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Sustainability assessment of best locations for waste printed circuit boards processing units: The Brazilian case

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Abstract: Waste Printed Circuit Boards (WPCB) are sources of valuable elements. In most developing countries, the WPCBs of formal chains are exported to treatment overseas given the absence of proper recycling plants, transferring the high-added value to developed nations. This study proposed a method to identify the best locations to implement WPCB recycling facilities considering sustainability criteria. The method was applied to the Brazilian case and consisted of state and municipal levels analysis based on 11 indicators related to the three sustainability dimensions, logistics criteria and geoprocessing tools. The results suggested São Paulo state (SP) as the main pole for WPCB processing in Brazil, with an estimated potential of WPCB generation of almost 24 t/d, and São Caetano do Sul and Jundiaí as the main favourable WPCB recycling municipalities. This study demonstrated that sustainable logistics for WPCB value recovery in developing countries is possible and desirable for achieving more circular patterns.

Keywords: E-waste; Waste Printed Circuit Boards; Recycling; Urban Mining; Developing countries.

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São Paulo. Vol. 26, 2023

Original Article

DOI: http://dx.doi.org/10.1590/1809-4422asoc0107r3vu2023L3OA

1. Introduction

Waste electrical and electronic equipment (WEEE or e-waste) is considered the fastest-growing waste stream worldwide (AWASTHI et al., 2018; FORTI et al., 2020; PETRIDIS et al., 2020). The main concerns about e-waste are related to its hazardous potential for being composed of toxic metals and other substances that might generate environmental impacts and health diseases (ILANKOON et al., 2018; KAYA, 2020a; KIDDEE et al., 2013). The growing amounts of electronics will make it increasingly difficult to achieve the 2030 Sustainable Development Goals (SDGs), especially those related to environmental protection and public health safety (AWASTHI; LI, 2019).

Nonetheless, most of these devices contain elements of high added value. Waste Printed Circuit Board (WPCB) is one of the most valuable fractions of e-waste, being composed of approximately 30% ceramic, 30% polymers and 40% metals (KAYA, 2020a). In the metals' fractions, some categories can be considered: the valuable base metals (e.g., Sn, Fe, Cu, Zn, Pb, Al etc.), precious metals (Au, Ag etc.); platinum group metals (Pd, Pt, Rh, Ir, Ru etc.); scarce metals (Te, Ga, Se, Ta and Ge); and hazardous metals (e.g., Pb, Hg, Be, Cr, As, Sb, Cd etc.) (CHEN et al., 2016; KAYA, 2020a; ZENG et al., 2017). Even considering that WPCB corresponds to a small portion (3%-6%) of the total e-waste generated in the world, the huge total e-waste quantities on a global scale still contribute to this component being significantly generated (GHOSH et al., 2015).

The recent understanding of the e-waste value has influenced the advances in Urban Mining (XAVIER et al., 2019) and sustainable growth (GHIMIRE; ARIYA, 2020). In the developing world, however, even though the e-waste generation might be significant, the lack of proper advanced recycling technology (that addresses the local needs) to recover such valuable materials corroborates to flows of e-waste exportation to smelteries in developed countries, which offer only a partial value for the sold materials, besides being expensive solutions due to logistics and shipping charges (TURAGA et al., 2019). The WPCB exportation for recovering precious metals is a current procedure in some developing countries, as in the case of Brazil (DEMAJOROVIC et al., 2016; OTTONI, 2021), but this solution can impact the feasibility of recycling plants in such countries and compete with the capability of recyclers in reaching the collection and recycling targets established by regulations. Insofar as the valuable e-waste components are exported, the recovery potential of valuable materials decreases, as the high-added value is transferred to developed nations (DEMAJOROVIC et al., 2016), and discourages the establishment of technological solutions for e-waste processing.

Also, this current e-waste management pathway might contribute to increasing greenhouse gas (GHG) emissions, and, therefore, influence the climate crisis, especially because of the emissions related to the exportation overseas and the extraction of metals from virgin mines. E-waste incineration, landfilling (NING et al., 2017), and exportation are no longer desirable (and sometimes even permitted) considering the environmental impacts and global legislations requirements (KAYA, 2020a), and this reality promotes the analysis of other value recovery possibilities for e-waste.

