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Waste Electrical and Electronic Equipment (WEEE): global and contemporary challenge to production chains and the urban environment

Resíduos de Equipamentos Elétricos e Eletrônicos (REEE): desafio global e contemporâneo às cadeias produtivas e ao ambiente urbano

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Abstract: In recent years, Waste Electrical and Electronic Equipment (WEEE) has grown three times faster than the world's population and 13% more than the world's Gross Domestic Product (GDP). Only 17.4% of this waste is properly treated and uncertain disposal poses risks to the environment and human health. The objective of this study is to present an alignment with regard to the generation, management and legislation of WEEE and its interface with eco-design, cleaner production and reverse logistics. The methodology uses a qualitative approach based on bibliographic and documentary research aligned with the Prisma protocol. The results indicate that industrialization and higher income levels of the population in increasing urbanization have led to an increase in the consumption of electrical and electronic equipment, which, together with the short life cycles of this equipment, recycling difficulties and physical and legal infrastructure, has generated an exponential increase in WEEE. In this scenario, the precepts of the circular economy emerge as a solution to this global problem.

Keywords: Waste Electrical and Electronic Equipment (WEEE); Cities; Circular economy; Sustainability.

Resumo: Nos últimos anos, os Resíduos de Equipamentos Elétricos e Eletrônicos (REEE) cresceram três vezes mais rápido que a população mundial e 13% mais que o Produto Interno Bruto (PIB) mundial. Somente 17,4% desses resíduos são tratados adequadamente e o despejo incerto impõe riscos ao meio-ambiente e à saúde humana. O objetivo desse estudo é apresentar um alinhamento sobre a geração, gestão e legislações aplicadas aos REEE e sua interface com o eco-design, produção mais limpa e logística reversa. A metodologia tem abordagem qualitativa baseada na pesquisa bibliográfica e documental alinhada ao protocolo Prisma. Os resultados apontam que a industrialização, maiores níveis de renda da população em crescente urbanização levam ao aumento do consumo de equipamentos eletroeletrônicos, que associados aos curtos ciclos de vida desses equipamentos, dificuldades de reciclagem e de infraestrutura física e legal geram o aumento exponencial das REEE. Nesse cenário, os preceitos da economia circular surgem como uma rota de solução a essa problemática mundial.

Palavras-chave: Resíduos de Equipamentos Elétricos e Eletrônicos (REEE); Cidades; Economia circular; Sustentabilidade.

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1 Introduction

The increase in the production of goods and consumption has led to the generation of waste becoming one of the major challenges of contemporary societies (Aguiar et al., 2021). The disposal of Waste Electrical and Electronic Equipment (WEEE) (e-waste) in 2019 set a new record of 53.6 metric tons, of which it is estimated that only 17.4% was disposed of adequately (United Nations, 2021). In other words, 82.6%, 44.3 Mt of WEEE was not disposed of properly, impacting the environment and human health (Caetano et al., 2019; Forti et al., 2020), due to the toxic substances contained in this waste. The International Telecommunication Union (ITU, 2021) warned that global WEEE is expected to reach 74 MT by 2030, becoming the fastest growing stream of household waste, almost doubling over a period of sixteen years. According to the ITU (2021) "[...] e-waste quantities are rising three times faster than the world's population and 13% faster than the world's GDP during the last five years." According to Forti et al. (2020), the continent that generated the most WEEE in 2019 was Asia, with 24.9 Mt. In that year, America generated 13.1 Mt, Europe 12 Mt, Africa 2.9 Mt and Oceania 0.7 Mt. An analysis of per capita generation shows Europe in front, with 16.2 kg per resident, followed by Oceania, with 16.1 kg, America, with 13.3 kg, Asia, with 5.6 kg and Africa, with 2.5 kg. Furthermore, WEEE recycling rates are not advancing in keeping with the increase in this waste. In 2019, Europe recycled around 42.5%, Asia 11.7%, America 9.4%, Oceania 8.8% and Africa 0.9%.

Industrialization and the higher income levels of a population in increasing urbanization have led to an increase in the consumption of Electrical and Electronic Equipment (EEE). This equipment, in turn, has increasingly shorter life cycles due to advances in technology, which, together with few repair options for these products, generate an increase in WEEE (Gollakota et al., 2020; Forti et al., 2020).

Conceptually, EEE or its end-of-life parts that have been discarded by owners, are considered WEEE or electronic waste (e-waste). This waste contains hazardous but valuable materials (Baldé et al., 2017; Xavier et al., 2017; Kumar et al., 2017; Ilankoon et al., 2018; Forti et al., 2020). EEE encompasses a wide variety of products and materials, ranging from household appliances to toys, computers, cell phones, equipment used in medicine, industrial automation, information and communication technologies, transport and energy generation (Baldé et al., 2017; Ilankoon et al., 2018; Forti et al., 2020).

The existing literature addresses issues related to WEEE, especially legislation. However, there is a lack of studies linking regulation to eco-design, cleaner production and reverse logistics in production systems based on the circular economy. Therefore, the aim of this study is to present a theoretical alignment regarding the generation and management of WEEE and its interface with eco-design, cleaner production and reverse logistics. From this perspective, the study contributes to the field by furthering the discussion on WEEE, exposing elements and approaches in order to understand and adopt more assertive policies and take bolder actions in the management of WEEE.

