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Electronic waste recycling in the Brazilian scenario: difficulties and proposals

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ABSTRACT
Electrical and electronic equipment consumption has increased in recent years, generating a large amount of waste that can cause environmental and social impacts. This work aimed to analyze the main difficulties and proposals to improve electronic waste recycling in Brazil as well as to identify which types of waste are most generated and recycled in the country. For this, a systematic literature review was carried out, using national and international databases. By analyzing the results, it was found that the main challenges are the lack of public awareness, infrastructure, inspection and the need to implement reverse logistics. The main suggestions are to adopt a circular economy model, improve data collection, promote collector training, develop local capacity to recover materials and increase environmental education. The most generated types of waste are the green line followed by the brown line, and the most recycled are the green line. It can be concluded that electronic waste recycling is a strategic activity for Brazil, which can bring economic and environmental benefits, but which requires greater articulation among the different actors involved.

KEY WORDS: Systematic Literature Review; Reverse Logistic; Electronic Equipment; Electronic Equipment Lines.

1 INTRODUCTION

According to the Brazilian Association of Standards and Techniques (ABNT (*Associação Brasileira de Normas e Técnicas*); 2012), devices that depend on electrical energy or electromagnetic fields to function, or that serve to generate, transmit, convert and measure these forms of energy, are called electronics (EE). These devices can have domestic, industrial, commercial or service use and include devices such as TVs, computers, cell phones, refrigerators, mixers, drills and cameras.

Electronic waste (EEW) is generated when EE are no longer used or lose their functionality, either due to planned obsolescence or perceptive obsolescence. They can also be known as e-waste, electronic waste, or technological waste. The main generators of EEW in Brazil are public or private institutions, including companies from different areas and residences (CARDOSO, 2013; DA SILVA et al., 2023).

Planned obsolescence is a practice that encourages consumerism by making consumers exchange their products for a newer one without the real need. This can occur when a particular product leaves the industry with a reduced shelf life, and a classic example this is from the Phoebus cartel, which artificially reduced the durability of incandescent light bulbs in the 1920s (MONTEIRO, 2018; FERREIRA, 2022). In recent years, the average lifespan of a computer has decreased from 4.5 years in 1992 to around 2 years in 2005, resulting in greater quantities of computers being disposed of or exported to developing countries (KIDDEE et al., 2013; CHAKRABORTY et al., 2021).

Perceptual obsolescence is a practice of making consumers believe that their products are out of date or out of fashion, even if they still function perfectly. It is a marketing strategy that exploits trends, fashions and technological innovations to induce consumers to buy new products. A typical example of perceptual obsolescence is the case of smartphones, which are constantly released with new features and designs, making previous models seem obsolete (ROSSINI, 2017; HARRIS, 2023).

EEW recycling is a necessity given the large volume of waste generated each year. More than 53 million tons of this waste were generated in 2019 worldwide, while the number of devices grew by around 4%. In Brazil, 2.1 million tons of EEW were generated in 2019, ranking

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fifth among the largest producers of this type of waste in the world (ABRELPE, 2020; FORTI, 2020).

EEW disposal is one of the most worrying global environmental problems due to improper disposal, mainly in illegal landfills. EEW contain a variety of materials that can release toxic substances into the environment and human health if not disposed of correctly. Among these substances, toxic metals (such as barium, beryllium, cadmium, cobalt, chromium, copper, iron, lead, lithium, lanthanum, mercury and manganese) and organic compounds such as polychlorinated biphenyl stand out, which can cause damage to the system nervous system, the reproductive system, the immune system and the environment (Kiddee et al., 2013). Improper EEW disposal can occur through landfills or incineration, which can lead to leaching into groundwater or emission of toxic gases into the atmosphere. EEW recycling can also pose contamination risks if not done carefully and safely (KIDDEE et al., 2013; DA SILVA et al., 2023).

EEW also contain precious metals that could be reused in Brazil, but as there is no technology to reuse them, these metals end up being collected and exported to recycling companies in Europe or North America (Dias et al., 2022). Moreover, many EEW are exported to developing countries, where they are recycled precariously and informally, these practices contribute to depletion of natural resources and social inequality (FRANZOLIN, 2020).