Given this scenario, the implementation of recycling units in developing countries should be considered, mainly because of their potential to increase circular and sustainable patterns in the electronics sector. Therefore, in the present study, a methodological proposal was developed aiming at identifying the best locations to implement such plants (main potential e-waste recycling hubs) considering sustainability criteria and Geographic Information System (GIS) tools, with application in the Brazilian case. For this purpose, the current overview of geographical characteristics, e-waste generation/flows and primary logistics agents (here defined as the formalized agents, such as companies and waste picker cooperatives, that work in the preprocessing and/or processing stages, or, generally, as "recyclers") in the studied country were evaluated.

2. E-waste/WPCB recycling

The recycling process starts with the introduction of WPCB, which can be populated (with electronic components) or unpopulated (without such components, or bare WPCB), into the dismantling stages, depending on the adopted process in the recycling plant. The objective of this phase is to remove the solders and electronic components from the boards. After a screen classification (stage to classify materials by size), the components without damage are directed to resell or reuse, and the remaining ones (damaged or malfunctioning parts) are recycled through physical and metallurgical processes, such as gravimetric, magnetic, flotation, leaching, pyrometallurgical and/or hydrometallurgical processes to recover the valuable elements (HABIB et al., 2020). The unpopulated WPCBs are directed to a shredder, then to a pulverizer, for reducing the size and recovering mixed metals and resin powders, and, finally, to the air separator and electrostatic separator, to obtain copper powder (Cu, Sn, Pb) and separated resin and fibre powder (KAYA, 2019). The pulse duster is used to prevent air pollution caused by the generated dust.

The advanced (or complete) recycling stages of resources recovery from WPCB consider the effective separation of both metal fraction (MF) and non-metal fraction (NMF), which is indispensable for efficient recycling. These processes include mechanical separation, MF refining steps and NMF upgrading to increase their added value (KAYA, 2020b; NING et al., 2017), including supercritical fluid extraction, plasma treatment and hydrothermal method. In the current context, pyrometallurgical and hydrometallurgical processes are the main processing routes for extracting valuable metals from e-waste and can be followed by electrometallurgical/electrochemical refining processes for selected metal recovery (KHALIQ et al., 2014). Pyrometallurgical WPCB recycling routes are generally used worldwide with high investment costs, temperatures, energy expenditure and environmental problems. The hydrometallurgical method is more predictable and easily controlled than pyrometallurgical processes (KAYA, 2020b), although it cannot completely recover all metals without other complementary approaches (HAO et al., 2020), besides requiring large quantities of reagents and producing high volumes of effluent waste (MAGODA AND MEKUTO, 2022). Promising biological processes are under development for e-waste value recovery (KAYA, 2020b), even though there are only limited studies at the laboratory scale on biometallurgical routes so far for e-waste (KHALIQ et al., 2014) given their limitations on controlling the reactions and long operational periods (MAGODA AND MEKUTO, 2022).

The literature points to the centralized facilities employing advanced technologies in the developed world's highly regulated industrial environment (integrated smelters and refineries). These facilities can extract valuable metals, recover a large variety of elements and isolate hazardous substances efficiently, closing the loop of valuable fractions and reducing the environmental impact arising from large quantities of e-waste (HAGELÜKEN, 2006; KAYA, 2018). Even though the processing time is short in the pyrometallurgical treatment, smelting is an energy-intensive (> 1200°C) process, and the initial investment and energy costs are very high (KAYA, 2020b). The small WPCB recycling plants present a processing capacity of 0,2-0,3 t/h (or 4,8-7,2 t/d) of WPCB input, while the medium plants correspond to 0,3-1 t/h (4,8-24 t/d) and the large, to 1-1,5 t/h (24 – 36 t/d), even though some companies can still present higher capacity, as the case of Umicore and Elden (KAYA, 2019). The literature indicates 16 main e-waste recycling plants in the world (KAYA, 2019; KHALIQ et al., 2014), mostly established in developed countries, especially because of the more favourable economic conditions to implement such units. This reality shows the gaps and fragilities in a matter of the practice of urban mining strategies geographically.