The methodology employs a qualitative approach and uses secondary data collected through bibliographic and documentary research of scientific productions in the Scopus and Web of Science databases and electronic platforms, preferably from the last five years. The keywords are waste electrical and electronic equipment, circular economy, cities and sustainability. In this research, the Prisma protocol checklist was used for the systematic review, which helped to formulate the title, abstract, introduction, methods, literature review, discussions and conclusions, being structured in four phases: identification, selection, eligibility and inclusion. The results of the content analysis of the reviewed articles are presented in Sections Two to Five, and are based on the analysis categories: concept and classifications, generation, management, legislation, eco-design, cleaner production and reverse logistics of WEEE, which serve as literature selection criteria. The discussion and conclusions are presented in Sections Six and Seven.

2 The relationship between GDP, Per Capita GDP, population and urbanization in the generation of WEEE

The United States, China and India are the largest generators of e-waste in the world, accounting for 38% of the WEEE produced in 2019, with approximately 20 Mt (United Nations, 2021). Brazil is among the world's largest producers of electronic equipment and it is estimated that only 3% of WEEE is disposed of properly (Baldé et al., 2017). The generation of WEEE is a growing concern for most countries and is mainly concentrated in regions with greater economic growth and urbanization. According to Kumar et al. (2017) and Kusch & Hills (2017), studies combining data on WEEE generation, GDP, Per Capita GDP and population growth from 50 countries showed that there is no significant correlation between population growth and WEEE generation. However, there is a linear relationship between GDP growth and the amount of WEEE generation in countries and the evolution of Per Capita GDP with the disposal of WEEE per inhabitant. Kumar et al. (2017) exemplified the results with data from China, the United States and India, to which we have added Brazil in Table 1.

Table 1. GDP, Per Capita GDP, population and WEEE generation (2019).

Country	WEEE (kt)	WEEE per capita (kg)	Population (millions)	GDP (millions of US$)	Per Capita GDP (US$)	% of urban and rural population
United States	6,918	21.0	328,239.52	21,433,226.00	65,297.5	82.46-17.54
China	10,129	7.2	1433.78	14,342,902.84	10,216.7	58.79-41.21
India	3,230	2.4	1 366.42	2,875,142.31	2,099.6	34.47-65.53
Brazil	2,143	10.2	211,049.53	1,839,758.04	8,717.2	86.83-13.17

Source: Prepared based on Forti et al. (2020), World Bank (2021).

Table 1 shows that the United States and China have the highest global GDPs and most of the WEEE is concentrated in these countries, given their thriving economic growth and large populations. A comparison of the data from China, the United States and India shows that the size of the population of India influences the amount of WEEE generated, but when disposal per inhabitant is compared, India has low WEEE generation, as its Per Capita GDP is significantly lower. According to Forti et al. (2020), urbanization influences the consumption of EEE and accelerates the generation of waste. A comparison of the three countries shows that India is more rural than urban, which influences the population's consumption habits. 65.53% of the population, that is, over 895 million people, live in rural areas. Brazil has the lowest GDP and population, but it has the highest percentage of urban population and higher Per Capita GDP than India, and these factors influence the generation of WEEE per capita, which is higher than China and India.

The increase in national and per capita income, industrialization and urbanization, added to the intense marketing of EEE, has significantly altered consumption habits. People seek to keep up with other members of their society by acquiring increasingly more new product models, seeking updates that are sometimes unnecessary in terms of the technical features of equipment. With planned obsolescence, product life cycles, especially electronic devices for personal use, are becoming shorter and there are few options to repair EEE, leading to disposal and the purchase of new models, increasing the amount of WEEE in all territories. Approximately 1 billion cell phones, tablets and notebooks are discarded within five years of use (Kumar et al., 2017; Ilankoon et al., 2018; Forti et al., 2020). The development of technologies to repair cell phones, for example, even if they do not result in large volumes, are invaluable to consumers who do not have sufficient income to buy new cell phones, providing access to digital information while preserving the environment (Schroeder et al., 2019).

3 WEEE management variables

The growing generation of WEEE, low collection and recycling rates and inappropriate disposal pose risks to the environment and human health (Caetano et al., 2019; Forti et al., 2020). WEEE contains potentially toxic materials such as the mercury used in 55-inch flat-screen TVs and fluorescent lamps, and the flame retardants added to the plastics that coat smaller EEE. Even if toxic materials are replaced in the production chain by safer materials, informal and illegal disposal poses risks to the environment (Forti et al., 2020). Around 50 t of mercury and 71 t of flame-retardant plastics were disposed of in informal waste streams in 2019. Furthermore, refrigerant gases exacerbate global warming. "[...] A total of 98 Mt of CO2-equivalents were released into the atmosphere from discarded fridges and air-conditioners that were not managed in an environmentally sound manner. This is approximately 0.3% of global energy-related emissions in 2019" (Forti et al., 2020, p. 15).

