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The role of BRICS metropolises in the management of Waste Electrical and Electronic Equipment

O protagonismo de metrópoles do BRICS na gestão de Resíduos de Equipamentos Elétricos e Eletrônicos

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ABSTRACT

Urban population forecasts project a rise of over two billion inhabitants in cities in three decades, accounting for over two-thirds of consumption and half of waste generation on the planet with Waste Electrical and Electronic Equipment (WEEE) being the flow with the highest growth rate. It is estimated that by 2030, WEEE volumes will reach 74 Mt. The BRICS (Brazil, Russia, India, China, and South Africa) countries will be responsible for a significant share of this consumption and waste in globally prominent metropolises. The aim of this study is to describe WEEE management policies in BRICS metropolises, identifying the actors involved, in order to support the structuring of policies and actions for the sustainable management of this waste. The methodology employs a qualitative approach through case studies: São Paulo, Moscow, Delhi, Beijing, and Johannesburg. The results demonstrate the relevant role that these metropolises play in the sustainable and inclusive management of WEEE, articulating in synergy with the actors to implement policies and related circular actions, aligned with national legislation and appropriate for their territories.

Keywords: role of metropolises; management of waste electrical and electronic equipment; policies and actions; actors; BRICS.

RESUMO

O aumento populacional urbano projeta um incremento de mais de dois bilhões de habitantes nas cidades em três décadas, abarcando mais de dois terços do consumo e metade da geração de resíduos do planeta, sendo os Resíduos de Equipamentos Elétricos e Eletrônicos (REEE) o fluxo de maior crescimento. Calcula-se que em 2030 os volumes de REEE alcancem 24 Mt. Os países BRICS (Brasil, Rússia, Índia, China e África do Sul) serão responsáveis por uma parcela significativa desse consumo e desperdício em metrópoles de destaque global. O objetivo desta pesquisa é descrever políticas de gestão dos REEE em metrópoles BRICS, identificando seus atores, a fim de subsidiar a estruturação de políticas e ações para a gestão sustentável desses resíduos. A metodologia emprega a abordagem qualitativa nos estudos de casos: São Paulo, Moscou, Delhi, Pequim e Joanesburgo. Os resultados indicam a relevância do protagonismo das metrópoles na gestão sustentável e inclusiva dos REEE, articulando-se em sinergia com os atores na implantação de políticas e ações circulares relacionadas, alinhadas às legislações nacionais e adequadas a sua territorialidade.

Palavras-chave: protagonismo das metrópoles; gestão de resíduos de equipamentos elétricos e eletrônicos; políticas e ações; atores; BRICS.

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Introduction

The rising population and growth in urban migration have led to global challenges regarding access to healthcare, education, and basic sanitation, as well as the sustainable management of waste based on the circular economy principle of reduce, reuse, and recycle.

According to the World Cities Report 2022, the global urban population will rise from 56.0% in 2021 to 68.0% in 2050. Even with the brief slowdown during the Covid-19 pandemic, an increase of 2.2 billion people in urban centers is estimated (UN-Habitat, 2022). Currently, cities consume, on average, around 70.0% of the planet's natural resources and 60.0% of global energy, generate around 50.0% of the world's waste, and emit 75.0% of greenhouse gases. It is estimated that metropolises will be responsible for 91.0% of consumption growth and 81.0% of total consumption between 2015 and 2030. In this context, around 50.0% of cities with over 100 thousand inhabitants already suffer from a scarcity of water, inputs, food, and energy, which exacerbates urban challenges, while dealing with increasingly frequent natural disasters as an effect of climate change (Petit-Boix and Leipold, 2018; Williams, 2019).

In this scenario, the rise in average income has boosted the purchasing power of the population, which, combined with successful marketing by producers and retailers of Electrical and Electronic Equipment (EEE), has increased the consumption of new EEE. Furthermore, advances in technology and planned obsolescence have led to higher volumes of Waste Electrical and Electronic Equipment (WEEE), especially in metropolises, which have large populations (Bizerra et al., 2023).

In 2019, global data indicated the generation of 53.6 Mt of WEEE, of which only 17.4% was disposed of properly. It is estimated that by 2030, WEEE volumes will reach 74 Mt, making it the current fastest-growing waste stream. Improper disposal of WEEE poses risks to human health and impacts the environment, as this waste may contain toxic substances (Forti et al., 2020; Gollakota et al., 2020; United Nations, 2020; International Telecommunication Union, 2021; Cheshmeh et al., 2023). On the other hand, WEEE is an excellent source of resources for urban mining, providing opportunities for income generation and the transition to the circular economy, mitigating environmental impacts (Xavier and Ottoni, 2019).

At this juncture, China, India, and the United States generate around 38.0% of the world's WEEE disposal. Brazil, a major producer of electronics, ranks fifth globally in WEEE generation (Baldé et al., 2017; Forti et al., 2020). Brazil, China, and India, together with Russia and South Africa, make up the BRICS diplomatic group formed in 2009. According to World Bank Data (2022), these emerging countries are home to 41.2% of the world's population and 30.0% of the global territory, and responsible for 25.7% of the world's Gross Domestic Product (GDP) in 2021. However, following the global trend, the generation of WEEE in these countries is high and has grown exponentially. In 2019, China generated 10,129 kt, India 3,230 kt, Brazil 2,143 kt, Russia 1,631 kt, and South Africa 416 kt (Forti et al., 2020).

