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ENVIRONMENTAL IMPACTS OF HEAVY METALS IN ELECTRONIC WASTE: ECOSYSTEM RISKS AND THE IMPORTANCE OF REVERSE LOGISTICS

IMPACTOS AMBIENTAIS DOS METAIS PESADOS PRESENTES NO LIXO ELETRÔNICO: RISCOS AO ECOSSISTEMA E A IMPORTÂNCIA DA LOGÍSTICA REVERSA

IMPACTOS AMBIENTALES DE LOS METALES PESADOS EN LOS RESIDUOS ELECTRÓNICOS: RIESGOS PARA EL ECOSISTEMA Y LA IMPORTANCIA DE LA LOGÍSTICA INVERSA

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ABSTRACT

The accelerated growth in the consumption of electrical and electronic equipment has intensified the generation of electronic waste, commonly known as e-waste. When improperly disposed of, these residues represent a significant threat to the environment due to the presence of heavy metals such as lead, mercury, cadmium, arsenic, nickel, and chromium. Such elements can contaminate soil, water resources, and living organisms, compromising ecosystem balance. This article aims to analyze the environmental impacts caused by heavy metals in electronic waste, highlighting ecological risks, bioaccumulation, biomagnification, and the importance of reverse logistics as an environmental mitigation tool. The adopted methodology consists of a literature review based on recent publications, technical reports, environmental legislation, and scientific studies on electrical and electronic waste. The results indicate that inadequate e-waste management amplifies the risks of environmental contamination and reinforces the need for educational actions, public policies, formal recycling, and the implementation of efficient reverse logistics systems. It is concluded that the correct disposal of electronic waste is essential for ecosystem protection and the construction of a sustainable environmental culture.

KEYWORDS: *Electronic Waste. Heavy Metals. Environmental Impact. Reverse Logistics. Ecosystem. Sustainability.*

RESUMO

O crescimento acelerado do consumo de equipamentos eletroeletrônicos tem intensificado a geração de resíduos eletrônicos, conhecidos como lixo eletrônico ou *e-waste*. Esses resíduos, quando descartados de forma inadequada, representam uma ameaça significativa ao meio ambiente devido à presença de metais pesados como chumbo, mercúrio, cádmio, arsênio, níquel e cromo. Tais elementos podem contaminar o solo, os recursos hídricos, os organismos vivos e comprometer o equilíbrio dos ecossistemas. Este artigo tem como objetivo analisar os impactos ambientais causados pelos metais pesados presentes no lixo eletrônico, destacando os riscos ecológicos, a bioacumulação, a biomagnificação e a importância da logística reversa como instrumento de mitigação ambiental. A metodologia adotada consiste em revisão bibliográfica, baseada em publicações recentes, relatórios técnicos, legislações ambientais e estudos científicos sobre resíduos eletroeletrônicos.

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Os resultados indicam que a gestão inadequada do lixo eletrônico amplia os riscos de contaminação ambiental e reforça a necessidade de ações educativas, políticas públicas, reciclagem formal e implantação de sistemas eficientes de logística reversa. Conclui-se que a destinação correta dos resíduos eletrônicos é essencial para a proteção dos ecossistemas e para a construção de uma cultura ambiental sustentável.

PALAVRAS-CHAVE: Lixo Eletrônico. Metais Pesados. Impacto Ambiental. Logística Reversa. Ecossistema. Sustentabilidade.

RESUMEN

El crecimiento acelerado del consumo de equipos eléctricos y electrónicos ha intensificado la generación de residuos electrónicos, conocidos como basura electrónica o e-waste. Estos residuos, cuando se desechan de forma inadecuada, representan una amenaza significativa para el medio ambiente debido a la presencia de metales pesados como plomo, mercurio, cadmio, arsénico, níquel y cromo. Tales elementos pueden contaminar el suelo, los recursos hídricos y los organismos vivos, comprometiendo el equilibrio de los ecosistemas. Este artículo tiene como objetivo analizar los impactos ambientales causados por los metales pesados presentes en la basura electrónica, destacando los riesgos ecológicos, la bioacumulación, la biomagnificación y la importancia de la logística inversa como instrumento de mitigación ambiental. La metodología adoptada consiste en una revisión bibliográfica basada en publicaciones recientes, informes técnicos, legislaciones ambientales y estudios científicos sobre residuos eléctricos y electrónicos. Los resultados indican que la gestión inadecuada de la basura electrónica amplía los riesgos de contaminación ambiental y refuerza la necesidad de acciones educativas, políticas públicas, reciclaje formal e implantación de sistemas eficientes de logística inversa. Se concluye que el destino correcto de los residuos electrónicos es esencial para la protección de los ecosistemas y para la construcción de una cultura ambiental sostenible.