Policies that include appropriate strategies for WEEE management is a topic under discussion around the world and are intended to control the risks involved (Ilankoon et al., 2018). Forti et al. (2020) pointed out that low- and middle-income countries do not have the infrastructure for the proper management of WEEE and certain countries do not have any policy or actions to this end. In these cases, WEEE is usually handled by the informal sector and treated with no regulation and minimum care regarding protection, causing serious damage to the environment and the health of workers, as well as the children who help with the work or play in areas where electronic waste is managed.

WEEE management has aroused the interest of world leaders and the corporate environment, not only because of the inherent risks, but also as an alternative source of resources, given the growing scarcity of natural resources. The recycling of WEEE provides an opportunity for a market for secondary materials, which is in keeping with the paradigms of the circular economy in the sustainable management of resources in closed circuits, reducing the amount of electronic waste and the global demand for the exploitation of natural resources (Kumar et al., 2017; Ilankoon et al., 2018; Forti et al., 2020). WEEE can contain precious metals such as gold, silver and platinum, critical materials such as cobalt and palladium and non-critical metals such as iron and aluminum. It is estimated that in 2019, the value of materials found in WEEE amounted to US$ 57 billion, with gold, copper and iron accounting for most of this amount (Forti et al., 2020).

The concentration of rare and expensive metals in EEE that are critical for industry has fueled urban mining in WEEE. According to Cossu & Williams (2015, p. 1), urban mining extends from mining in landfills to "[...] the process of reclaiming components from any kind of anthropogenic stocks, including buildings, infrastructure, industries, and products [...]." Urban mining needs to consider the risk and return of material recycling and consider a broader scope of circular economy strategies.

Urban mining in WEEE aims to recover secondary raw materials from available urban stocks and enables the re-entry of WEEE into the production chain in the form of products, components, materials and substances. The magnitude of these processes and systems will depend on the decision makers, who will influence the extent of WEEE recovery (Ottoni et al., 2020). World electronics production in 2019 required approximately 39 Mt of iron, aluminum and copper. If these materials were fully recycled from WEEE, it would be possible to reuse around 25 Mt of them, reducing the demand for iron, aluminum and copper exploration by 64.10% (Forti et al., 2020).

WEEE management systems, from the local to the national and international level, require regulations that clearly define the responsibilities of every party involved. The attributions of these parties must form sectoral agreements, which are reflected in regional and local actions. EEE manufacturers, distributors, collectors, recyclers and representatives of society together with federal, state and municipal public administrations must set achievable and challenging goals, determine which processes, systems and structures will be used to stop the generation of WEEE and reuse the secondary materials of this waste in the production chain (Kumar et al., 2017; Forti et al., 2020).

An understanding and commitment between the parties involved and coherent legislation, minimize illegal and informal actions. WEEE management is hampered by illegal and informal acts that obscure the real dimension and quantity of WEEE flows. It is known that there are large flows of electronic waste exports from developed countries to developing countries from north to south. However, the Basel Convention, the European Union's WEEE export restriction targets, and the ban on waste imports imposed by China, have brought about major changes in the routes of these flows (Forti et al., 2020). These authors observed the formation of other routes being taken, with WEEE being shipped regionally as well as from north to south, seeking the treatment of waste in places where it is often neither technically nor economically feasible. There are regional routes between Western and Northern Europe to Eastern Europe, circuit board export routes from the Southern Hemisphere to the Northern Hemisphere, and movements from China to Southwest Asian and African countries. Forti et al. (2020) claimeed that there are still illegal cross-border movements from developed countries to the informal economy of developing countries. Developed countries generally have stricter legislation regarding WEEE, while developing countries have poor legislation and infrastructure in this respect, which facilitates illegal and informal trade (Forti et al., 2020).

Furthermore, developed countries export used equipment under the umbrella of EEE reuse by developing countries. However, a large majority of this equipment becomes waste when it reaches its destination, either due to transport conditions or the real intention of discarding the waste. The treatment of this waste or so-called commonly used equipment is handled by informal workers who are inadequately equipped, thus putting human health and the environment at risk. It is estimated that exports of used EEE or WEEE account for 7% to 20% of the total electronic waste generated on the planet (Forti et al., 2020).

4 Legislation of WEEE in developed and developing countries

National legislation on WEEE has advanced in recent years. Currently, 78 countries have some form of regulation on the issue (Baldé et al., 2017; Forti et al., 2020) and 189 countries have signed the Basel Convention on the control of transboundary movements of hazardous waste and its final disposal, which came into force in 1992 (Forti et al., 2020; Basel Convention, 2021). The general intention of waste legislation is to develop efficient, sustainable and safe e-waste collection, recycling and management systems (Kumar et al., 2017).

The Basel Convention is a multilateral international treaty that aims to regulate the transit of waste considered environmentally and socially hazardous, and this includes certain electronic waste (Baldé et al., 2017). The Basel Convention largely regulates the trade of hazardous waste, restricting illegal transit. However, the lack of consensus on a universal definition of what is classified as electronic waste and the exports and imports of used equipment destined for reuse continue to a large extent to conceal the transboundary transit of hazardous waste. The promotion of conferences between the parties involved has sought to establish a greater consensus among nations (Baldé et al., 2017; Forti et al., 2020).