The exponential increase in WEEE generation and the scarcity of resources put pressure on actors involved in the WEEE value chain to take actions that reduce damage to the environment and public health, and enable the reintroduction of secondary materials into production chains. Consequently, metropolises, as major generators of WEEE, have begun to occupy a prominent place in circular policies and actions for their management. Therefore, this study aimed to describe local WEEE management policies and actions in BRICS metropolises, identifying the different actors in the processes inherent to WEEE, to support the development of policies and actions for the sustainable management of this waste.

To this end, the methodology follows a qualitative approach in multiple case studies, in which the metropolises of São Paulo, Moscow, Delhi, Beijing, and Johannesburg were selected — cities of considerable economic, social, and political importance in the BRICS and on the global stage.

The results indicated that all the BRICS countries have laws on WEEE management, either specifically or included in broader waste regulations. However, WEEE extended producer responsibility schemes, which allow their recycling, are also being structured in these markets, seeking to incorporate the various actors involved in the market, government, and society in the WEEE value chain. Furthermore, the importance of the leading role of metropolises in implementing policies and actions for the inclusive and sustainable management of WEEE, in compliance with national legislation, is evident.

Methodology

The methodology followed a qualitative approach, of an applied nature, employing the multiple case study method with cross-synthesis proposed by Yin (2015). This research adopted the steps recommended by Ruthes and Silva (2015) for bibliometric analysis, which are based on the Knowledge Development Process – Constructivist (ProKnow-C) of Lacerda et al. (2012), and the multicriteria prioritization method. The systematic research review adhered to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) protocol (Galvão et al., 2015), which undergoes four phases: identification, selection, eligibility, and inclusion, supporting the structuring of the title, summary, introduction, methods, literature review, discussions, and conclusions. In addition, the premises of Bardin's content analysis (2008) were adopted to analyze the collected data.

The technique used secondary data from bibliographic research on scientific production from the Scopus and Web of Science databases, as well as research of documents available on government websites and non-governmental institutions portals, conducted between 2015 and 2022, in 263 reference sources. In order to segment and analyze the roles of the different actors in the processes inherent to the management of WEEE, they were clustered into three segments: i. govern-

ment; ii. market; and iii. society, in accordance with the classification of Monteiro (2019) and Vieira et al. (2020).

The keywords used were "role of metropolises", "management of waste electrical and electronic equipment", "policies and actions", "actors" and "BRICS". The selection of metropolises followed the precepts of an intentional sample, in which the criteria of a metropolis in each BRICS country were chosen, with significant economic, social, and political prominence in the BRICS and on the global stage.

The enormity and challenges of the metropolises of São Paulo, Moscow, Delhi, Beijing, and Johannesburg

The globalized metropolises of São Paulo, Moscow, Delhi, Beijing, and Johannesburg are of great economic, social, and political importance in the BRICS countries. Excep for São Paulo and Johannesburg, those cities are also the administrative capitals of their countries.

São Paulo is located in the southeast region of Brazil and is home to the largest metropolitan region in the country. The city is administratively divided into 32 sub-prefectures in a territorial area of 1,521.11 km^2, and, according to the Brazilian Institute of Geography and Statistics (IBGE, 2020) data, had a population of 12,325,232 residents, GDP of US$131.32 billion per year, GDP *per capita* of US$10,936.86 (above the national average), and a human development index (HDI) of 0.805. However, the city is a victim of social inequality. In 2017, while the average worker received 4.2 minimum wage, 31.6% of households had a monthly income of up to half a minimum wage per inhabitant (IBGE, 2021). Resulting of a strong process of industrialization and immigration, São Paulo has become the largest consumer market in the country and the largest generator of WEEE. The city generates around 534,000 tons of WEEE per year (Rodrigues et al., 2020), but only recycles around 3.0% of this waste (Pedro et al., 2021).

Moscow, a federated city, is the country's largest economic, scientific, and cultural center, located in the western part of Russia, with an area of 2,511 km^2 and 12 administrative divisions. The metropolis has an estimated population of 12.6 million inhabitants and its metropolitan region has around 20 million inhabitants, representing over 10.0% of the Russian population and making it the largest metropolis in the country (Organization for Economic Co-Operation and Development [OECD], 2021). The city contains the greatest industrial hub on the land. Between 2010 and 2019, economic growth was 12.4%, when it recorded a GDP of US$324.94 billion. The city's GDP *per capita* is 2.5 times higher than the Russian national average and accounts for 20.0% of the national GDP. Moscow houses 15.0% of the country's companies and attracts 50.0% of the foreign investment in the country. In this scenario, it has the lowest unemployment and informal work rates in the country, with 1.8 and 3.6%, respectively, in 2018, driven by the high levels of education of the local population. It is estimated that 99.0% of the active population have completed secondary education and 75.0% have attended higher education courses. However, Moscow faces challenges that plague large global metropolises, such as pollution, which exceeds levels recommended by the World Health Organization (WHO), high volumes of waste generation, social inequality, housing shortage, high cost of living compared to other Russian cities, and a shrinking active population. The generation of municipal solid waste *per capita* in 2020 was 370 kg and the recycling rate for the same year was 22.3%, below the OECD average of 416 kg and recycling of around 40.0% (OECD, 2021, World Bank, 2019).

