits the ability of the national territory for efficient treatment. Without specific technologies to deal with electronic components, it is impossible to recover valuable materials and reduce contamination by hazardous waste containing flame retardants, heavy metals, among others.

According to Işıldar et al. (2019), in recent years, considerable research efforts have been undertaken to develop environmentally friendly biotechnological processes to recycle WEEE. Selectivity toward individual metals, cost-effectiveness, and eco-innovation are the potential advantages of these processes.

Kazançoglu et al. (2020) point out that, unlike developed countries, emerging economies collect and recycle WEEE (when sent for treatment) without any classification. Thus, useful and valuable parts, components and even products that can be reused are incinerated (irregularly) or disposed of in landfills.

Moreover, the lack of adequate technologies for recycling is also intrinsically related to the challenge 2C *Intelligent WEEE collection systems not applied.* The effectiveness of smart WEEE collection systems depends on the ability to efficiently recycle and reuse the collected materials. Without advanced recycling technologies, the implementation of intelligent WEEE collection systems becomes unfeasible since the collected materials would have a limited and inadequate destination.

Popa et al. (2017) highlighted the lack of a fully automated waste collection system that can separate different types of waste, along with a smart city platform dedicated to this type of system. This gap in the specialized literature and in the patents examined in the United States and the European Union highlights the urgent need to develop adequate recycling systems to collect, segregate, recycle/reuse, and recover WEEE, especially in small municipalities that demand optimized solutions.

The challenge *Heterogeneous composition hinders treatment* is a root cause because the heterogeneous composition of WEEE makes the process of classifying and segregating WEEE and recycling processes with high selectivity challenging. Due to the variety of electronic components, chemicals, and materials in equipment, it is complex to selectively separate the elements that can be recovered from those that require separate treatment. This mixes materials, which, in turn, hinders the proper treatment of WEEE and can lead to improper disposal of this waste, contributing to the problem of improper disposal (challenge 1B).

In several developed countries, the separation of WEEE poses a significant challenge due to its intricate composition. Rajesh et al. (2022) and Shahabuddin et al. (2022) note that the handling and processing of WEEE are still complex issues due to material diversity, including hazardous, precious, and other elements.

Moreover, the heterogeneous composition of WEEE challenges recycling companies (challenge 4C). The lack of standardization in electronic equipment hinders the development of effective recycling processes. Each device can contain a unique combination of materials and components, requiring customized recycling approaches. The absence of specialized and equipped recycling companies in Brazil to deal with this diversity makes the treatment of WEEE even more complicated and expensive.

Finally, it is concluded that the main contribution of CRT is to direct efforts to these six root causes. Their organization makes it possible to identify which should be eliminated or minimized as a priority. Root causes give rise to others and are rather unnoticeable by the organization. By eliminating them, it will be possible to perceive a chain reaction on all the other dysfunctions consequent to them, and it will be possible to reach the solution of the main unwanted effect, presented at the top of the CRT.

3.3 Stage 3 – Proposition of guidelines and strategies to implement and operationalize the WEEE RLS in small Brazilian municipalities

The analysis conducted in Stages 1 and 2 found six root causes, the impact of which is deeply intertwined with the faced challenges. These root causes, by constituting the center of the issues at hand, serve as the foundation for the guidelines and strategies below. Each proposed guideline corresponds to a specific root cause, which is explicitly shown in Table 3. The proposed approach directly focuses on the core areas of these concerns, aiming at formulating pragmatic and targeted solutions that can address the challenges in a holistic and lasting way.

Thus, Table 3 shows the proposed guidelines that are individually discussed below.