Legislation on WEEE is important as it regulates the responsibilities and actions of the parties involved. However, its effectiveness depends on its enforcement. The development of national, regional and local e-waste policies should prioritize measures that are aligned with the circular economy. Thus, WEEE management ceases to focus only on collection and recycling and has begun to rethink product design, with more durable, sustainable and easily recycled components (Baldé et al., 2017; Forti et al., 2020).

Currently, the most advanced legislation on the management of WEEE is found in European countries that incorporate it into a circular economy strategy, followed by countries in North America, East Asia and South Asia. On the other hand, countries in much of Africa, Central Asia, the Caribbean and Polynesia lack national legislation on WEEE (Baldé et al., 2017). However, even in European Union countries, which have set a recycling target of 65% of EEE placed on the market, there are disparities in the outcomes of enforcing this legislation, ranging from 12% in Malta to 82% in Estonia (Forti et al., 2020).

Most national legislation is based on the principle of Extended Producer Responsibility (EPR), with manufacturers and importers responsible for the entire product life cycle, including end-of-life management (Baldé et al., 2017; Xavier et al., 2021), either individually or collectively. Another modality of waste management accountability is Shared Responsibility SR), with different levels of accountability attributed to all parties involved: producers, importers, distributors, traders, governments and consumers (Guimarães & Ribeiro, 2016; Xavier et al, 2021).

Japan was one of the first countries to legislate waste management and apply the Extended Producer Responsibility strategy to e-waste management, employing the circular economy principles of the 3Rs (reduce, reuse and recycle) and promoting policies and actions for a sustainable society (JICA, 2012; Forti et al, 2020). The country has managed to build a robust legal framework and an advanced and formal infrastructure for the collection and treatment of electronic waste (Forti et al., 2020).

The European Union began to take more comprehensive measures regarding the sustainable use of natural resources and waste management in 2000, instituting legislation on the use of resources, eco-design of products, cleaner production systems, reuse of secondary materials, and recycling of waste. The EU also took actions to raise society's awareness of responsible and sustainable consumption (Milios, 2018). The European directives on WEEE and plans to transition to the circular economy serve as a basis for drafting legislation on the subject in Member States and other countries (Zeng et al., 2017; Patil & Ramakrishna, 2020; Xavier et al., 2021; European Commission, 2021a).

In the United States, there is no national legislation for WEEE management. However, 25 states have laws that to some extent regulate the management of this waste, covering 75 to 80% of the country's population. Most states apply Extended Producer Liability, but each state decides on its own collection, recycling and disposal methods. At the national level, the federal government adopts regulatory policies, which determine the management of waste for certain categories of EEE (Forti et al., 2020).

China strengthened its legal framework for WEEE management in the 2000s. In 2008, the Circular Economy Promotion Law was instituted, which became the national strategy for sustainable development (Guo et al., 2017; McDowall et al., 2017; Cui & Zhang, 2018; Zhu et al., 2019; Fan & Fang, 2020). In 2011, China introduced the Management Regulation on WEEE Recycling (Zhou et al., 2017; Tong et al., 2018a) and in 2012 it adopted the Extended Producer Responsibility strategy and determined the use of secondary materials in new products (Zhou et al., 2017; Patil & Ramakrishna, 2020). At the same time, it formed a structure of funds from producers and the government to subsidize the implementation of formal and qualified recyclers in self-sufficient recycling networks at the provincial level (Zhou et al., 2017; Tong et al., 2018a; Zhao & Bai, 2021). As of 2017, China set a schedule for banning the import of e-waste (Patil & Ramakrishna, 2020). The Chinese government's target is for 20% of new EEE to be made of secondary materials and for 50% of WEEE to be recycled by 2025. Currently, the collection and recycling rate is around 15% (Forti et al., 2020).

In 2011, India instituted regulations for WEEE management and employed the Extended Producer Responsibility principle (Awasthi et al., 2018; Turaga et al., 2019; Forti et al., 2020; Arya & Kumar, 2020). The challenge the country faced was to formalize e-waste management, which was mostly undertaken by the informal sector. It is estimated that 90% of WEEE is processed by the informal sector (Turaga et al., 2019).

Brazil, a major producer of EEE and the fifth largest generator of WEEE, instituted the National Solid Waste Policy (PNRS) in 2010 through Law 12,305, legislating, among other things, on Shared Responsibility for EEE and a mandatory reverse logistics system for these products and their components (Brasil, 2010; Lopes dos Santos, 2020). The PNRS instituted shared responsibility for the life cycle of products, consisting of a set of actions coordinated by producers and traders, importers and distributors, consumers and those responsible for cleaning services and solid waste management to reduce the volume of generated waste and minimize the impacts on public health and the quality of the environment (Brasil, 2010). Article 25 of Law No. 12,305 (Brasil, 2010) emphasizes that "[...] the public authorities, the business sector and the community are responsible for the effectiveness of actions intended to ensure compliance with the National Solid Waste Policy."

In 2019, the Sector Agreement for the Implementation of the Reverse Logistics System for Household Appliances and their Components was signed by the federal government, producers, distributors and the National Electronic Equipment Waste Manager - Green Eletron (Brasil, 2019).