In Brazilian legislation, EEW management is proposed in the Brazilian National Solid Waste Policy (PNRS - *Política Nacional de Resíduos Sólidos*), instituted by Law 12,305 of August 2, 2010 (BRASIL, 2010) and regulated by Decree 10,936 of January 12, 2022 (BRASIL, 2022). PNRS establishes the principles, objectives, instruments and guidelines for solid waste management in the country, including EEW (Ambiente, 2022; Soler, 2022). One of the instruments of PNRS is reverse logistics, which is the set of actions to collect, transport, treat and dispose of waste in order to minimize negative impacts and maximize economic and environmental benefits (BRASIL, 2010).

EEW's reverse logistics can contribute to reduction of greenhouse gas emissions, preservation of natural resources, generation of employment and income, social inclusion and circular economy (CAUMO, 2013; DE ALMEIDA FIGUEIREDO et al., 2021). Reverse logistics is mandatory for manufacturers, importers, distributors and traders of EE products and their components (BRASIL, 2010; SOLER, 2022). To implement reverse logistics, economic agents must enter into sectoral agreements with the government, which are acts of a contractual nature signed between the federal government and manufacturers, importers, distributors or traders. Sectoral agreements establish the goals and responsibilities of those involved in EEW's reverse logistics (SOLER, 2022).

In this context, this work aimed to present, briefly and clearly, the main difficulties and proposals to improve EEW recycling as well as which type of EEW is most produced and which is most recycled in Brazil.

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2 MATERIALS AND METHODS

To achieve the proposed objectives of this work, literature mapping was carried out to collect secondary data in recent studies on EEW management, considering the following aspects:

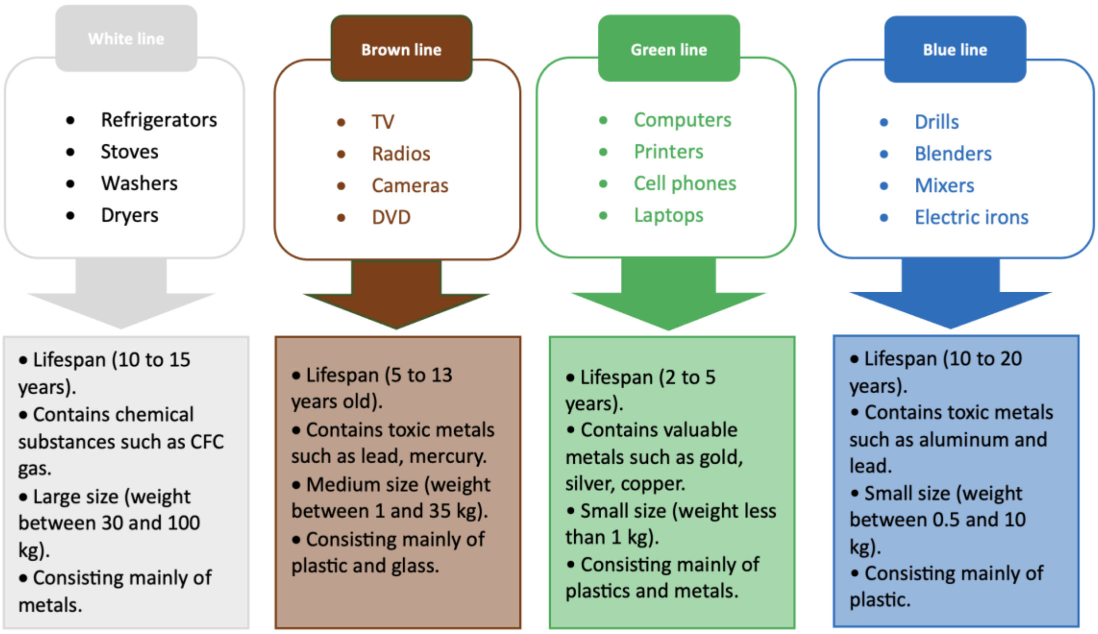
i) What are the difficulties in increasing the recycling rate of EEW in Brazil?

ii) What are the proposals to improve EEW reuse in Brazil?

iii) Which line according to the classification according to the Brazilian Agency for Industrial Development (ABDI - *Agência Brasileira de Desenvolvimento Industrial*) is most generated and recycled in Brazil?