On the other hand, developing countries keep fostering largely unregulated artisanal procedures based on labour-intensive and environmentally hazardous approaches (ILANKOON et al., 2018). The study by Yoshida, Terazono, et al. (2016) highlighted that the environmental costs of the lack of adequate recycling technologies and infrastructure for some types of e-waste in Asian developing were significant, and a better option would be the investment in a full collection and recycling chain within the countries that generate e-waste. Even though this is a huge problem in developing nations, in some developed ones, the lack of proper technology for e-waste recycling can be a challenge for a more sustainable and circular path. Khaliq, Rhamdhani, et al. (2014) stated that the lack of copper smelting and refining operations is one of Australia's biggest barriers to e-waste recycling.

In Mexico, e-waste recycling companies limit their operations to disassembly of equipment, recovery of useful parts, and the grinding and separation of materials, focusing on reprocessing plastic, glass and copper, while valuable material is sent abroad for the recovery of precious metals (LUNDGREN, 2012).

In India, informal recycling operations are strong and influence the pattern of e-waste recycling (LUNDGREN, 2012). India generates 2Mt of e-waste each year, but about 90% of the collected waste is processed in the informal sector, and the formal recycling companies are limited to manual dismantling and segregation of e-waste with few formal facilities capable of extracting precious metals, being dependent of exporting the valuable fraction to smelters in developed countries (TURAGA et al., 2019). The authors pointed out that the Government-supported efforts developed smaller-scale and cost-effective processes to recover precious metals from WPCBs but highlighted the need to be implemented on a large scale within the formal sector or piloted for safe implementation in the informal sector. In this context, the microfactory concept is mainly based on a small-size factory able to produce small dimension products thereby saving resources and can also be applied to e-waste processing in developing countries (TURAGA et al., 2019). According to Sahajwalla and Gaikwad (2018), the microfactories can process metals, ceramics and glass from e-waste, are scalable and can be adapted for large and small throughput purposes. In terms of solutions for WPCB, Sahajwalla and Gaikwad (2018) highlighted the possibility of using microfactories to transform end-of-life printed circuit boards into supercapacitors, sustainable composite panels and carbon microfibers and foams.

In China, nearly 130 e-waste recycling enterprises were registered on the e-waste Dismantling Enterprise list in 2016 (HONDA et al., 2016). However, formal treatment is still in its early stages and most of the e-waste is recycled informally, given the widespread existence of informal e-waste collectors and recyclers, resulting in difficulties for formal recyclers to access e-waste products, as they are unable to compete with the price given higher formal treatment costs (HONDA et al., 2016).

In the case of Brazil, one of the biggest e-waste "urban mines" in the Americas, the formal chains of WPCB are all practically still exported to recovery plants abroad, due to the absence of specific processing and recycling plants in the country, transferring the e-waste economic value to other nations. Several primary logistics agents act in the country's electronics sector's reverse chain (ARAUJO; XAVIER, 2019; DIAS et al., 2018; SOUZA, 2019), especially numerous small units and a few large companies. According to Souza (2019), these last recyclers purchase valuable e-waste components, offer treatment and disposal of hazardous fractions, and shred the WPCB to export to large recyclers in the international market – mostly the European ones.

Some studies on the recycling of WPCB in Brazil have been published in the last years (DA SILVA et al., 2015; SILVA et al., 2019; SILVAS et al., 2015), focusing on the details of laboratory-scale processes. Da Silva, Augusto, et al. (2015) suggested a route considering the mechanical processes followed by hydrometallurgical and biohydrometallurgical solutions since the country already has the basic competencies for the development of these technologies in other applications, as in the case of primary mining.

In terms of logistical studies, Ottoni, Dias, et al. (2020) assessed the best routes between e-waste hotspots and primary logistics agents in the Metropolitan Region of Rio de Janeiro, Brazil. Lopes dos Santos (2020) analyzed the location of formal recyclers in the São Paulo Macrometropolis and found out that all recyclers interviewed perform the first stages of e-waste processing (data destruction, sorting and dismantling), some also operate with waste physical fragmentation, and none perform the advanced recycling level.

However, the absence of logistics studies with a focus on identifying e-waste generation hotspots for enabling the implementation of e-waste/WPCB advanced recycling units in developing countries is observed as one of the main gaps in the literature regarding e-waste management and urban mining approach.