In 2020, inspired by the Sector Agreement, Decree 10,240 was issued, regulating the implementation of the reverse logistics system for electric and electronic domestic appliances and their components at the national level. The decree establishes the structuring, implementation and operation of reverse logistics systems for 215 EEE in the country, presenting the legally required goals and deadlines, in addition to defining the responsibilities of the players involved (Brasil, 2020). In Brazil, as in other developing countries, collection by the informal sector (e.g., people with no business license) has been recognized as important in the configuration of reverse logistics in different sectors in the country, including WEEE.

At the regional level, São Paulo State (São Paulo, 2020a) updated its State Solid Waste Plan in 2020 and maintains its commitment to reverse logistics for WEEE, which, among other measures, sets down the conditions for environmental licensing for EEE producers to implement reverse logistics systems. The city of São Paulo, which is a major generator of WEEE, at approximately 534,000 t per year (Rodrigues et al., 2020), of which around 3% is recycled (Pedro et al., 2021), established in 2020 through Law No. 17,471, in parallel with state legislation, compulsory reverse logistics for WEEE by producers, importers, distributors and traders in proportion to the products marketed in the municipality and with their own resources. At the same time, campaigns were begun to raise society's awareness (São Paulo, 2020b). The law set the goal of recovering 35% of e-waste by the end of 2024 based on the volume placed on the market in 2023. The Integrated Solid Waste Management Plan of the Municipality of São Paulo, in force since 2014 (São Paulo, 2014) included themes aligned with the PNRS, such as shared responsibility, social inclusion of recyclable collectors and reverse logistics of WEEE, with goals for the implementation of collection and recycling points.

Examples have shown that countries, states and municipalities have made advances over time in specific e-waste legislation in terms of prevention, reuse, remanufacturing and recycling with safe and healthy standards for people and the environment. WEEE management as an implementation strategy for the circular economy is associated with fundamental concepts for the sustainability of the production chain and product life cycle, such as eco-design, cleaner production and reverse logistics.

5 Eco-design, cleaner production and reverse logistics

The eco-design concept has been widely incorporated into sectors of the economy in which products have a short life cycle and their materials can cause damage to the environment and human health, as is the case of the EEE sector (Micheaux & Aggeri, 2021). Furthermore, the design of EEE is among the most complex, with up to 69 elements from the periodic table, using precious metals (gold, silver, copper, platinum, palladium, ruthenium, rhodium, iridium and osmium), critical materials (cobalt, palladium, indium, germanium, bismuth and antimony) and non-critical materials (aluminum and iron). Thus, the WEEE recycling market is continually challenged by the need for new safe and economically viable recycling techniques, either due to the widespread use of components or because products are not designed for dismantling, reuse and recycling (Forti et al., 2020).

The strategic application of eco-design goes beyond the primary goal of identifying, assessing and mitigating environmental impacts to incorporate circular economy principles. These include actions to: use recycled, secondary and more ecological materials; employ the lowest feasible number of components and plastics; improve the energy efficiency of materials and products; prolong the life of products; make it possible for products to be repaired; adapt products to be dismantled and recycled; remove hazardous and polluting materials from products; and design cleaner and more sustainable production, distribution and consumption processes (Gu et al., 2017; Kapuran, 2018; Forti et al., 2020; Micheaux & Aggeri, 2021; European Commission, 2021b; Ellen MacArthur Foundation, 2021). The European Union, for example, has adopted directives since 2005 that establish rules for the eco-design of energy-consuming products, among which are several EEE. The rules aim to improve the environmental performance of such equipment (European Commission, 2021a).

The benefits of applying the eco-design concept extend to reducing raw materials and energy consumption in product production, optimizing cost management, improving production technologies, using eco-design as a market differential and to comply with laws and obtain environmental certifications (Kapuran, 2018).

From this perspective, authors and organizations are considering the eco-design approach to products for circular design, in which product design is expanded to a holistic view of scenarios and shaped for circular systems, in which waste is reinserted into the supply chain instead of being discarded (Moreno et al., 2016; Den Hollander et al., 2017; Wastling et al., 2018; Ellen MacArthur Foundation, 2021).

Of equal importance to the aims of eco-design, the concept of cleaner production seeks to optimize production processes and reduce their cost by analyzing every process and product in the production chain. Preventive action in production aims to eliminate any form of waste (material, energy), reducing raw material consumption and waste generation, limiting the impacts of production on the environment and incorporating the principles of corporate social responsibility (Alves & Oliveira, 2007; Silva et al., 2015; Hens et al., 2018). The fundamental principle underlying cleaner production is to eliminate waste during the production process rather than at the end (Silva et al., 2015).

Hens et al. (2018) highlighted that cleaner production uses cleaner technologies, which extract and use natural resources as efficiently as possible throughout the production process and generate durable, repairable and recyclable products with the lowest possible environmental and social impact.

Cleaner production tackles waste on two fronts. On the first front, the aim is to reduce waste, either at the source or through internal recycling by altering the process or product, replacing materials and technologies. On the second front, the goal is reuse, either through remanufacturing or the external recycling of materials (Alves & Oliveira, 2007).