Beijing is located in northern China and is administered directly by the national government. The metropolis is divided into 16 administrative districts distributed over an area of 16,410.54 km^2 and has a population of 21.5 million inhabitants (The People's Government of Beijing Municipality, 2021), although the population is smaller than in 2016 when it reached 21.7 million inhabitants (Exame, 2017). In 2019, with the main investments in the digital economy, GDP reached 547.9 billion dollars, with an average growth of more than 6.0% p.a., and *per capita* income achieved of US$25,456.95. The unemployment rate remained at around 4.5% and the number of people receiving some type of government benefit grew by an average of 4.3%. At the end of that year, 65 thousand people in urban areas and 37 thousand in rural areas received the minimum subsistence allowance, while the number of people benefiting from pension insurance programs reached 2 million, and those with health insurance reached 4 million.

After decades of strong urban, population, and industrialization expansion that resulted in high levels of pollution, the national government and local administration have enacted policies to contain population growth and reverse environmental impacts. Beijing's urban plan for 2016-2035 states that the city cannot exceed 23 million inhabitants and its built area must be reduced by 2,760 km^2 by 2030 (Exame, 2017; The People's Government of Beijing Municipality, 2021). The combination of one of China's richest cities and also one of the most populous generates large volumes of WEEE for processing. It is estimated that in 2015, more than 2.31 million units of large household appliances were discarded (Gu et al., 2016).

Delhi, located in the north of India, with an area of 1.484 km^2, is subdivided into 11 districts and administered by the national and local governments. In 2018, its population reached 28.5 million residents (United Nations, 2018; Government of National Capital Territory of Delhi, 2021). The Delhi government, in keeping with the national Digital India strategy, invests in policies that promote the technology market, whose software exports in 2018 totaled US$338.17 million. Delhi's GDP for 2020 was estimated at US$108.33 billion, marking a growth of 7.7% between 2015 and 2020 (Parveen et al., 2019; India Brand Equity Foundation, 2021). Delhi's *per capita* income reached US$4,764.86 (2020), ahead of the national *per capita* income of US$1,717.06 (2020) (Government of National Capital Territory of Delhi, 2021).

On the other hand, the governments are making efforts to control air, water, and noise pollution, as well as WEEE. It is estimated that the metropolis generates 200,000 t of WEEE annually (Hindustan Times, 2021; The Hindu, 2021) and is responsible for 9.5% of the country's annual amount, with the highest *per capita* generation in India at 11.3 kg/year per inhabitant (Arya and Kumar, 2020; Koshta et al., 2021).

Furthermore, Delhi receives WEEE from various parts of India to be traded, dismantled, and processed, mostly by the informal recycling sector (Dutta and Goel, 2021), forming the largest informal recycling center in India with over 5,000 informal EEE recycling points (Awasthi and Li, 2017; Toxics Link, 2019; Arya and Kumar, 2020; Abalansa et al., 2021; Kim and De Vasconcelos Barros, 2021; Koshta et al., 2021). Delhi has the largest electronics market in South Asia and the Nehru Place Market. Located in the south of Delhi, the market has stores selling electronics from global brands and an extensive network of formal and informal repair and resale points for used EEE, reassembled EEE, and WEEE (Corwin, 2018).

Johannesburg has an estimated population of 5.4 million inhabitants (Cooperative Governance and Traditional Affairs, 2020; World Bank Data, 2022). It is located on the eastern plateau of South Africa in an area of 1,644 km^2 divided into seven regions, and is the largest city in the country in terms of size, population, and economy. The metropolis is home to over 70.0% of the country's companies, housing industries in various sectors, generating 16.5% of the national wealth, and employing 12.5% of South Africa's economically active population. In 2018, Johannesburg recorded a GDP of US$60.32 billion, with a growth rate of 0.77% p.a. In this scenario, the local government estimates that the informal sector is responsible for around 13.0% of the city's economy. However, the metropolis also faces global challenges of economic and population growth, migratory flows, urbanization and social inequality, rising consumption, and waste volumes. The population growth rate has reduced since 2011, from 3.5% to an average of 2.4% p.a., but is higher than the national average. The increase in the number of people living in poverty aggravates historical inequalities. From 2008 to 2018, the number of people living in poverty increased by 23.2%, reaching 2.3 million people (Cooperative Governance and Traditional Affairs, 2020; World Bank Data, 2022). Waste generation, in turn, is growing progressively. From 2019 to 2020 there was an 18.0% increase in the amount of waste dumped in landfills, reaching 1,299,353 t in 2020 (City of Johannesburg, 2020, 2022). According to Samson (2021), there are 8,000 informal collectors of recyclable materials in Johannesburg, who collect an average of 128 kg per day from dumpsters, public roads, and landfills. Many of them have worked as collectors for decades, with the activity passed down through generations, and saving the metropolis around 49 million dollars a year by diverting waste from landfills.

In brief, Table 1 (BRICS Metropolises: socioeconomic data) affords a comparative view of the importance of these cities.

The comparison of the metropolises shows that Delhi has the largest population, estimated at 28.5 million (2018), followed by Beijing, with 21.5 million (2020), a city that practices population control. São Paulo and Moscow have similar populations, at over 12 million, whereas Johannesburg has an estimated population of 5.4 million (2019). Beijing and Moscow have the largest territorial areas of the selected metropolises, while São Paulo, Delhi, and Johannesburg have territorial areas between 1,484 and 1,645 km^2. The highest GDP and GDP *per capita* are concentrated in Beijing and Moscow, followed by São Paulo, Delhi, and Johannesburg with the lowest numbers. In addition to national expression, these metropolises stand out on global markets, as well as specifically in the production and commercialization of EEE and WEEE recycling markets.

Nevertheless, all of the cities in question face challenges common to metropolises worldwide, such as growing waste generation, damage to the environment and public health caused by generalized pollution that are aggravated by climate change, social inequality, and lack of opportunities to generate income and meet the requirements of the active population.