One way of classifying EEW is based on the type of product, which follows the categories defined by ABDI (ABDI, 2013). According to this classification, EEW can be divided into four lines. Figure 1 shows EEW categories divided by lines.

Figure 1: Classification and characterization of electronic waste by lines



Source: adapted from ABDI, 2013; TOLEDO, 2015.

The methodology used to carry out mapping was systematic bibliographic review, seeking to understand the relationships, concepts and ideas that connect two or more topics (ALMEIDA, 2011).

Following the methodological procedure proposed by Kitchenham (2007), the following steps were performed, which are shown in Figure 2:

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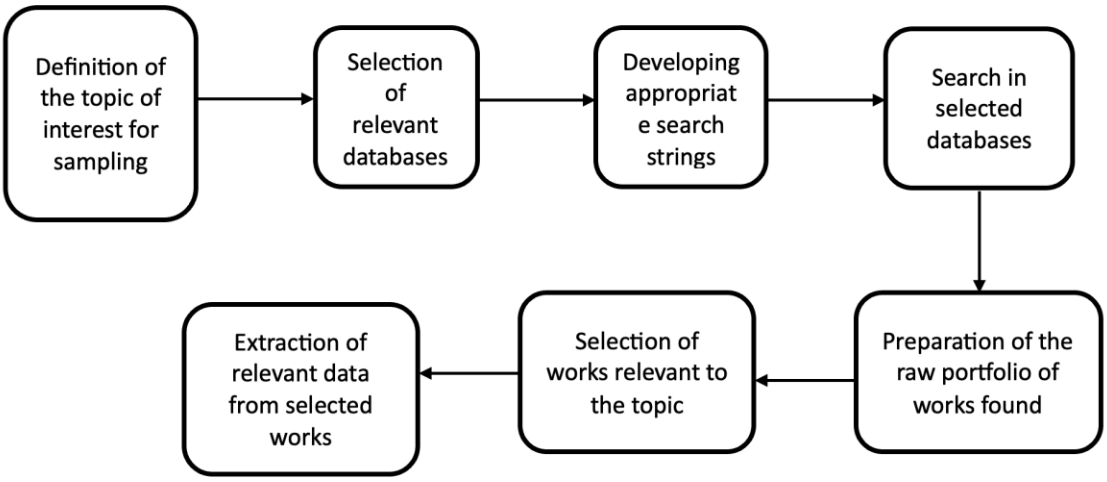
Figure 2: Flowchart of the systematic literature review steps



Source: prepared by the authors, 2023.

Chart 1 summarizes the aspects investigated, the strings and the query base. For the portfolio elaboration, Boolean logic was used with the "AND" operator, which results in studies that contain the search terms simultaneously.

Chart 1: Aspects investigated related to electronic waste management

Investigated aspects	Strings	Databases
Difficulties in electronic waste management	"Waste", "Electronics" and "Difficulties"	Google Scholar
Proposals to improve waste reuse	"Waste" plus "Recycling" or "Reuse", "Electronics" and "Proposals"	Google Scholar
Which line of waste is most generated and recycled in Brazil	"Waste", "Line (white, brown, green and blue), "Generation", "Recycling", and "Electronics"	Google Scholar

Source: prepared by the authors, 2023.

After selecting these filters in Google Scholar, pre-selected studies were read in full and categorized according to year, authors, EEW under study, Brazilian scenario and method of reuse or recycling.

Expressions were searched in singular and plural to optimize searches. The inclusion criteria for studies were:

i) Papers published between 2012 and 2022 covering a 10-year interval to associate with advances after approval by PNRS;

ii) Papers related to the Brazilian scenario;

iii) At least one Brazilian author.

The flowchart in Figure 3 shows the steps and criteria used to select papers.