The benefits of cleaner production are measured in the sum of technological innovations, commercial advantages, cost reduction, new business opportunities, mitigation of environmental risks and burdens and reduction of pollutant emissions. This leads to more sustainable economic growth, a better environment and working conditions, motivating employees, creating internal innovation and improving the image of the product and the company in the market in which it operates (Alves & Oliveira, 2007).

Rajput & Singh (2020) and Shayganmehr et al. (2021) showed that today's increasingly globalized markets require companies to adopt flexible and reliable smart production processes, with high quality and low cost. The concept of Industry 4.0 provides the foundations for the digital transformation of the production chain using, for example, Big Data and the IoT. Smart systems based on exact data connected to networks lead to accurate and efficient cleaner and circular production processes. Shayganmehr et al. (2021) explained that Industry 4.0 approaches allow the integration of the concept of cleaner production with that of the circular economy in pursuit of sustainability. Industry 4.0 technologies enable faster and more assertive decision making by maximizing the efficiency of production processes, reducing the use of resources, optimizing processes, reducing waste and environmental impacts, aiding the reuse, remanufacturing and recycling of materials. The combination of Industry 4.0, cleaner production and the circular economy create ethical and sustainable business opportunities, with efficient production processes and improved environmental management.

However, the closed cycles of circular economy materials depend on reverse logistics for the reverse flow of end-of-life products to producers for the reuse of their materials or environmentally appropriate disposal (Silva et al., 2015; Ghisolfi et al., 2017; Islam & Huda, 2018; Tosarkani et al., 2020).

The reverse flow of materials encompasses the performance of several actors, such as collectors, transporters and recyclers in infrastructures of collection points, recycling, repair, remanufacturing and disposal centers. Their purpose is part of the main goal of waste management to reduce, reuse and recycle materials (Islam & Huda, 2018; Isernia et al., 2019; Tosarkani et al., 2020). However, circular and reverse logistics systems require solutions in closed-loop networks, the economic feasibility of collection and recycling points, formation of a secondary market, after-sales services, material recovery techniques, qualified labor and environmentally safe projects (Islam & Huda, 2018).

The exponential growth in the quantity of e-waste that might contain hazardous substances, as well as valuable ones, has prompted national and regional governments to enact policies of accountability for the management of this waste. Extended Producer Responsibility and Shared Responsibility are examples of policies that employ reverse logistics systems for EEE at the end of its life cycle, providing opportunities for the recycling and reuse of WEEE materials in the production chain, reducing the exploitation of natural resources (Islam & Huda, 2018; Isernia et al., 2019).

Isernia et al. (2019) observed that the objectives of reverse logistics systems are highly congruent with the goals and characteristics of circular economy systems. Both aim for sustainable socio-economic development and have economic aspects that include care for the environment and waste management with objectives of cycles of repair, reuse, recycling and proper disposal.

In this context, it can be seen that both developed countries such as EU nations and developing countries such as China, India and Brazil, began to implement national and regional regulations for reverse logistics systems with a focus on recycling materials, later advancing to legislation that focuses on product design, regulating the use of hazardous substances in new EEE placed on the market, moving on to more advanced stages of circular production systems.

6 Discussion

Effective WEEE management, which reduces generation, reuses and recycles waste helps to achieve the goals of Agenda 21 and the Sustainable Development Goals (SDGs) of Agenda 2030. The issue of electronic waste is related to several SDGs (11, 8, 6, and 3) and in particular SDG 12 (Responsible production and consumption), which highlights in goal 12.5 the reduction of waste generation, preventing, reducing, recycling and reusing materials. Meanwhile, target 12.4 emphasizes the proper management of waste, especially chemical and hazardous waste (United Nations, 2021). Agenda 21 aims to promote the social and sustainable development of countries. Sustainable development is also built on the quality of processes and outcomes, the result of society's learning. "The joint and collaborative learning among different stakeholders that, through interaction, increases their capability to perform joint tasks related to environmental problems and build social capital" (Xavier et al., 2019b, p. 7).

The application of the concepts of sustainability and the circular economy to WEEE management paves the way for the conservation of natural resources, the valuing and reuse of secondary materials and lower environmental and social impacts (Gu et al., 2017; Islam & Huda, 2018; Silva, 2019). However, it is necessary to monitor and improve the management of secondary materials, especially toxic and hazardous ones, prioritizing their replacement with more sustainable materials (Gu et al., 2017; Kumar et al., 2017). Gu et al. (2017) emphasized that it was necessary to aim to reduce the amount and extend the useful life of EEE. The authors stressed that investments in research are needed to reduce the use of toxic substances, and promote eco-design, the recycling of materials and more sustainable production processes.

Andersen (2022) showed that EEE supply, production and logistics chains, which remain underused, are becoming more digitized and can be used to advance the circularity of processes. Silva (2019, p. 164) concluded that migrating to the circular economy depends on "[...] a productive structure that interconnects production chains, and that a new model is created based on the change in consumption habits, production systems and institutional relationships."