PALABRAS CLAVE*: Basura Electrónica. Metales Pesados. Impacto Ambiental. Logística Inversa. Ecosistema. Sostenibilidad.*

1. INTRODUCTION

Technological advancement and the increase in electronic equipment consumption have significantly modified the production, consumption, and disposal patterns of contemporary society. Cell phones, computers, televisions, batteries, chargers, printers, and various electronic devices now have increasingly shorter life cycles, either due to technological obsolescence or frequent replacement by more modern models.

According to the Global E-waste Monitor 2024, the world generated approximately 62 million tonnes of electronic waste in 2022, with a forecast to reach 82 million tonnes by 2030 (BALDÉ et al., 2024). This scenario highlights a global concern, as only a portion of this waste is collected and recycled in an environmentally sound manner.

Electronic waste has a complex composition, containing materials of high economic value, such as gold, copper, aluminum, and rare earths, but also hazardous substances, especially heavy metals. When disposed of in dumpsites, inadequate landfills, or handled

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informally, these residues can release contaminants capable of reaching the soil, water, air, and living organisms.

According to the World Health Organization, electronic waste can become a threat to health and the environment when not disposed of or recycled correctly (WHO, 2024). This statement reinforces the urgency of educational actions, selective collection policies, formal recycling, and reverse logistics.

1.1. General Objective

To analyze the environmental impacts caused by heavy metals present in electronic waste, with an emphasis on the risks to the ecosystem and the importance of reverse logistics as a mitigation strategy.

1.2. Specific Objectives

I) Identify the main heavy metals present in electronic waste;

II) Describe the impacts of these contaminants on soil, water, and living organisms;

III) Explain the processes of bioaccumulation and biomagnification;

IV) Discuss the importance of reverse logistics in the management of electrical and electronic waste;

V) Relate the problem to the role of environmental education and university extension projects.

1.3. Justification

The relevance of this study is associated with the growth of electronic waste generation and the environmental risks resulting from the improper disposal of these residues. The heavy metals present in electrical and electronic equipment can remain in the environment for long periods, affecting the quality of soil, water, and biodiversity.

Furthermore, university extension projects can act as instruments for environmental awareness, bringing the university and community closer through education, selective collection, and the correct disposal of electronic waste.

1.4. Methodology

The methodology used in this article is qualitative in nature, based on a bibliographic and documentary review. International reports, scientific publications, Brazilian legislation, institutional

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documents, and recent studies related to electronic waste, heavy metals, ecotoxicology, reverse logistics, and sustainability were consulted.

2. LITERATURE REVIEW

2.1. Concept of Electronic Waste

Electronic waste, also called Waste Electrical and Electronic Equipment (WEEE), corresponds to all electrical and electronic equipment discarded due to obsolescence, breakage, technological replacement, or loss of utility. Main examples include computers, cell phones, televisions, printers, batteries, chargers, cables, and small household appliances (BALDÉ *et al.*, 2024).

According to the Global E-waste Monitor 2024 report, electronic waste represents one of the fastest-growing solid waste streams in the world. In 2022, approximately 62 million tonnes of electronic waste were generated, with only 22.3% being formally collected and recycled in an environmentally sound manner (BALDÉ *et al.*, 2024).

The World Health Organization (WHO) highlights that electronic waste contains valuable materials suitable for reuse, but also presents potentially toxic substances that can cause environmental impacts and risks to human health when disposed of improperly (WHO, 2024).