Table 3 - Guidelines and strategies to implement and operationalize the WEEE RLS

Guidelines	Matching challenge	Strategies
D.1 Strengthening capacity building and awareness programs for WEEE RLS	1A The population and LRS entities' lack or insufficient training and awareness	E 1.1 Develop comprehensive training and awareness programs for different audiences tailored to their specific needs E 1.2 Integrate environmental education from childhood in schools, addressing topics related to WEEE management, responsible consumption, recycling, and reuse E 1.3 Provide technical training for professionals involved in WEEE management, focusing on safe and sustainable practices E 1.4 Conduct regular public awareness campaigns through various communication channels E 1.5 Establish partnerships with local organizations and non-governmental organizations specialized in environmental education and waste management E 1.6 Implement a continuous monitoring and evaluation system to measure program effectiveness E 1.7 Provide clear information on WEEE management practices and the benefits of active participation
D.2 Establishment of a network of disposal points suitable for WEEE	1D Inadequate distribution of WEEE disposal points	E 2.1 Conduct a strategic location assessment to identify regions with high demand for WEEE disposal points E 2.2 Establish public-private partnerships to optimize WEEE collection infrastructure E 2.3 Ensure broad coverage of disposal points in urban and rural areas E 2.4 Use monitoring technologies such as mobile apps and tracking systems for real-time information on disposal point locations E 2.5 Implement recycling and reuse programs for collected WEEE
D.3 Strengthening the collection and expansion of WEEE disposal points	2A Collection rate and WEEE collection/disposal points	E 3.1 Extend existing agreements for medium/large municipalities to small municipalities E 3.2 Set geographic targets for expanding the WEEE collection network E 3.3 Implement incentive programs for collection E 3.4 Collaborate with private sector companies to establish collection networks E 3.5 Invest in recycling infrastructure for safe dismantling and recovery of valuable materials E 3.6 Implement continuous monitoring to track collected WEEE and collection point effectiveness
D.4 Strengthening of WEEE Receiving and Sorting Centers	2B Insufficient WEEE receiving and sorting plants	E 4.1 Assess demand and coverage to identify deficiencies in receiving and sorting centers E 4.2 Develop expansion plans for receiving and sorting center infrastructure E 4.3 Explore public-private partnerships for new receiving and sorting centers E 4.4 Introduce advanced sorting and automation technologies for efficiency E 4.5 Provide specialized training for center workers E 4.6 Implement continuous monitoring and auditing for center operation E 4.7 Integrate associations into the WEEE reverse logistics system E 4.8 Invest in associations and capacity-building programs E 4.9 Include WEEE management in municipal solid waste plans with regular reviews

Guidelines	Matching challenge	Strategies
D.5 Stimulating research and development of WEEE recycling technologies	4B Research and development shortage of WEEE recycling technologies	E 5.1 Foster collaboration between academia and the electronics industry E 5.2 Create innovation centers for WEEE recycling technologies E 5.3 Provide financial incentives for research and development E 5.4 Promote innovation competitions and challenges E 5.5 Establish norms and standards for WEEE recycling technologies E 5.6 Create knowledge and collaboration networks for sharing advancements
D.6 Development of adaptive technologies to treat heterogeneous WEEE compositions	4D Heterogeneous composition hinders treatment	E 6.1 Develop automated sorting systems for different materials E 6.2 Design treatment facilities with adaptable and flexible modules E 6.3 Develop multiphase treatment processes for selective material recovery E 6.4 Explore energy recovery technologies for heterogeneous waste E 6.5 Allocate resources for research and development of innovative technologies E 6.6 Develop standards and norms for WEEE treatment technologies

Source: Authors (2022).

Enhancing capacity building and awareness programs for WEEE is crucial for effective management in small municipalities. Tailored programs should specifically target various audiences, including local residents, industry workers, government authorities, and the private sector. Moreover, integrating environmental education in schools from an early age fosters a culture of responsibility that can have lasting impacts on community behavior.

In addition to educational initiatives, technical training for professionals involved in waste management is essential to ensure safe and sustainable practices are implemented consistently. To complement these efforts, regular public awareness campaigns utilizing diverse communication channels can effectively highlight the importance of responsible waste management. Collaborating with local organizations and NGOs can further enrich awareness programs, enabling them to reach wider audiences and increase engagement at the community level.