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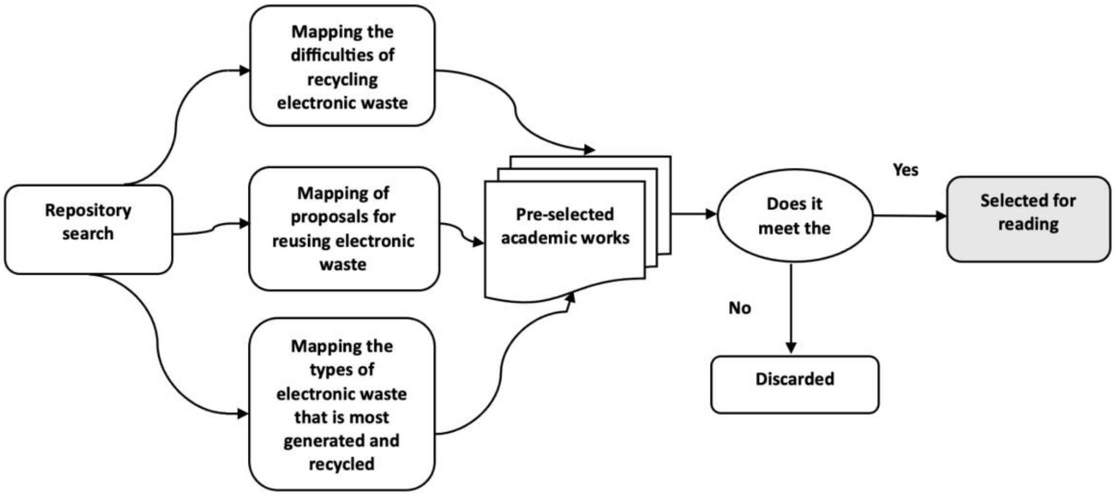
Figure 3: Flowchart of selection and application of criteria to select papers



Source: prepared by the authors, 2023.

3 RESULTS AND DISCUSSION

Secondary data collection for mapping the literature in Google Scholar resulted in a total of 7,200 studies. After applying the criteria relevant to the aspects investigated, the difficulties in EEW management, the proposals to improve waste reuse, the most generated and recycled line of waste in Brazil, the total number of studies were obtained, which can be viewed in Figure 4.

After reading the studies relevant to each aspect investigated, those that stood out for their contribution were selected for analysis. Relevant data were extracted from the selected studies.

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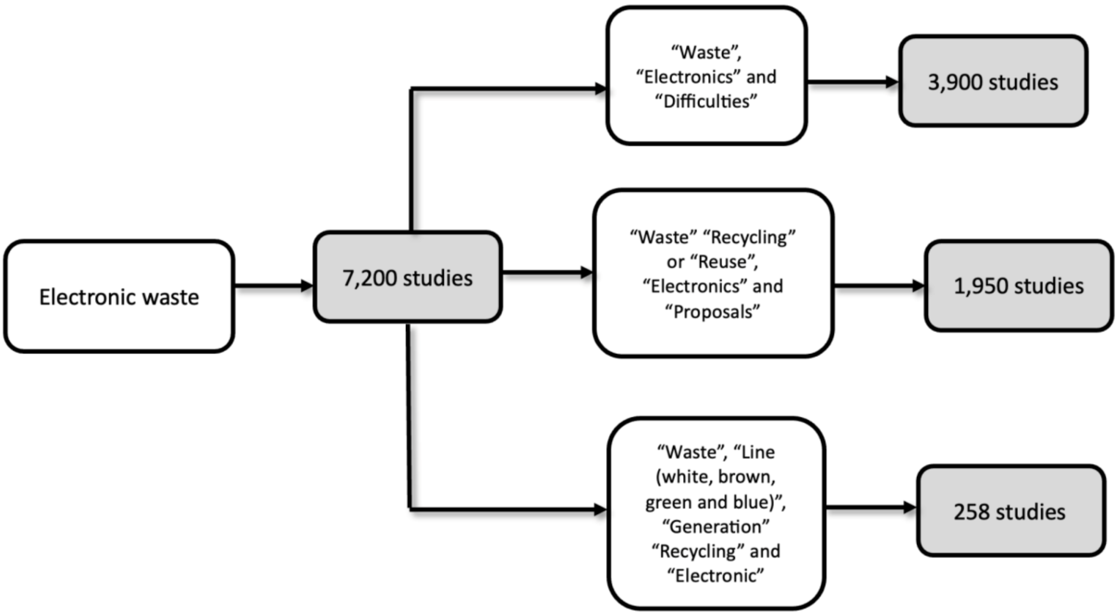
Figure 4: Flowchart of the number of studies after the systematic bibliographic review steps



Source: prepared by the authors, 2023.