2.2. Heavy Metals Present in Electronic Waste

Electronic waste has a complex composition, containing plastics, glass, ferrous metals, non-ferrous metals, and various hazardous chemical substances. Among these substances, heavy metals stand out, known for their high environmental persistence and toxic potential (WHO, 2024).

According to the Global E-waste Monitor 2024, discarded electronic equipment contains large amounts of metals such as copper, aluminum, iron, nickel, lead, tin, and cobalt. The report estimates that in 2022 alone, global electronic waste contained about 70 million kilograms of lead and 34 million kilograms of cobalt embedded in discarded equipment (BALDÉ *et al.*, 2024).

Lead is widely used in electronic solders, printed circuit boards, and batteries. Mercury can be found in sensors, switches, lamps, and certain electronic components. Cadmium is frequently used in rechargeable batteries and semiconductors, while arsenic may be present in specific microelectronic components (WHO, 2024).

According to the WHO, lead is one of the substances most frequently released into the environment during inadequate storage, disposal, or informal recycling practices of electronic waste (WHO, 2024).

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2.3. Soil Contamination

The improper disposal of electronic waste in dumpsites, irregular landfills, or vacant lots favors the gradual release of heavy metals into the soil. This process occurs mainly due to the action of rain, humidity, and the physical degradation of electronic components (WHO, 2024).

The presence of heavy metals in the soil can compromise microbiological activity, reduce fertility, alter biogeochemical cycles, and directly affect plant growth. Furthermore, many of these elements exhibit high environmental persistence, remaining available in the environment for decades (WHO, 2024).

As highlighted by the European Commission's Joint Research Centre (JRC), the inadequate disposal of electronic waste significantly contributes to soil and water contamination, in addition to causing the loss of valuable mineral resources that could return to the production cycle through recycling (JRC, 2024).

2.4. Water Contamination

The leaching of heavy metals constitutes one of the main mechanisms of water contamination associated with electronic waste. During this process, toxic substances are transported by rainwater to rivers, lakes, reservoirs, and groundwater (WHO, 2024).

The World Health Organization emphasizes that inadequate recycling practices, such as open burning, acid baths, and informal dismantling of electronic equipment, favor the dispersion of contaminants into different environmental compartments, including surface and underground water bodies (WHO, 2024).

Among the most concerning contaminants are mercury, lead, and cadmium, which are capable of causing toxic effects in aquatic organisms and significantly altering the balance of aquatic ecosystems (WHO, 2024).

2.5. Bioaccumulation and Biomagnification

The heavy metals present in electronic waste have the capacity to accumulate in living organisms over time, a phenomenon known as bioaccumulation. This process occurs when the absorption of the substance is greater than its elimination by the organism (WHO, 2024).

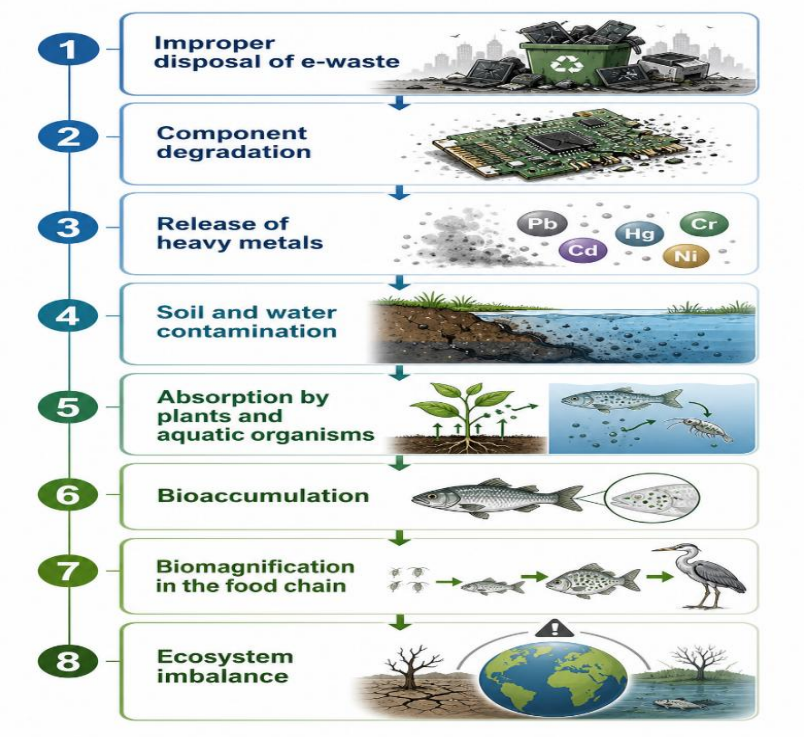
When contaminated organisms are consumed by other organisms at higher trophic levels, biomagnification occurs, characterized by the progressive increase in the concentration of the contaminant along the food chain. This phenomenon is especially relevant for elements such as mercury and lead, which exhibit high toxicity and environmental persistence (WHO, 2024).