Baldé et al. (2017) and Forti et al. (2020) argued that most legislation focuses on collection and recycling, while regulations to reduce electronic waste through the repair and reuse of equipment are limited to a few experiments. The authors warned that current regulations and legislation have not ended cross-border movements of toxic and hazardous electronic waste. Significant percentages of WEEE continue to be discarded in developing countries, either through exports of used equipment or illegal trade. Forti et al. (2020) reported that around 15% of used EEE from the European Union is exported outside the bloc.

Tong et al. (2018a) and Andersen (2022) argued in favor of harmonizing the parties and WEEE legislation. EEE is produced by major global manufacturers, while legislation is drafted at the national level. Extended Producer Responsibility, which uses waste management organizations, remains focused on recycling targets, freeing manufacturers from their primary responsibility to reduce, reuse and recycle materials. Baldé et al. (2017) and Forti et al. (2020) showed that accountability in developing countries faces further implementation problems due to the lack of infrastructure for e-waste collection and treatment and failure to comply with international standards. Spheres of government can support and facilitate the necessary investments in infrastructure for collection and recycling, promote market visions in line with the circular economy and encourage the use of local collectors and recyclers. Tong et al. (2018b) stressed that regulating producer responsibility triggers the formation of new market niches for recycling WEEE, creating opportunities for income generation, formalization of the informal sector and social inclusion.

Informal activities are observed in the WEEE value chain in most countries, especially developing countries. In India, it is estimated that 95% of recycled waste is collected by the informal sector (Arya & Kumar, 2020). In China, an estimated 18 million people are involved in informal waste activities (Steuer et al., 2018). In Brazil, the National Movement of Waste Pickers (MNCR, 2021), comprising 1829 waste picker organizations (cooperatives and associations), estimates that there are currently around 800,000 active pickers in Brazil. According to Arya & Kumar (2020) and Abalansa et al. (2021), this practice has been ongoing for generations, guaranteeing income for thousands of people and boosting the recycling market, which has led to its institutional recognition and the implementation of actions to integrate the informal sector (collection) with the formal sector (recycling) in several countries such as India and Brazil. "The biggest hurdle is to ensure the safe and sustainable recycling process [...]. The attempt can only be possible with the mutual integration or merging the informal sector into the formal unit and legalizing their role in the E-waste management" (Arya & Kumar, 2020, p. 16).

Forti et al. (2020) highlighted that the effectiveness of legislation and national WEEE management plans will also depend on the clear allocation of responsibilities to all parties involved in society. In WEEE management systems, responsibilities, structures and processes must be transparent, economically viable, socially inclusive and environmentally sound. Silva et al. (2019) proposed a multi-stakeholder waste management policy approach that includes informal organizations. Kumar et al. (2017) showed that partnerships and technical cooperation are required between governments, producers, importers and distributors, and national and international regulatory bodies need to work together to improve waste management systems and reduce the amount of WEEE.

Gollakota et al. (2020) emphasized the urgent need to adopt national and local WEEE management strategies. The authors listed ten core issues that compromise effective e-waste management and pointed out urgent interventions, especially in developing countries: (i) integration of the formal and informal sectors; (ii) registration of formalized networks; (iii) enforcement of strict laws; (iv) regulated cross-border movements; (v) producer responsibility; (vi) consumer awareness; (vii) improvement of eco-design projects; (viii) investments in recycling centers; (ix) improved disposal facilities and (x) replacing traditional techniques with sustainable technologies integrated into networked systems.

The main global and contemporary discussions on dimensions related Waste Electrical and Electronic Equipment (WEEE) are summarized in Table 2.

Table 2 shows that the conceptualization and categorization of WEEE remain latent issues of discussion and fundamental to understanding WEEE generation and management in the production process and in the urban environment that legislation should address, regulating the market and society with the purpose of directing them towards sustainable development. In this context, the elements of eco-design, cleaner production and reverse logistics need to be aligned in systems based on circular economy principles. It should be noted that the WEEE theme is related to environmental, social and economic, but also cultural and institutional issues that determine the reality of each country, exposing the complexity and great challenge of contemporary societies regarding WEEE in the environment of organizations and cities.

Table 2. Dimensional alignment of global discussions on WEEE.