A critical aspect of managing WEEE is the establishment of a comprehensive network of disposal points. This involves strategically assessing locations to identify regions with high demand for disposal services. Municipalities should consider specific approaches tailored to rural areas, ensuring that collection infrastructure is optimized through collaborative efforts. Education and awareness campaigns play a vital role in informing the public about proper disposal practices, thereby increasing the utilization of these disposal points.

To strengthen the collection process and expand disposal points effectively, municipalities can pursue agreements at the state level. This strategic approach can facilitate the expansion of collection points across various locations, particularly in underserved areas. Additionally, implementing incentive programs and forming partnerships with the private sector can significantly enhance public participation in waste disposal initiatives.

As the volume of WEEE continues to grow, enhancing receiving and sorting centers becomes increasingly critical. Public-private partnerships can optimize processing efficiency through the integration of advanced sorting technologies. Investing in worker training, coupled with continuous monitoring and audits, ensures high-quality operations. Furthermore, integrating associations into the reverse logistics system can simplify the collection process and enhance overall infrastructure, promoting greater efficiency in waste management.

The need for innovation in WEEE recycling technologies is paramount. Stimulating research and development in this area requires collaboration between academic institutions and the electronics industry. Financial incentives, innovation competitions, and adherence to quality norms can drive progress and motivate stakeholders to invest in new solutions. Establishing knowledge networks and fostering collaboration will ensure the exchange of ideas and best practices, thereby accelerating advancements in WEEE recycling.

Finally, developing adaptive technologies capable of treating heterogeneous WEEE compositions is essential for optimizing resource recovery. Implementing automated sorting systems and adaptable treatment facilities can enhance processing capabilities. Furthermore, investing in research and development, alongside establishing industry standards, is crucial for addressing the complexities associated with heterogeneous waste.

Overall, the implementation of these strategies can significantly strengthen WEEE management, promote sustainable practices, and contribute to environmental preservation and resource conservation. To effectively address the challenges associated with WEEE management and promote sustainable solutions, collaboration among various stakeholders is crucial. This collective effort will pave the way for a more sustainable approach to managing this growing environmental concern.

4 Conclusion

The Survey stage obtained 131 responses. It is noteworthy that, despite some divergences, all challenges were validated for the next stage, a clear sign of their relevance and pertinence. Although disagreement peaked at 22.1%, it is important to note that most respondents agreed with all challenges. The overall average of disagreement (10.1% for the 13 challenges) suggests that, on average, participants found a solid basis for agreeing to the proposals. Overall agreement reached 77.6%, reflecting their comprehensive support for the identified challenges.

The elaboration of the CRT showed that the main undesirable effect was challenge *1B Inadequate disposal of WEEE*, together with six root causes, namely: *The population and LRS entities' lack or insufficient training and awareness, Inadequate distribution of WEEE disposal points, Collection rate and incipient WEEE collection/disposal points, Insufficient WEEE receiving and sorting plants, Research and development shortage of WEEE recycling technologies, and Heterogeneous composition hinders treatment.*

Finally, in the last stage, it is concluded that the set of guidelines and strategies proposed offer a tool for decision-makers that can foster the implementation and operationalization of the WEEE RLS in small Brazilian municipalities.

However, it is important to note that the perceptions collected reflect a geographical concentration in the south and southeast regions, particularly in Espírito Santo. This represents a methodological limitation that must be considered when interpreting and generalizing the results.

Even though the challenges were validated by a geographically diverse sample, the stronger response rate from certain states may have influenced some of the findings.

In addition, while opinion divergences were observed, they were managed by maintaining all validated items, considering them representative of the complexity and heterogeneity of the study context. The authors recognize that environmental challenges may vary regionally and that future studies should expand the reach to other Brazilian regions to increase representativeness.

Data availability statement

The dataset that supports the results of this paper is available at SciELO Data and can be accessed via https://doi.org/10.48331/SCIELODATA.MH6QK1.

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