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According to the WHO, contaminants from electronic waste can travel long distances after their release into the environment, expanding the reach of environmental impacts and increasing risks to biodiversity and human health (WHO, 2024).

Figure 1 schematically illustrates the process of environmental contamination resulting from the improper disposal of electronic waste. It is observed that the degradation of electrical and electronic components favors the release of heavy metals into the soil and water resources, allowing their absorption by plant and aquatic organisms. From this moment, the process of bioaccumulation begins in exposed organisms and, subsequently, biomagnification along the food chain. As a consequence, contaminants reach increasingly higher levels at different trophic levels, compromising the ecological balance, biodiversity, and environmental quality of terrestrial and aquatic ecosystems (WHO, 2024; PARVEZ *et al.*, 2021; BALDÉ *et al.*, 2024).

Figure 1. Environmental contamination flow from electronic waste



Source: Prepared by the author based on Decree No. 10,240/2020 and SINIR.

3. ANALYSIS OF THE ECOLOGICAL IMPACTS OF ELECTRONIC WASTE AND THE IMPORTANCE OF REVERSE LOGISTICS

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The literature analysis demonstrates that electronic waste constitutes one of the fastest-growing solid waste streams in the world. According to the *Global E-waste Monitor 2024*, approximately 62 million tonnes of electronic waste were generated in 2022, with a projected growth to 82 million tonnes by 2030 (BALDÉ *et al.*, 2024). This increase is directly related to technological advancement, reduced equipment lifespan, planned obsolescence, and the growth in electronic device consumption (VARGAS; CAMPOS; LUNA, 2024).

The results of the literature review indicate that the environmental impacts of electronic waste are intensified when improper disposal occurs in dumpsites, vacant lots, landfills without environmental control, or water bodies. Under these conditions, toxic components present in the equipment can undergo physical and chemical degradation, releasing heavy metals into the environment (WHO, 2024).

3.1. Impacts on the terrestrial ecosystem

In the terrestrial environment, heavy metals from electronic waste can alter the chemical and biological properties of the soil, directly affecting the microbiota responsible for organic matter decomposition and the maintenance of biogeochemical cycles (WHO, 2024).

Among the main contaminants are lead (Pb), cadmium (Cd), and chromium (Cr), which can reduce soil fertility, interfere with enzymatic processes, and compromise plant development (PARVEZ *et al.*, 2021). Furthermore, these elements exhibit high environmental persistence, remaining active for decades after their release into the environment (BALDÉ *et al.*, 2024).

Plants can absorb heavy metals through their roots, accumulating them in their plant tissues. This process facilitates the transfer of contaminants to herbivorous organisms and, subsequently, to higher levels of the food chain, expanding ecological risks (WHO, 2024).

3.2. Impacts on the aquatic ecosystem

In aquatic ecosystems, the environmental risks associated with electronic waste are even more significant due to the high mobility of contaminants. The leaching of heavy metals allows these substances to reach rivers, lakes, reservoirs, and groundwater (WHO, 2024).

Mercury (Hg), cadmium (Cd), and lead (Pb) are considered some of the most concerning contaminants for aquatic environments, potentially causing physiological changes, reduced reproduction, organism mortality, and loss of biodiversity (PARVEZ *et al.*, 2021).