Dimension	Global discussions	Authors/Organs
Concept and categories	EEE or its end-of-life parts that have been discarded by the owner are considered WEEE (e-waste).	Baldé et al. (2017), Forti et al. (2020), Ilankoon et al. (2018), Kumar et al. (2017), Xavier et al. (2017, 2019a)
	Classification of EEE and WEEE follow common production line and recycling characteristics.	
Global scenario of WEEE	Income levels, advances in technology and urbanization influence WEEE generation.	Baldé et al. (2017), Forti et al. (2020), United Nations (2021).
GDP, Per Capital GDP, population and urbanization	Higher individual income and urbanization further increase the generation of WEEE, which surpasses the country's GDP and population growth.	Kumar et al. (2017), Kusch & Hills (2017), Forti et al. (2020)
WEEE management	The global issue of WEEE management is related to the themes of Agenda 21 and SDGs, specifically the management of environmental and human health risks, economic feasibility, finite resources, the circular economy, informal sector, urban mining, secondary market, and illegal trade.	Cossu & Williams (2015), Kumar et al. (2017), Ilankoon et al. (2018), Steuer et al. (2018), Caetano et al. (2019), Silva et al. (2019), Silva (2019), Xavier et al. (2019b), Forti et al. (2020), Ottoni et al. (2020), Abalansa et al. (2021), MNCR (2021), United Nations (2021).
Legislation in developed and developing countries	Signing the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal of 1992, which includes certain electronic waste.	Andersen (2022), Arya & Kumar (2020), Awasthi et al. (2018), Baldé et al. (2017), Basel Convention (2021), Brasil (2010, 2020), Cui & Zhang (2018), European Commission (2021a), Fan & Fang (2020), Forti et al. (2020), Guimarães & Ribeiro (2016), Guo et al. (2017), JICA (2012), Kumar et al. (2017), McDowall et al. (2017), Milios (2018), Patil & Ramakrishna (2020), Tong et al. (2018a, b), Turaga et al. (2019), Xavier et al. (2021), Zhao & Bai (2021), Zhou et al. (2017), Zhu et al. (2019)
	Predominant management of Extended Producer Responsibility in both cases. Brazil embraces shared responsibility.	
	Developed countries: specific laws for WEEE management starting in the 2000s and advancing towards regulations aligned with the circular economy from the beginning of the production cycle. Collection and treatment are undertaken by formal sectors.	
	Developing countries: specific laws for the management of WEEE from the late 2000s. Emphasis on proper management of hazardous waste and recycling of materials. The collection and treatment of electronic waste are largely undertaken by informal sectors. Legislation advances from the treatment of WEEE to the circular economy.	

Table 2. Continued…

Dimension	Global discussions	Authors/Organs
Eco-design	Eco-design: projects that include replacing raw materials with more sustainable materials, reducing product and packaging volume, extending the shelf life of products, designing for reuse, remanufacturing and recycling.	Moreno et al. (2016), Den Hollander et al. (2017), Gu et al. (2017), Kapuran (2018), Wastling et al. (2018), Forti et al. (2020), Micheaux & Aggeri (2021), European Commission (2021b), Ellen MacArthur Foundation (2021).
Cleaner production	Cleaner Production: optimizing production processes and reducing the costs involved. Use of advanced technologies to produce more efficient and sustainable EEE and promote the reuse of WEEE.	Alves & Oliveira (2007), Silva et al. (2015), Hens et al. (2018), Rajput & Singh (2020), Shayganmehr et al. (2021).
Reverse logistics	Use of advanced technologies to produce more efficient and sustainable EEE and to promote the reuse of WEEE.	Silva et al. (2015), Ghisolfi et al. (2017), Islam & Huda (2018), Tong et al. (2018a), Isernia et al. (2019), Lopes dos Santos (2020), Forti et al. (2020), Tosarkani et al. (2020),
	Reverse Logistics: reverse flow of WEEE to producers for the reuse of their materials or environmentally safe disposal.	

Source: Prepared by the authors (2021).

7 Conclusions

The increase in population, urbanization and individual income levels, together with technological advances and planned obsolescence, which lead to shorter EEE life cycles, make the generation and amount of WEEE a challenge for production chains and the urban environment. WEEE management is not limited to its proper disposal in reverse logistics networks, but requires a rethink on the design of equipment within the concept of eco-design, cleaner and more sustainable production processes and the reuse of secondary materials from WEEE in systems based on the circular economy. Countries need to act downstream at the international, national and local levels to manage urban mining and secondary market operations, curbing illegal trade, implementing effective recycling and disposal systems to reduce environmental and social impacts and pressure on finite natural resources.

Countries, especially developing ones, need to advance their WEEE management legislation and strictly enforce these laws. National, state and municipal governments in international cooperation must agree on demands that the world's EEE producers improve eco-design projects and sustainable production processes in line with the circular economy. In addition, there is a need for greater unity between national and local legislation and international treaties, as well as the responsibilities of producers and waste management organizations.

In developing countries, there is an urgent need to integrate the formal and informal sectors, as the latter is responsible for much of the collection and treatment of WEEE in these countries. National, regional and local governments, in partnerships with private organizations, can take action in this sector, enabling the necessary recycling infrastructures, raising consumer awareness, qualifying and formalizing labor as a means of generating income, social inclusion and environmental protection.

In this respect, cities, which generate a considerable amount of WEEE, and are where the parties involved in waste management converge, can take positive actions to address the challenges imposed by e-waste generation, reflecting significantly the results of national waste management plans.

The aim of this study was to further the discussion on WEEE generation and management, showing its interface with eco-design, cleaner production and reverse logistics, and relating the issue to urban variables. As the study provided a theoretical alignment of scientific productions, it can serve as a basis for future empirical research on WEEE.

Author’s contribuition

Nádia Mara Franz e Christian Luiz da Silva.worked on the conceptualization and theoretical-methodological approach. The theoretical review was conducted by Nádia Mara Franz e Christian Luiz da Silva. Data collection was coordinated by Nádia Mara Franz e Christian Luiz da Silva. Data analysis included Nádia Mara Franz e Christian Luiz da Silva. All authors worked together in the writing and final revision of the manuscript.

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