3.1 Systematic literature mapping: main difficulties to increase the recycling rate of electronic waste in Brazil

For mapping the main difficulties, two articles and two academic works were selected for a more careful analysis. The chosen works are listed in Chart 2.

Chart 2: Selected studies associated with difficulties in recycling electronic waste in Brazil

Year	Journal/academic work	Authors	Titles
2015	Doctoral thesis, USP	Mendes	*Responsabilidade compartilhada pelo ciclo de vida do produto na cadeia de resíduos eletroeletrônicos*
2016	Journal of Cleaner Production	Guarnieri, Silva, Levino	Analysis of electronic waste reverse logistics decisions using Strategic Options Development Analysis methodology: A Brazilian case
2018	Master's dissertation, UFPB	Nóbrega	*Mapeamento dos resíduos eletroeletrônicos em um hospital público: inventário e a logística reversa.*
2018	*Perspectivas Contemporâneas*	De Brito Morigi	*A Importância das cooperativas de reciclagem na consolidação dos canais reversos de resíduos eletroeletrônicos: Um estudo sobre uma cooperativa de reciclagem em Maringá-PR*

Source: prepared by the authors, 2023.

During analysis, it was possible to verify that the main challenges in recycling EEW are:

- Low awareness of the population about the importance of the correct EEW disposal and the benefits of recycling for the environment and the economy (DE BRITO MORIGI, 2018).
- Lack of adequate infrastructure and technology for EEW processing, which limits the efficiency and quality of recycling and prevents the use of all equipment components (NÓBREGA, 2018).
- Lack of control and inspection of recycling activities by public agencies, which can generate occupational and environmental risks resulting from exposure to toxic and dangerous substances present in EEW (MENDES, 2015).
- Need to implement reverse logistics, which involves shared responsibility between manufacturers, importers, distributors, traders and consumers in EEW management, as provided for in PNRS (Guarnieri, *et al.*, 2016).

Considering the challenges related to the control and inspection of recycling activities and the need to implement reverse logistics, the Brazilian National Information System on Solid Waste Management (SINIR - *Sistema Nacional de Informações sobre a Gestão dos Resíduos Sólidos*) was created, which aims to collect, systematize and make available information on solid waste management in the country. SINIR was created by Law 12.305 of August 2, 2010, which instituted PNRS. However, SINIR only started collecting data from 2019 onwards, through three modules: "states and municipalities", "waste transport manifest (WTM)" and "national solid waste inventory" (SINIR, 2023).

With regard to EEW, SINIR makes it possible to monitor the flow of these materials, from generation to the environmentally appropriate final destination, through reverse logistics. SINIR also provides data on collection points, sorting, recycling, treatment and final disposal units for this waste as well as public consortia and sectoral agreements involved in this process. (SINIR+, 2023).

Among the managing entities registered with SINIR is Green Eletron, a non-profit reverse logistics manager for EE and batteries. It was created in 2016, and has more than 8.000 collection points across the country and recycled 4,600 tons of EEW and batteries in 2022 in Brazil (Green Eletron, 2023). Thus, Green Eletron aims to properly receive and store the collected waste and transport it from collection points to the environmentally appropriate consolidation or final disposal points, aiming at reuse, recycling, recovery or final disposal. (SINIR+, 2023).

With regard to public awareness and lack of infrastructure and adequate technology for EEW processing, these are still problems that continue to persist. To minimize inappropriate disposal and work on the importance of environmentally sound disposal, environmental education campaigns should be implemented to increase EE delivery rates and minimize incorrect disposal.

Regarding the lack of infrastructure and adequate technology for EEW processing, it is necessary to develop public-private partnerships to stimulate research that allows reusing electronic components.