Additionally, contaminated sediments can act as pollutant reservoirs, re-releasing heavy metals into the water column under certain physicochemical conditions, prolonging environmental effects for long periods (WHO, 2024).

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3.3. Ecological risks associated with heavy metals

Heavy metals possess characteristics that significantly expand their environmental risk potential: high toxicity, environmental persistence, and bioaccumulation capacity (PARVEZ *et al.*, 2021).

Unlike many organic wastes, these elements do not undergo short-term natural degradation, progressively accumulating in ecosystems. Consequently, small amounts continuously discarded can generate significant cumulative impacts over time (WHO, 2024).

Another important aspect is trophic biomagnification, the process by which the concentration of contaminants progressively increases at different levels of the food chain. This phenomenon can affect predatory organisms, birds, mammals, and even human populations that consume contaminated organisms (PARVEZ *et al.*, 2021).

In areas where informal recycling or improper disposal of electronic waste occurs, environmental risks tend to be amplified by the absence of technical control, environmental monitoring, and adequate waste treatment systems (VARGAS; CAMPOS; LUNA, 2024).

3.4. Reverse logistics as an environmental mitigation strategy

Reverse logistics is considered one of the primary strategies to minimize the environmental impacts associated with electronic waste. In Brazil, Decree No. 10,240/2020 regulates the implementation of the reverse logistics system for household electrical and electronic products, establishing shared responsibilities among manufacturers, importers, distributors, retailers, consumers, and public authorities (BRASIL, 2020).

According to Vargas, Campos, and Luna (2024), the formal Brazilian electronic waste recycling system represents an important tool for promoting the circular economy, reducing improper waste disposal, and increasing the recovery of valuable materials present in discarded equipment.

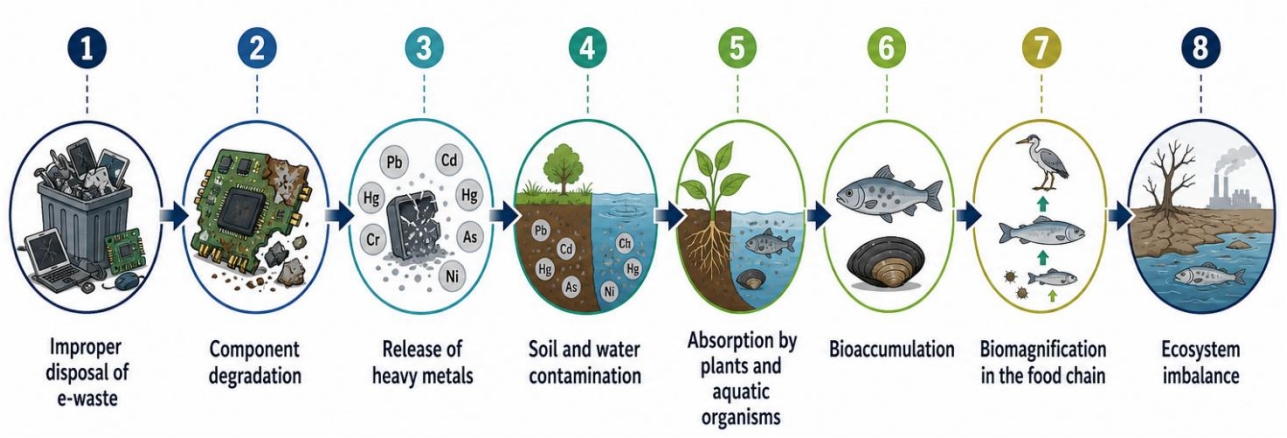
In this context, reverse logistics allows waste to return to the production cycle through collection, sorting, dismantling, recycling, and component reuse, reducing the need for the extraction of new natural resources (VARGAS; CAMPOS; LUNA, 2024).

Extension projects contribute directly to this process by promoting environmental education, community awareness, the implementation of collection points, and the forwarding of waste to specialized recycling companies. These actions strengthen socio-environmental responsibility and expand society's participation in the sustainable management of electronic waste (BRASIL, 2020; VARGAS; CAMPOS; LUNA, 2024).

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Figure 2 presents a simplified flow of reverse logistics applied to electronic waste, highlighting the main stages involved in the process of environmentally sound disposal of these residues.