3. Methodology

The adopted methodology was based on two main scales (**Figure 1**) applied in the

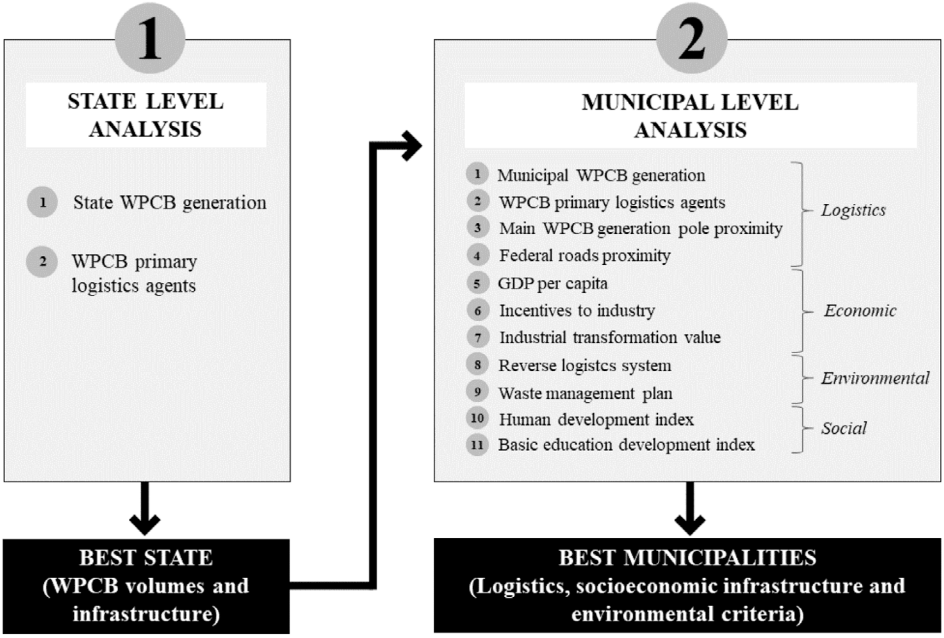
Brazilian case study: (i) State level, which encompassed the assessment of the current outlook of the state WPCB generation estimates and the distribution of the main primary logistics agents (formal organizations working at preprocessing and/or processing stages), working with WPCB, considering that the e-waste stream is established from hotspots to recyclers; (ii) Municipal level, with sustainability and logistics criteria for the selection of best locations (municipalities) for implementing an e-waste/WPCB advanced recycling plant.

3.1. Assessment of WPCB Brazilian states' overview

As a matter of simplification, a first-stage analysis was proposed at a state level, aiming at filtering from the 5,570 Brazilian municipalities distributed into the 27 federative units the ones with more adequate conditions to be further assessed with more details. Therefore, the state WPCB hotspots and the number of WPCB primary logistics agents across the country were the two decisive criteria for refining the final scope. After selecting the most favourable state according to such criteria, the analysis turned into a municipal scale.

The hotspots of e-waste and WPCB generation were estimated in this study due to the absence of an official e-waste database with such information (OTTONI et al., 2020; SOUZA, 2019). Therefore, considering that Forti, Baldé, et al. (2020) estimated that Brazil generated about 10.2 kg/inhabitant in 2019, this value was adopted as an annual Brazilian generation factor. The approximation of the WPCB generation values was supported by the fact that printed circuit boards (PCBs) are present in practically all electronic equipment and account for 3% of its mass (MISHRA et al., 2021). Thus, as a matter of simplification, the factor of 0.306 kg/inhabitant (3% of 10,2 kg/inhabitant) of WPCB annual generation was considered, being multiplied by the number of inhabitants in the desired geographical units (the state and municipal scales), obtained from last Brazilian demographic census (IBGE, 2010). For logistics purposes, daily WPCB values were considered on an annual basis of 365 days. In the first stage, the values of WPCB generation per Brazilian state were considered to promote a broader overview of the main hotspots along with the country that could indicate the potential poles to receive an advanced recycling unit. The estimates on the municipal WPCB generation hotspots were further used to point out the municipalities with the best potential to directly supply the recycling plant within the biggest generator states identified in the previous steps of this study.