Regarding WEEE, national data appear to have been identified in recent studies but few cities are able to quantify the generation of electronic waste and the percentage actually recycled. In this respect, studies on WEEE management in São Paulo calculated that, in 2020, 534,000 t/year were generated and around 3.0% were recycled. In Delhi, in the same year, around 200,000 t/year were generated, and in Beijing, data from 2015 indicated that 2,31 million large EEE were discarded that year (Gu et al., 2016; Rodrigues et al., 2020; Pedro et al., 2021). However, it should be noted that the parties involved in WEEE management in BRICS countries at the national and local level, especially in metropolises, are coordinating and implementing WEEE reverse logistics networks to enable the recovery of this waste.

The role of BRICS metropolises in the management of Waste Electrical and Electronic Equipment

The municipal government of São Paulo, which is the largest consumer and waste generating market in Brazil, has enacted policies and implemented actions that enhance national and regional regulations

Table 1 – BRICS Metropolises: socioeconomic data.

	São Paulo	Moscow	Delhi	Beijing	Johannesburg
Estimated population (millions)	12.3 (2020)	12.6 (2019)	28.5 (2018)	21.5 (2020)	5.4 (2019)
Territorial area (km^2)	1,521	2,511	1,484	16,410	1,645
GDP (US$ billions)	131.32 (2020)	324.94 (2019)	108.33 (2020)	547.90 (2019)	60.32 (2018)
Per capita GDP (US$)	10,936.86 (2020)	22,060.00 (2018)	4,764.86 (2020)	25,456.95 (2019)	1,779.53 (2018)

Source: Cooperative Governance and Traditional Affairs (2020); Government of National Capital Territory of Delhi (2021); IBGE (2021); OECD (2021); The People's Government of Beijing Municipality (2021); United Nations (2018); World Bank Data (2022); Grant (2019).
BRICS Metropolises: socioeconomic data. Population, territorial area, total and per capita gross domestic product (GDP).

on waste management, specifically with regard to WEEE. The state government adopts policies that aim to boost the recycling of WEEE. These include the conditions for the granting of environmental licenses to producers of electronics and the presentation of extended producer responsibility schemes, according to Brazilian Secretary of the State Environment – SMA Resolution nº 45/2015. São Paulo's Integrated Solid Waste Management Plan includes allowances for social awareness campaigns, the integration of the informal sector, and the system of shared responsibility of producers and targets for the implementation of WEEE extended producer responsibility schemes networks, aimed at achieving 35.0% recycling of WEEE in 2024. The details of this plan are further strengthened by the Climate Action Plan of the municipality of São Paulo 2020–2050 (São Paulo, 2014, 2020a, 2020b, 2020c). It is noteworthy that there is heavy emphasis on the work of collectors of recyclable materials in the city and an attempt is made to integrate them into cooperatives licensed by the government to work in the recycling of recyclable materials and WEEE. As an example, the Coopermiti (2021) recycling cooperative works with WEEE, processing 40t/month. The WEEE extended producer responsibility schemes and recycling networks supported by producers are among the most advanced in the country. However, the final processing of some materials, such as precious metals, is exported to countries such as Belgium, the United States, and China for final treatment. Furthermore, the used and repaired market for EEE is expanding in the metropolis. This is either due to the population's financial difficulties in acquiring new EEE or society's awareness of sustainable consumption (Lopes dos Santos, 2020).

In Russia, Moscow is home to the country's largest industrial hub combined with a range of research and development centers. Even the services sector is expanding considerably. The metropolis stands out for its high levels of education, employment, and formal work (World Bank, 2019; OECD, 2021). In waste management, the municipal government updated the aforementioned regulations in 2020 in keeping with national legislation, which prohibits the disposal of WEEE in regular trash bins, with organizations and citizens subject to fines if they fail to comply (Heidemann and Bogdanov, 2020).

In 2021, the implementation of the public-private partnership for recycling the city's WEEE was initiated, in addition to extended producer responsibility systems. The project, which is supervised by the Russian Environmental Operator (REO), a federal agency, aims to reintroduce 95.0% of WEEE materials into production chains and form a circular economy in Moscow. The partner company is Ecopolis Corporation, which must collect, sort, and channel WEEE to recyclers in the region. With these measures, it is estimated that the entire volume of WEEE in the metropolis will be processed (OECD, 2021; Ecopolis Corporation, 2022; Russian Environmental Operator, 2022).

Simultaneously, research and development institutes seek to develop and improve recycling technologies and work to raise awareness and train stakeholders (government, organizations, and society) in WEEE management. This role is also undertaken by the E-Waste Academy in Moscow (United Center for International Industrial Cooperation in the Russian Federation, 2022). In addition to these projects, others are being implemented to increase the adequate channeling of WEEE. These projects include Eco-Taxi, with recyclers collecting WEEE from homes free of charge, and partnerships with retail chains to provide WEEE collection points in their stores (Aim2Flourish, 2022; Oris Prom, 2022; Sko Electronics – Recycling, 2022).

In Delhi, the economy is advancing in the services sector in line with national Digital India policies, which encourage the formation of startups and research and development centers in the information technology market (Parveen et al., 2019; India Brand Equity Foundation, 2021). However, the metropolis faces the challenge of combating pollution and managing the largest flow of WEEE in the country, increased by Indians' habit of storing WEEE and the movement of WEEE from other regions of India to be sold, reconditioned and processed in Delhi's formal and informal market.