Figure 2. Reverse logistics of electronic waste



Source: Prepared by the author based on Decree No. 10,240/2020 and SINIR.

As illustrated in Figure 2, the efficiency of reverse logistics depends on the integrated participation of consumers, companies, public institutions, and organizations responsible for recycling electronic waste. The existence of accessible collection points, associated with adequate sorting and reuse processes, allows for a significant reduction in the amount of equipment discarded in inappropriate locations. In addition to environmental benefits, this system favors the recovery of strategic raw materials, job creation in the recycling sector, and the strengthening of sustainability practices. In this context, environmental education initiatives and university extension projects play a fundamental role in raising public awareness and strengthening reverse logistics as an instrument for environmental protection and sustainable development (BRASIL, 2020; VARGAS; CAMPOS; LUNA, 2024).

4. RESULTS AND DISCUSSION

The analysis of scientific literature highlights that the accelerated growth of electronic waste generation has consolidated itself as one of the main environmental challenges of the 21st century. According to the *Global E-waste Monitor 2024*, global e-waste production reached approximately 62 million tonnes in 2022, with projections of continuous growth for the coming

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years, driven by the increased consumption of technological equipment, planned obsolescence, and the reduction in the lifespan of electronic devices (BALDÉ *et al.*, 2024).

The analyzed studies demonstrate that the improper disposal of these residues represents a major source of environmental contamination due to the presence of heavy metals such as lead, mercury, cadmium, arsenic, nickel, and chromium. These elements exhibit high persistence in the environment and can remain active for long periods, promoting chemical, physical, and biological changes in terrestrial and aquatic ecosystems (WHO, 2024).

Results found in the literature indicate that soil contamination occurs primarily through the degradation of electronic components exposed to environmental conditions, favoring the gradual release of toxic substances. This contamination can compromise soil fertility, reduce microbiological activity, and affect vegetation development, directly impacting natural ecological processes (PARVEZ *et al.*, 2021).

In aquatic environments, the impacts become even more concerning due to the dispersion capacity of the contaminants. The leaching of heavy metals allows these substances to reach rivers, lakes, and groundwater, affecting aquatic organisms at different trophic levels. Studies show that prolonged exposure to mercury, lead, and cadmium can cause physiological, reproductive, and behavioral changes in various species, contributing to the reduction of biodiversity and ecological imbalance (WHO, 2024; PARVEZ *et al.*, 2021).

Another relevant aspect observed in the literature refers to the phenomena of bioaccumulation and biomagnification. These processes favor the progressive increase in the concentration of contaminants along the food chain, expanding ecological risks and intensifying environmental impacts on organisms located at higher trophic levels. As a consequence, the effects of contamination extend beyond disposal sites and can affect entire ecosystems, compromising environmental quality and the maintenance of biodiversity (PARVEZ *et al.*, 2021).

In contrast, the analyzed studies highlight that the implementation of efficient reverse logistics systems and formal recycling constitutes one of the main strategies to minimize the environmental impacts associated with electronic waste. Material recovery, component reuse, and the environmentally sound disposal of waste contribute to the reduction of environmental contamination, in addition to promoting economic benefits related to the circular economy and the conservation of natural resources (VARGAS; CAMPOS; LUNA, 2024).

Thus, the results of the literature review reinforce the need for the expansion of public policies, the strengthening of reverse logistics systems, environmental inspection, and environmental education actions aimed at raising public awareness about the risks of improper e-waste disposal. Such measures are fundamental to reducing the environmental impacts caused

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by heavy metals and promoting a more sustainable management of electrical and electronic equipment at the end of its useful life.

4.1. Global growth of electronic waste generation

The growing production of electrical and electronic equipment has contributed to the significant increase in electronic waste generation on a global scale. According to *The Global E-waste Monitor 2024* report, the amount of electronic waste generated worldwide has shown continuous growth in recent decades, driven by technological advancement, increased consumption, and the reduction in the lifespan of electronic devices (BALDÉ et al., 2024).

Table 1 presents the evolution of global electronic waste generation between 2010 and 2022, as well as the projection for the year 2030.