Figure 1 – Scheme of the methodology adopted in this study



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The main e-waste primary logistics agents list was obtained from the preliminary results of the DAT4RE Project, developed by the Center for Mineral Technology (CETEM), a research institute in Brazil (CETEM, 2021). The list of 272 e-waste primary logistics agents was filtered to consider the companies that work at any stage of WPCB management, verified through their website information and contacted via e-mail and phone calls. Regarding the processing stage, most companies work with segregation and some of them even with shredding for purposes of exportation. The largest companies (with a capital share equal to or higher than R$ 1.000.000,00, equivalent to US$ 186,198.90 in the first quarter of 2021) of this sample were selected. These primary logistics agents were mapped using the georeferencing software ArcGIS.

3.2. Assessment of WPCB Brazilian states' overview

The remaining municipalities of the selected state were assessed considering 11 indicators related to the three sustainability dimensions and logistics criteria, as similarly proposed in the study of Ottoni et al. (2020). As indicated in Motta and Barreto (2019), the selection of the indicators was based upon three premises: a) To be applicable to e-waste management; b) To be measurable using primary or secondary data; c) To be objective and easy to understand for information gathering. **Table 1** summarizes the adopted indicators, their measuring units, dimensions and sources.

Table 1 – Indicators to assess the best potential municipalities for implementing e-waste/WPCB advanced recycling plants in Brazil

Indicator	Year	Measuring unit	Dimension	Source
Municipal WPCB generation	2019	Tonnes per day	Logistics	(FORTI, BALDÉ, *et al.*, 2020, IBGE, 2010, MISHRA, JHA, *et al.*, 2021)
Distance to the main WPCB generation pole (municipality)	-	Km	Logistics	Georeferencing tools
WPCB primary logistics agents	2021	Units	Logistics	(CETEM, 2021)
Proximity to main roads	2019	Km range	Logistics	(DNIT, 2019)
Municipal GDP per capita	2018	US$	Economic	(IBGE, 2017)
Municipal financial incentives to industry	2019	YES or NO	Economic	(IBGE, 2019)
Industrial Transformation Value (ITV) in the electronics sector**	2016	%	Economic	(SEADE, 2019)
Municipality considered in the Sectoral Agreement for electronics RLS	2020	YES or NO	Environmental	(BRAZIL, 2020)
Existence of Municipal Waste Management Plan (MWMP)	2021	YES or NO	Environmental	Web search engines
Municipal Human Development Index (HDI)	2010	0 (less developed) to 1 (most developed)	Social	(IBGE, 2017)
Basic Education Development Index (BEDI) (estimated to 2019)	2019	0 (less developed) to 10 (most developed)	Social	(INEP, 2018)

Notes:

WPCB: Waste Printed Circuit Board; GDP: Gross Domestic Product; ITV: Industrial Transformation Value; RLS: Reverse Logistics System; MWMP: Municipal Waste Management Plan; HDI: Human Development Index; BEDI: Basic Education Development Index

* Based on the quotation of R$ 1.00 = US$ 0.18, of February 25, 2021

** Just available for municipalities in São Paulo state

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The municipal WPCB generation is important as a metric of the material value recovery potential in the assessed municipality. The distance to the main WPCB generation hotspot and proximity to the main roads were other fundamental indicators for logistics, as the distance is directly related to transportation costs, which generally represent the largest proportion of the total costs of the reverse logistics operation (DOAN et al., 2019). Also, the presence of WPCB primary logistics agents in each municipality was considered as the higher distances between generation points and recycling industries can make recycling less beneficial to the environment (NILSSON et al., 2017), especially in terms of GHG emissions and energy expenditure derived from the transport of these materials.

The economic indicators were based on the gross domestic product (GDP) per capita, especially because of the direct relation between the e-waste generation and the wealth level of a certain community (KUMAR et al., 2017). The municipal financial incentives to the industry and the Industrial Transformation Value (ITV) in the electronics sector was considered in this analysis as mechanisms that encourage the recycling industry in such municipalities. As environmental indicators, the existence of a reverse logistics system (RLS) for e-waste in the municipality and the adoption of a municipal waste management plan (MWMP) were relevant indicators of more suitable locations.

Finally, the Municipal Human Development Index (HDI), which measures social and economic development in populations, and the Basic Education Development Index (BEDI), related to the level of basic education, were the social indicators chosen as they point out the quality of life of the population in the assessed municipalities. Most of these indicators were also adopted in the study of Ottoni (2021).

The obtained secondary data of the indicators of **Table 1** was organized in Excel spreadsheets and converted into shapefiles format, to be further processed in ArcGIS software. Maps were generated to help the analysis of the best locations for implementing the advanced recycling plants.