3.2 Systematic literature mapping: what are the proposals to improve electronic waste reuse in Brazil

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For the most relevant proposals for EEW reuse in Brazil, 2 scientific articles were chosen that stood out for their contribution to the topic. The studies chosen for reading are listed in Chart 3.

Chart 3: Studies that selected the proposals for improving electronic waste reuse in Brazil

Year	Journal	Authors	Titles
2022	Environmental Technology & Innovation	Santos, Ogunseitan	E-waste management in Brazil: challenges and opportunities of a reverse logistics model
2022	Cleaner Waste Systems	Dias, Palomero, Cenci, Scarazzato, Bernardes	Electronic waste in Brazil: generation, collection, recycling and the covid pandemic

Source: prepared by the authors, 2023.

The most relevant proposals for EEW reuse in Brazil are:

- Implement a circular economy model that encourages the recovery of valuable EEW materials and reduces the environmental impact of disposing of these wastes (DIAS, *et al.*, 2022).
- Improve data collection and monitoring of EEW generation, collection and recycling to assess the effectiveness of existing regulations and identify gaps and opportunities (DIAS, *et al.*, 2022).
- Promote the formalization and professionalization of EEW collectors, especially small and medium-sized ones, to improve their working conditions and environmental performance (DIAS *et al.*, 2022; SANTOS *et al.*, 2022).
- Build local capacity to recover valuable EEW end materials such as gold, silver and rare earth elements rather than exporting them to other countries (DIAS, *et al.*, 2022).
- Raise awareness and educate consumers and producers about the benefits and challenges of reusing and recycling EEW (SANTOS *et al.*, 2022).

Circular economy is a strategic concept that seeks material and energy reduction, reuse, recovery and recycling. It aims to reduce the disposal of this waste and consequently the extraction of new raw materials, the objective and the reinsertion of these materials that would be discarded back to the production process, adding value again to the product (CIRCULAR, 2017; FERREIRA, 2022)

In Brazil, there are several companies that work with recycling EEW, but there are still many challenges and it needs a lot of investment and incentives. Some of the Brazilian companies that recycle EEW and stand out in this segment are:

"*Reciclo Inteligência Ambiental*", located in the city of São Paulo, SP, focuses on EE reverse logistics and has been in existence since 2004. It is a social enterprise that operates in EEW collection, sorting, dismantling and final destination, generating income for collectors' cooperatives and promoting social inclusion and environmental education (AMBIENTAL, 2023). E-waste that has been operating since 2010 and works with EEW recycling (E-LIXO, 2023).

There is also "*Recicladora Urbana* (ReUrbi), located in Jacareí, SP, which is a startup that has developed a technology to separate metals present in EEW through a sustainable chemical process, without generating emissions or waste. The company was founded in 2012,

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and specializes in logistics and reverse manufacturing in IT and telecommunications EE disposals, committed to circular economy (ReUrbi, 2023).

Some initiatives that have been carried out and aim to improve EEW reuse in Brazil are:

The "*ReciclaTech*" Program, which was created in 2018 by the Brazilian Association of the Electrical and Electronics Industry (Abinee - *Associação Brasileira da Indústria Elétrica e Eletrônica*), which aims to implement an EEW reverse logistics system throughout the country, involving manufacturers, importers, distributors, traders and consumers (ABINEE, 2023).

"*Projeto E-lixo Maps*", developed by the *Universidade Federal de Santa Catarina* (UFSC), was launched in 2010, which consists of an application that maps EEW collection points in several Brazilian cities, informing the type of material accepted and opening hours (EGOV UFSC, 2023).

3.3 Systematic literature mapping: which line of electronic waste according to the classification according to the Brazilian Agency for Industrial Development is most generated in Brazil

Regarding EE lines, 3 scientific articles were chosen that stood out for their contribution to the topic and a report by Green Eletron. The studies chosen for reading are listed in Chart 4.