It is estimated that around 50 thousand people in the city work directly and indirectly in WEEE recycling, with the informal WEEE market coexisting with precarious working conditions and child labor (Pandey and Govind, 2014; Awasthi and Li, 2017; Corwin, 2018; Parveen et al., 2019; Toxics Link, 2019; Arya and Kumar, 2020; Abalansa et al., 2021; Dutta and Goel, 2021; Hindustan Times, 2021; Kim and De Vasconcelos Barros, 2021; Koshta et al., 2021; The Hindu, 2021). In this scenario, the government of Delhi uses the structure of Non-Governmental Organizations (NGOs) and education and research institutions, providing funding and forming partnerships to raise society's awareness in order to adopt safer and more sustainable practices in the handling and treatment of WEEE, as well as in the training of stakeholders and the integrating and formalizing informal workers.

For these purposes, NGOs and education and research institutions, in turn, have formed partnerships with associations of WEEE collectors, producers, and recyclers. Examples of these actions are the work of the NGO known as Toxics Link and the partnership between the Chintan Environmental Research and Action Group, the Electronic Waste Recyclers Association. and the Safai Sena recyclers group (Arya and Kumar, 2020; Dutta and Goel, 2021; Government of National Capital Territory of Delhi, 2021). Furthermore, the government monitors and inspects consumers' disposal of EEE on a large scale and is implementing a model ecopark project, which, supported by advanced technologies, will collect and recycle WEEE, with the integration of the informal sector (Hindustan Times, 2021; The Hindu, 2021; The Times of India, 2021).

In China, Beijing faces the challenge of containing waste volumes and reversing its environmental impacts after decades of rapid population growth and industrial expansion (Exame, 2017; The People's

Government of Beijing Municipality, 2021). The WEEE market in the metropolis has a network of formal and informal actors who interact in the processes inherent to the collection, sale, refurbishing, and processing of this waste. The local government has taken a series of steps to formalize these activities, as many of them are carried out in precarious and unsafe locations for workers and the environment (Wang and Mishima, 2019). In this respect, Steuer et al. (2018) showed that the formal management of WEEE is expanding in Beijing. According to these authors, data indicate that in 2005 around 57.0% of this waste was collected by informal means, and in 2012 this number dropped to around 30.0%.

The local government, based on the Beijing Five-Year Plan (2021–2025) to make the metropolis a model for ecological actions, has taken measures and implemented projects related to WEEE management, such as i. the supervision of activities related to WEEE management; ii. use of information and communication technology (ICT) to computerize all processes inherent to waste management; iii. structure of a system of waste sorting managers made up of companies and residents covering the entire Beijing area, in addition to neighborhood supervisors, responsible for actions to raise awareness among the population regarding the standards set for waste management; iv. establishment of formal WEEE purchase stations in residential neighborhoods; v. implementation of WEEE recycling plants, such as that of the Huaxing Group, with the capacity to process 1.2 million tons of WEEE per year (The People's Government of Beijing Municipality, 2021).

In South Africa, Johannesburg is the country's economic and financial center, with emphasis on the African continent and the global market, with renowned research and development centers. However, the metropolis is also faced with the global challenges of rapid urbanization, which exacerbates social inequalities and the increasing generation of waste (Cooperative Governance and Traditional Affairs, 2020; World Bank Data, 2022). In the WEEE market, formal and informal actors are involved in the collection and processing of waste, as well as in the growing trade in used EEE, increased by international donations of second-hand EEE to local NGOs. It is estimated that there are around 8 thousand informal collectors of recyclables working in the city (Samson, 2021). In addition to the extended producer responsibility schemes implemented by EEE producers, the municipal public company Pikitup, which manages waste in the city, is also responsible for integrating and articulating all the parties involved in waste management aimed at reducing, reusing, and recycling large volumes of recyclables, including WEEE. Integration and coordination actions also seek to involve neighborhood associations, NGOs, cooperatives, and informal collectors (City of Johannesburg, 2020, 2022).

The following strategies related to the management of recyclable waste, which include WEEE, stand out in Pikitup's current planning: i. expansion of collection and processing centers; ii. actions to raise society's awareness; iii. integration and training of cooperatives and informal collectors; iv. viability of the formation of waste picker cooperatives; vi. employing the services of collectors and cooperatives in the early stages of recycling; and vii. coordination of partnerships between collectors and recyclers (Pikitup Johannesburg Soc Limited, 2022).

Synthesized cross-analysis of metropolis case studies of Waste Electrical and Electronic Equipment management

In a synthesized analysis of the case studies presented, Table 2 (BRICS — National legislation on the management of WEEE) and Table 3 (BRICS Metropolises: local policies and actions) list measures taken by stakeholders related to the management of WEEE in each metropolis. Meanwhile, Table 4 (BRICS Metropolises: actors and roles in WEEE management) summarizes and compares roles identified within the scope of metropolises in the management of WEEE played by actors from the government, market, and society.

In these scenarios, as shown in Tables 3 and 4, the metropolises appear to be establishing municipal regulations for WEEE management in a specific or detailed manner through urban waste management legislation, aligned with the national legislation listed in Table 2. Among the metropolises in question, it was found that Beijing, Moscow, Delhi, and São Paulo have specific regulations for WEEE management. In Johannesburg, no direct regulation of WEEE was identified but municipal waste management legislation reinforces the national commitment to reduce, reuse, and recycle waste, with priority actions for hazardous, industrial, and recyclable waste streams, which include WEEE. It is noteworthy that São Paulo, Moscow, and Delhi have even set annual goals for the recovery of WEEE.