The scoring point method for ranking the most favourable municipalities was based on the type of answer of each indicator. In the cases in which the indicators present the metric of YES/NO answers, the municipalities with NO as the answer were excluded from the analysis, and YES answers corresponded to the highest weights in that category to inform that the city meets the criteria of the indicator analyzed. The score zero was used for "not informed" or real zero values.

When the indicators presented the metrics based on numeric values, such data were scaled in ranges (1-10, in case of 10 cities to be analyzed, or 1-8, if eight cities were assessed, and so on). The Increasing Indicators represented those that increase the chances of the municipality to be chosen as the most favourable to receive a recycling facility, as in the case of WPCB generation, WPCB Primary logistics agents, GDP per capita, Electronics ITV, HDI and BEDI. The higher the value of the increasing indicator, the more favourable that municipality is, and, therefore, the higher the score it will receive. On the other hand, the Decreasing Indicator (in this case, Distance from the hotspot city), the lower the values, the higher the score the municipality will have on that indicator. For logistics purposes, the "Distance from the hotspot city" must be the minimum possible to reduce transportation costs and environmental impacts. In the case of tied indicator values, the scores are also tied. For example, if two cities in a group of 10 assessed cities had the same value of WPCB generation and these were the highest values of the sample, both cities would receive 9 as a score for this indicator since there was a tie (both cities must have the same score) and the lowest value of this indicator should be 1. Therefore, a score of 10 would be no longer possible in this example.

The total sum of the weights of each indicator provided the order of the most favourable municipalities, considering the preference for the highest sum. That is, the municipality with the highest total score would be the most suitable for implementing the WPCB recycling unit.

4. Results and Discussion

4.1. Brazilian WPCB overview

The current Brazilian outlook on WPCB generation and the main primary logistics agents' distribution along the Brazilian states were described in the map of **Figure 2 (a)**, and the comparison of these values in the biggest municipalities was represented in **Figure 2 (b)**.

Figure 2(a) emphasises the relevant concentration of companies working with WPCB especially in the axis Southeast-South regions, with its main pole in the state of São Paulo (SP). The total WPCB generation in Brazil can be estimated at 176.2 t/d, which corresponds to 64.3 kt per year, with different generation scenarios according to each state's specificities. The smallest generators are concentrated in the North region, reaching 1.9 t per day. States in the Midwest (13.66 t/d), South (25.14 t/d) and Northeast (47.85 t/d) regions generate higher estimated quantities of WPCB. Finally, most of the states in the Southeast region (74.09 t/d) and one state in the Northeast (Bahia) can be categorized as the highest WPCB generators.

Figure 2 – Brazilian overview: (a) Map of WPCB generation and primary logistics agents' distribution along with the states; (b) Graph with the comparison of WPCB generation levels and WPCB recyclers in the biggest municipalities