Chart 4: Studies that selected the electrical and electronic equipment lines that are most generated and recycled in Brazil

Year	Journal	Authors	Titles
2017	Environmental Science and Pollution Research	Azevedo, Araújo, Lararinhos, Tenório, Espinosa	E-waste management and sustainability: a case study in Brazil
2017	*Revista Brasileira de Geografia Física*	Vieira, Cappellesso, Guarnieri, Alfinito, Camara and Silva	*Diferença dos hábitos dos consumidores por tipo de resíduos eletroeletrônicos e o conhecimento da política nacional de resíduos sólidos (PNRS)*
2021	Green Eletron	Green Eletron	*Resíduos eletrônicos no Brasil - 2021*
2022	Sustainability	Guarnieri, Vieira, Cappellesso, Alfinito, Silva	Analysis of habits of consumers related to e-waste considering the knowledge of Brazilian national policy of solid waste: a comparison among white, green, brown and blue lines

Source: prepared by the authors, 2023.

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During the systematic literature mapping, it was possible to verify that the most generated EEW line in Brazil is the green line, followed by the brown line (VIEIRA *et al.*, 2017; GUARNIERI *et al.*, 2022).

According to the 2021 Electronic Waste in Brazil report, which carried out a survey of Brazilian consumers of EE and found that the most consumed products were cell phones, notebooks and tablets, which are small equipment, which belong to the green line. The 2022 study by Guarnieri *et al.* also found that the most discarded products were cell phones, notebooks and tablets (green line).

The most recycled EEW line in Brazil includes desktops, cell phones, laptops, which belong to the green line (AZEVEDO *et al.*, 2017).

Some initiatives that have been carried out in companies that currently sell the most cell phones, notebooks and tablets in Brazil and aim to improve EEW recycling from the green line in Brazil are:

Samsung has the “Samsung Recycle” program that has existed since 2017, which offers free and environmentally friendly disposal for EE products of any brand, in partnership with Green Eletron. The population can dispose of their small products, such as cell phones and tablets, in one of the collection bins located at authorized technical assistance centers or at Samsung stores. People can also participate in the “Smart Switch” program, which allows them to exchange their used smartphone, tablet or smartwatch for discounts on the purchase of a new product. The program forwards the collected cell phones and notebooks to qualified service providers licensed by the main environmental agencies, who carry out the sorting, disassembly, separation and recycling of electronic components. Recycled materials are sent back to the production chain. According to the company’s website, the program has collected more than 1,500 tons of EEW in Brazil since 2017, with 70% of this volume collected in 2022 (SAMSUNG, 2023).

Apple has initiatives for at least six years of recycling cell phones, notebooks, tablets and other branded products. People can recycle any Apple device at one of the two Apple stores in São Paulo or Rio de Janeiro, or send their device to Apple’s partner company in Brazil, *Solví Essencis Soluções Ambientais*, which carries out recycling free of charge and responsibly. People can also exchange their used Apple device for a discount on the purchase of a new Apple product. (APPLE, 2023).

4. FINAL CONSIDERATIONS

This systematic literature review revealed that Brazil faces several challenges to properly manage electronic waste, which is a potential source of environmental pollution and recovery of valuable materials. Among the main obstacles, the lack of awareness among the population about the importance of correct disposal of EEW, lack of adequate infrastructure for collecting and treating waste, lack of supervision and difficulty in implementing an efficient reverse logistics system stand out. These factors compromise the development of a circular economy, which aims to reduce the consumption of natural resources and increase reuse and recycling of EEW.

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Given this scenario, some proposals were presented to improve EEW management in Brazil, such as improve data collection on waste generation and disposal, encourage training agents involved in the EEW production chain, especially informal collectors, develop local capacity to recover strategic materials present in EEW, such as precious metals, and promote knowledge among the population in general overview of the environmental, social and economic benefits of disposing and recycling EEW.

The review also showed that the types of EEW most produced in Brazil are the green (computer and telecommunications equipment) and the brown ones (audio and video equipment), with the green ones presenting a higher recycling rate than the brown ones. However, there is still a large amount of EEW that is not recycled or that is recycled improperly, posing risks to human health and the environment.

Therefore, it is concluded that Brazil needs to advance in EEW management, seeking integrated and sustainable solutions that involve all actors in society. For future work, it is recommended to address EEW's potential as a source of strategic raw materials and their economic and environmental importance. Furthermore, it is suggested to carry out comparative studies with other countries that have successful experiences in EEW management, in order to identify best practices and lessons learned.

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