In all these metropolises, the local governments work to coordinate the stakeholders involved in activities related to the management of WEEE, promoting the research and development of recycling technologies and awareness programs for society regarding proper disposal and processing.

However, regarding the inclusion of the informal sector (pickers and recyclers) in the formal WEEE market, it was observed that municipalities adhere to national guidelines. Thus, São Paulo, Delhi, and Johannesburg seek to promote the integration of the informal sector, while Beijing focuses on monitoring the formalization of collection and recycling activities. In Moscow, research has not indicated any action that encompasses informal processes in WEEE management, if they exist in the city. It was observed that Beijing and Moscow focus their efforts on promoting the full circularity of recyclables to mitigate environmental impacts and scarcity of resources.

The WEEE markets in these metropolises are structuring and implementing extended producer responsibility networks in accordance with the producer accountability systems in force in their countries.

Table 2 – BRICS – National legislation on the management of Waste Electrical and Electronic Equipment.

Country	Legislation/year	Topic related to WEEE
Brazil	National Solid Waste Policy (2010).	It includes shared responsibility in waste management, requiring manufacturers, importers, distributors, and traders to implement networks of extended producer responsibility schemes for WEEE. It also recognizes the activity of recyclable waste pickers.
Russia	Production and Consumption Waste Act 1998 (revised 2014, 2017, 2021).	It sets the requirements for the collection, treatment, use, and disposal of production and consumption waste, which includes WEEE. It also establishes the extended producer responsibility system.
India	WEEE Management and Handling Act 2010 (revised 2011, 2016, 2018).	It regulates the management and handling of WEEE and restricts the use of hazardous materials in the manufacture and importation of EEE. It incorporates extended producer responsibility systems and includes implementation goals. It establishes Producer Responsibility Organizations as authorized WEEE managers, and recognizes all workers involved in the processes of collecting, dismantling, and recycling this waste.
China	China WEEE Directive (2009).	It establishes the guidelines for the management of WEEE, institutes extended producer responsibility, and requires EEE producers and importers to pay a tax to the national recycling fund.
South Africa	National Environmental Management Act: Waste (2008).	It regulates waste management at the national level, including WEEE. It establishes Extended Producer Responsibility, and imposes on every individual or company the obligation to properly dispose of WEEE.

BRICS - national legislation on the management of WEEE in Brazil, Russia, India, China, and South Africa.

Table 3 – BRICS Metropolises: local policies and actions.

BRICS Metropolises	Highlighted local policies and actions
São Paulo	Integrated solid waste management plan with specific norms for WEEE management. Integration of the informal sector. Agreement with cooperatives for WEEE recycling. Climate action plan for the city of São Paulo 2020–2050.
Moscow	Ban on disposing of WEEE in regular bins, subject to fines for non-compliance. Implementation of a public-private partnership in WEEE recycling, in addition to extended producer responsibility systems. Eco-Taxi Project collects WEEE from homes free of charge. E-Waste Academy's role in training parties involved in the management of WEEE (government, private sector, and other organizations). Education and research institutions work to raise society's awareness regarding proper disposal and the development of recycling technologies.
Delhi	Government provides financial support and partnerships to NGOs and consultancies for educational and research institutions in the production of data on waste and programs to raise awareness of society regarding proper disposal and processing. Supervision and control of large-scale consumer disposal of EEE. Implementation of an eco-park model project for the collection and recycling of WEEE with the application of advanced technologies and integration of the informal sector. Partnership between NGOs and associations of collectors and recyclers to train workers and implement safer and more sustainable work practices.
Beijing	Supervision of activities related to the management of WEEE. Use of ICT to computerize all processes inherent to WEEE management. City waste sorting system management system formed by companies and residents. Structure of neighborhood supervisors responsible for public awareness actions. Establishment of formal WEEE purchase stations in residential neighborhoods. Implementation of WEEE recycling plants.
Johannesburg	Campaigns to raise the awareness of society. Expansion of collection and recycling infrastructure. Integration of the informal sector, training collectors and cooperatives. Enabling the formation of cooperatives and partnerships with recyclers. Employment of the services of collectors and cooperatives in the early stages of recycling.

EEE: Electrical and Electronic Equipment; WEEE: Waste Electrical and Electronic Equipment; NGOs: Non-Governmental Organizations; ICT: Information and Communication Technology. BRICS Metropolises: local policies and actions in São Paulo, Moscow, Delhi, Beijing, and Johannesburg.

At the same time, the refurbishing and commercialization markets for used EEE and its waste are growing. As these structures advance, there has been growing interest from existing recyclers and investments in new recycling centers that meet the demand for WEEE processing in the metropolis. To this end, companies in partnership with education and research institutions and NGOs are investing in researching and developing WEEE recycling technologies, as well as in campaigns to raise society's awareness regarding proper disposal. Currently, WEEE generated in Beijing and Moscow can be fully recycled in their own countries, while that of São Paulo, Delhi, and Johannesburg is partly recycled in the country and then sent overseas for final processing.

In parallel, other actors are involved in activities related to WEEE management. Education and research institutions and NGOs stand out in terms of training public and private and formal and informal agents.

Table 4 – BRICS Metropolises: actors and roles in Waste Electrical and Electronic Equipment management.