Table 1. Evolution of global electronic waste generation

Year	Global e-waste generation (million tonnes)	Growth compared to the previous period (%)
2010	33.8	-
2014	44.4	31.4%
2019	53.6	20.7%
2022	62.0	15.7%
2030*	82.0	32.3%

Source: Adapted from BALDÉ *et al.* (2024).

The data presented in Table 1 demonstrate a continuous upward trend in global electronic waste generation. It is observed that global e-waste production nearly doubled between 2010 and 2022, increasing from 33.8 to 62 million tonnes. Projections indicate that this volume could reach approximately 82 million tonnes by 2030 if more effective measures for reduction, reuse, recycling, and reverse logistics are not implemented. This scenario reinforces the need for public policies, investments in waste management, and environmental awareness programs focused on the proper disposal of electrical and electronic equipment (BALDÉ *et al.*, 2024).

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4.2. Growth of electronic waste generation in Brazil

Brazil holds a prominent position among the largest generators of electronic waste in Latin America. The growth in access to technology, combined with the increased consumption of electrical and electronic equipment and rapid technological obsolescence, has contributed significantly to the rise in e-waste volumes generated annually in the country.

Based on the most recent data available from the *Global E-waste Monitor 2024* report (the international reference used in 2025) and updated information on electronic waste generation in Brazil for 2024/2025, Table 2 presents the main indicators related to e-waste generation and collection in Brazil.

Table 2. Indicators of electronic waste generation in Brazil (2025 Update)

Indicator	Value
Estimated population (2025)	212,583,750 inhabitants
Electrical and electronic equipment placed on the market	3.3 million tonnes
Electronic waste generated	3.2 million tonnes
Per capita electronic waste generation	15.1 kg/inhabitant
Electronic waste formally collected	102 thousand tonnes
Formal collection rate	3.2%
Equipment placed on the market per capita	15.5 kg/inhabitant

Source: Adapted from *Global E-waste Monitor 2024* (UNITAR/ITU), SINIR, and reverse logistics sector data in Brazil (2025).

The data presented in Table 2 demonstrate that Brazil remains among the largest generators of electrical and electronic waste in Latin America. In 2025, it is estimated that the country surpassed the mark of 3.2 million tonnes of electronic waste generated annually, representing approximately 15.1 kg per inhabitant. Despite the growth of reverse logistics programs and the expansion of collection points, the formal collection rate remains low, at around 3.2%, highlighting the need to strengthen public policies, increase public awareness, and ensure manufacturer participation in the sustainable management of these residues.

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4.3. Utilization of electronic waste in Brazil

The growing generation of electrical and electronic waste in Brazil highlights the need to strengthen collection, recycling, and reverse logistics systems. Despite the progress promoted by the National Solid Waste Policy – PNRS (BRASIL, 2010) and the actions of management entities such as ABREE and Green Eletron, a large portion of discarded equipment still does not receive environmentally sound disposal.

Table 3 presents an estimate of the current situation of electrical and electronic waste in Brazil in 2025, highlighting the rates of generation, formal collection, recycling, and material recovery potential.

Table 3. Estimated situation of electrical and electronic waste in Brazil (2025)

Indicator	Estimated Value
E-waste generated	3.2 million t/year
Formal collection (reverse logistics)	102 thousand t/year
Formal reverse logistics rate	3.2%
Effectively recycled/reused material	85 to 95 thousand t/year
Formal recycling rate	2.7% to 3.0%
Waste without proper disposal	97%
Material recovery potential	Up to 95% of components

Source: SINIR, ABREE, Green Eletron, and Global E-waste Monitor (2025).

The presented data demonstrate that Brazil faces significant challenges in electrical and electronic waste management. Although the country generates approximately 3.2 million tonnes of e-waste per year, only about 102,000 tonnes are collected through formal reverse logistics systems, corresponding to a rate of only 3.2%. This percentage reveals that the majority of waste still remains outside official management channels.