Actors/role	São Paulo	Moscow	Delhi	Beijing	Johannesburg
Government					
Specific current municipal legislation for WEEE	Yes (2020)	Yes (2020)	Yes (2021)	Yes (2019)	
Institution of recycling goals	x	x	X		
State as articulator of the parties involved	x	x	X	X	X
R&D in recycling technologies	x	x	X	X	X
Integration of the informal sector	x		X		x
Inclusion of recyclable material collectors	x		X		x
Government agencies involved in the awareness and training of stakeholders	x	x	X	X	x
Market					
Implementation of extended producer responsibility networks	x	x	X	X	x
Sale and reconditioning of used EEE and WEEE	x	x	X	X	x
Channeling WEEE to recyclers	x	x	X	X	x
WEEE recycling	Partial	Full	Partial	Full	Partial
R&D in recycling technologies	x	x	X	X	x
Campaigns to raise awareness of society	x	x	X	X	x
Society					
Non-governmental institutions act to train and raise awareness in society	x	x	X	X	X

EEE: Electrical and Electronic Equipment; WEEE: Waste Electrical and Electronic Equipment; R&D: research and development. BRICS Metropolises: actors and roles in Waste Electrical and Electronic Equipment (WEEE) management. Actors and roles of government, market and society in the management of WEEE in São Paulo, Moscow, Delhi, Beijing, and Johannesburg.

Moreover, awareness-raising actions in society rely on the help of local public and private media. However, commitment to environmental education is the responsibility of government spheres in all of the BRICS countries.

Furthermore, it is worth highlighting that the Beijing government, in line with the Chinese national government, invests in the application of advanced technologies in WEEE management used by smart cities. The use of ICT and Big Data technologies in the digitalization of all processes inherent to the management of WEEE aims to provide data with greater speed and precision for decision-making.

On the other hand, there is a notable articulation of the municipal governments of São Paulo, Johannesburg, and Delhi with the actors involved in the management of WEEE in the market and society in projects for the development of techno-social technologies, which provide opportunities for income generation and social inclusion. From this perspective, these metropolises maintain programs associated with education institutions, NGOs, and companies in the EEE and WEEE sectors to train formal and informal workers, encouraging the formation of associations and cooperatives of collectors and recyclers that can be accredited in WEEE recycling.

In addition to the analysis of WEEE management in the metropolises, Figure 1 (BRICS Metropolises: Flow of EEE and WEEE) shows the flow of WEEE from the EEE production chain, considering the formal and informal market for this waste, as well as the market for used EEE and WEEE.

Figure 1 shows that used EEE and WEEE leave the production chain destined for three WEEE market sectors that are interconnected to a greater or lesser degree in the markets of the metropolises as the result of relationships built over time. Therefore, the formal and informal WEEE market is identified, along with the used EEE market in which WEEE also circulates:

- The formal market receives the flow of WEEE from formal and informal collections, channeling it to formal recyclers and the national recycling industry, while certain materials are exported for final processing;
- The informal market, in parallel with the formal market, carries out collection activities and the initial processing of WEEE recycling. It is worth noting that Moscow was the only metropolis among those analyzed where the existence or non-existence of informal activities related to WEEE was not determined;
- The market for used EEE and WEEE (second-hand market), especially in metropolises, is expanding, either due to financial difficulties in acquiring new equipment or society's awareness of repairing and reusing EEE for sustainable consumption.

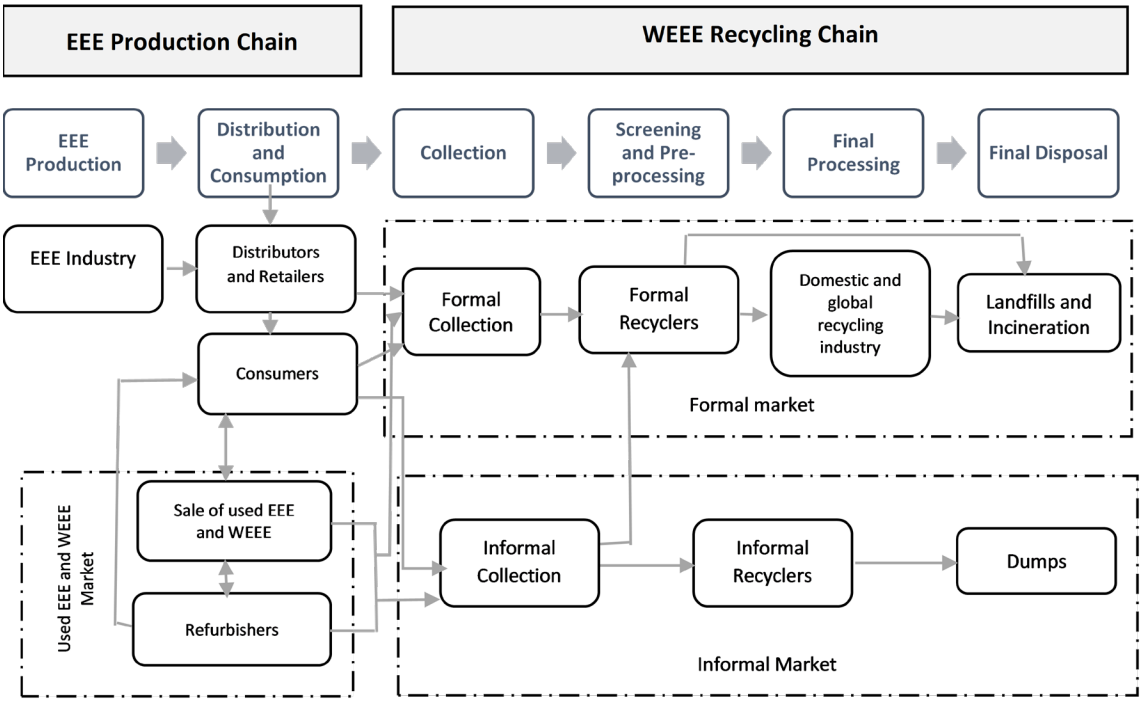

Figure 1 – BRICS Metropolises: flow of Electrical and Electronic Equipment and Waste Electrical and Electronic Equipment. Flow of Electrical and Electronic Equipment production chains and recycling of Waste Electrical and Electronic Equipment in São Paulo, Moscow, Delhi, Beijing, and Johannesburg.
Source: adapted from Lopes dos Santos (2020, p. 8).
EEE: Electrical and Electronic Equipment; WEEE: Waste Electrical and Electronic Equipment.