It is also observed that the formal recycling rate varies between 2.7% and 3.0%, indicating that only a small portion of discarded materials is effectively reused or reinserted into the production chain. Consequently, about 97% of electronic waste is still improperly disposed of,

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stored in households, or discarded in landfills and inappropriate locations, representing environmental and public health risks.

On the other hand, electrical and electronic waste possesses a high recovery potential, with up to 95% of its components being recoverable, including ferrous metals, aluminum, copper, plastic, glass, and precious metals. This scenario highlights the importance of expanding environmental education actions, implementing new collection points, and strengthening reverse logistics systems, aiming to increase recycling rates and promote the circular economy in the country. Thus, proper e-waste management can significantly contribute to the conservation of natural resources, the reduction of environmental impacts, and the generation of employment and income in the recycling sector.

4.4. Reverse Logistics Index

Brazil still presents a relatively low reverse logistics rate for electrical and electronic equipment. Considering the estimated generation of 3.2 million tonnes and the formal collection of approximately 102,000 tonnes, the national index stands at approximately: 3.2% of generated waste.

4.5. Refurbishment Index

Refurbishment is more difficult to measure because many devices are recovered by cooperatives, technical assistance, social projects, and private companies without a consolidated national registry. Sector studies indicate that between 5% and 15% of the collected material has potential for reuse or refurbishment. Thus, considering the 102,000 tonnes collected:

I) Estimated refurbishment: 5,000 to 15,000 tonnes/year;

II) Represents approximately 0.2% to 0.5% of the e-waste generated in the country.

4.6. Material Utilization Index

After dismantling and processing, the equipment can generate: steel; aluminum; copper; gold; silver; palladium; technical plastics; and glass.

Industrial recovery efficiency usually varies between 80% and 95% of the material received at specialized recycling plants. This means that, of the approximately 102,000 tonnes formally collected, about 85,000 to 95,000 tonnes return to the production chain as secondary raw materials.

Although Brazil is one of the largest generators of electrical and electronic waste in Latin America, reverse logistics rates remain low. It is estimated that only 3.2% of the e-waste

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generated annually is collected by formal reverse logistics systems. Among the collected equipment, part is destined for refurbishment to extend its useful life, and another portion is sent for recycling, allowing for the recovery of materials such as ferrous metals, non-ferrous metals, plastics, and electronic components.

Despite the progress promoted by management entities such as ABREE and Green Eletron, more than 95% of electrical and electronic waste still remains outside formal recovery systems, highlighting the need to expand collection infrastructure, increase public awareness, and strengthen public policies focused on the circular economy.

5. CONCLUSION

The present study analyzed the environmental impacts caused by heavy metals in electrical and electronic waste, demonstrating that the continuous growth of e-waste generation represents one of the main environmental challenges today. The presence of substances such as lead, mercury, cadmium, arsenic, nickel, and chromium makes these residues potentially hazardous when improperly disposed of, as such elements exhibit high environmental persistence, toxicity, and bioaccumulation capacity.

The literature review demonstrated that contamination resulting from the improper disposal of electrical and electronic equipment can significantly compromise the quality of soil, water resources, and terrestrial and aquatic ecosystems. Furthermore, the processes of bioaccumulation and biomagnification facilitate the transfer and increased concentration of these contaminants along the food chain, expanding ecological risks and impacts on biodiversity.

The analyzed data also evidenced the significant growth of e-waste generation on both global and national scales, contrasting with the low rates of formal collection and recycling observed currently. This scenario demonstrates the need to strengthen public policies focused on electrical and electronic waste management, as well as the expansion of reverse logistics systems provided for in Brazilian legislation.

In this context, reverse logistics stands out as an important strategy for reducing environmental impacts associated with electronic waste, promoting collection, reuse, recycling, and environmentally sound disposal. In addition to environmental benefits, this system contributes to the circular economy, the recovery of economically valuable materials, and the reduction of natural resource extraction.

Finally, it is concluded that mitigating the impacts caused by electrical and electronic waste depends on integrated action between the government, the productive sector, educational

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institutions, and civil society. Investments in environmental education, public awareness, expansion of collection infrastructure, and the strengthening of recycling programs are essential measures to promote more sustainable e-waste management and ensure the preservation of ecosystems for future generations.

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