It was found that formal and informal actors perform similar roles in the process flows of the WEEE value chains in the analyzed metropolises. However, the related activities carried out on the informal market are largely undertaken in precarious working conditions, posing risks to the environment and human health. Furthermore, it should be pointed out that the final place of disposal for waste from the formal market is landfills and incinerators, while from the informal market, it tends to be dumped in landfills scattered across public environments, causing greater environmental and social damage.

Clearly, each metropolis' local realities impose limitations and raise barriers to the successful implementation of policies and actions based on the circular economy associated with the sustainable management of WEEE, and contribute to the development of smart and sustainable cities.

Thus, the leading role of these metropolises in circular policies and actions for the management of WEEE seeks to present solutions to the increasing generation of WEEE, which coexist with social, environmental, and institutional problems. However, it is essential to consider that each city and each country have their historically constructed territoriality, shaping legislation and implementation programs, highlighting certain measures. However, it is understood that these policies and actions, in turn, can serve as a basis for other metropolises, and contribute to the success of related policies.

Conclusions

Given the importance of the leading role of metropolises in achieving positive outcomes in the management of WEEE, this study aimed to describe local WEEE management policies and actions in BRICS metropolises, identifying the different actors in the processes inherent to WEEE. To this end, the cases of São Paulo, Moscow, Delhi, Beijing, and Johannesburg were analyzed. In the WEEE value chain of these metropolises, the actions of government, market, and society agents in formal and informal WEEE markets were presented.

In the formal WEEE market, EEE producers, importers, distributors, and retailers, WEEE management entities, refurbishers, cooperatives/associations of collectors/recyclers, and pre-processing and final processing recycling companies interact. It is the task of EEE producers, importers, and traders to implement WEEE logistics networks in accordance with the producer accountability systems established by law. In these systems, waste must be collected and sent to licensed WEEE pre-processing and recycling channels. However, these systems were found to be still in the structuring phases in the metropolises, with varying degrees of implementation.

Regarding informal actors, with the exception of Moscow, the metropolises have an extensive informal market historically built for the collection, trade, repair, and pre-processing of WEEE, which need to be considered and included in the structuring and implementation of related public policies.

Beijing, Moscow, Delhi, and São Paulo have regulations for WEEE management. It was observed that following the alignment of national guidelines, the municipal governments of Beijing and Moscow focus their efforts on the circularity of materials. Meanwhile, the governments of São Paulo, Delhi, and Johannesburg seek solutions for the inclusion of collectors of recyclable materials and integration of the informal sector in the implementation of producer responsibility systems.

At the same time, other actors are involved in activities related to WEEE management. Education and research institutions and NGOs stand out in terms of training public and private and formal and informal agents. It is worth highlighting the role of these agents in the training and formalization of informal workers in local associations and cooperatives. In addition, they work to raise awareness among organizations and citizens regarding proper disposal and sustainable consumption. It was also noted that society's awareness and awareness actions rely on the help of local public and private media, although the commitment to environmental education is the responsibility of government spheres.

In this way, it appears that WEEE value chains are formed through the interrelationship of stakeholders in the government, market, and society, whose forms of action are shaped by local territoriality, the diversity of which must be considered in the framework for the intelligent and sustainable development of cities.

However, these metropolises share common points, allowing an analysis of limitations and propositions in order to structure relevant theoretical aspects with positive results in the management of WEEE. These adversities and limitations to WEEE management are found in government spheres, market sectors, and layers of society.

In this respect, the establishment of specific regulations for WEEE management is proposed, elucidating the responsibilities of the parties involved and making dealing with this waste a priority. The greater role of government spheres in articulating and establishing synergy with agents in the management of WEEE is recommended for the implementation of producer responsibility systems and the development of secondary resource markets. It is recommended that these systems should be more inclusive, integrating small businesses and the informal sector.

It can be concluded that these synergistic environments are still under construction in the BRICS metropolises but perceived individually in the presentation of the cases of São Paulo, Beijing, Delhi, Johannesburg, and Moscow. They play a leading role in the cities' WEEE management.

Local governments, aligned with their regional and national counterparts, meet the necessary conditions to structure public-private partnerships that can act on different processes in the WEEE value chain, ranging from training agents and developing techno-social technologies to promoting recycling plants and eco-industrial parks.

Given this panorama, the relevance of the leading role of metropolises in the sustainable management of WEEE is highlighted, coordinating in synergy with the actors involved in the implementation of policies and related circular actions, incorporating information and communication technologies for smart cities in the construction of sustainable, inclusive and resilient cities.

Further research should quantify and analyze data on the WEEE value chain, as well as cross-reference these data with the policies and actions adopted in each metropolis.

Authors' contributions

FRANZ, N.M.: conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original daft. SILVA, C.L.: conceptualization, formal analysis, funding, methodology, project administration, resources, supervision, visualization, writing – review & editing.

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