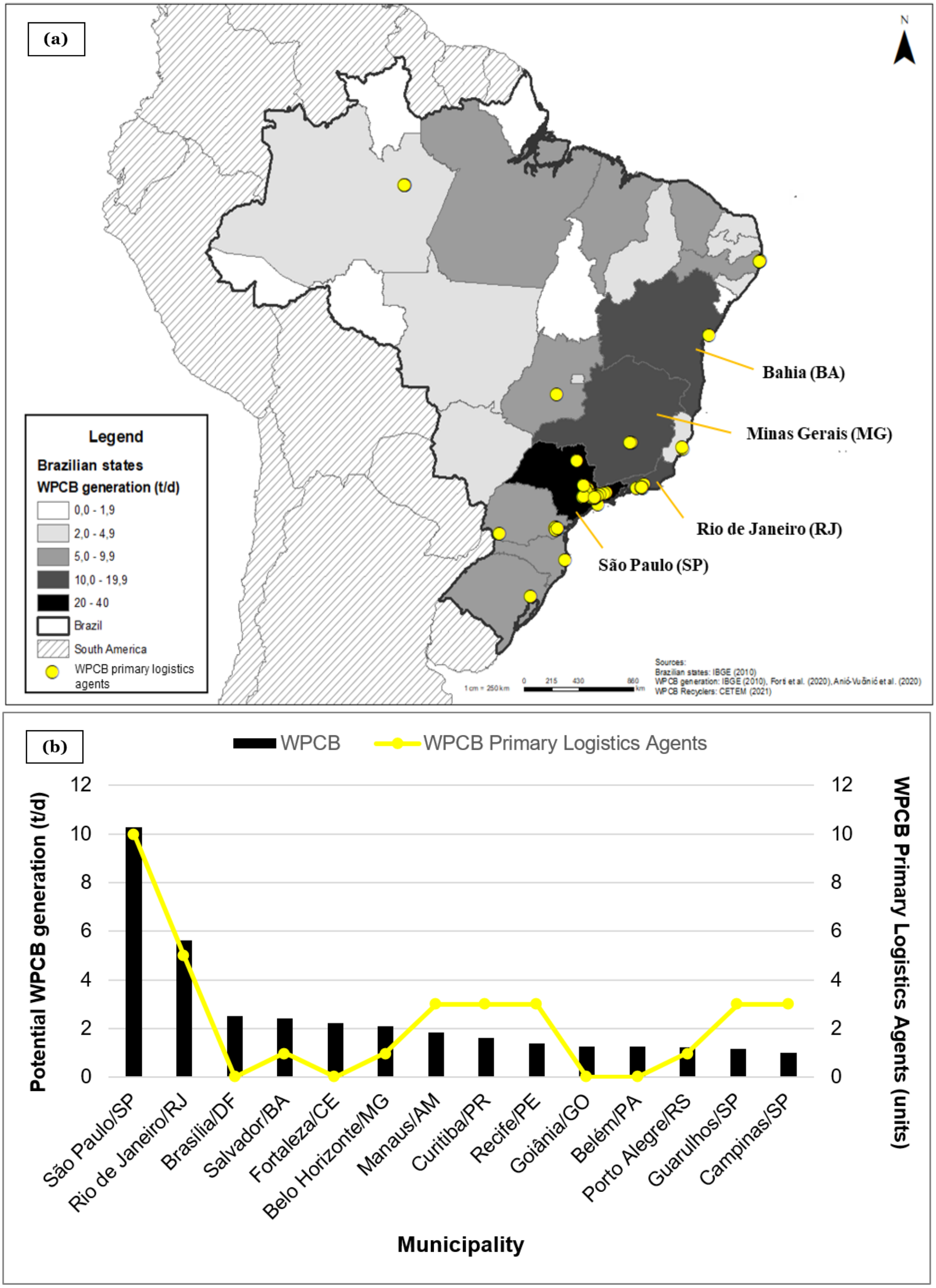

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Figure 2 (b) highlighted the Brazilian municipalities with WPCB generation above 1 t/d, in a total of 14 municipalities. From this sample, the city of São Paulo (capital of São Paulo state) and the city of Rio de Janeiro (capital of Rio de Janeiro state) remain the potential biggest WPCB generators (more than 10 t/d and 5 t/d, respectively) in the country and pursue the highest numbers of identified WPCB recyclers when compared to the other assessed cities. Some cities had a higher number of WPCB recyclers, even with a lower generation when compared to São Paulo and Rio de Janeiro, but it might be a result of the more intense exportation activities of the WPCB formal chain (in the case of Manaus, Curitiba and Recife) and the proximity with São Paulo city as the biggest WPCB generation pole (in the case of Guarulhos and Campinas). Therefore, São Paulo prevails as the biggest WPCB municipal hotspot in the country and is located in the state that detains the most advanced infrastructure for WPCB recycling in the Brazilian context, which, even so, reaches only until the intermediate recycling levels, as confirmed by the literature (AFONSO, 2018; DIAS et al., 2018; LOPES DOS SANTOS, 2020).

From the total WPCB generation value, 21.9% is generated in SP, with an estimated generation of 38.5 t/d, followed by Minas Gerais/MG (10.1%), Rio de Janeiro/RJ (8.2%) and Bahia/BA (7.1%). Considering the distribution of the total of 57 main WPCB primary logistics agents considered in this scope, 31 are established in SP, followed by RJ and Paraná (PR), which detain six companies each. These data can be contrasted with the state GDP per capita values, in which the Federal District, SP and RJ represent the highest values in this indicator (IBGE, 2018). MG (10°) and PR (6°) are also representatives in the list of the biggest GDP per capita values by state in Brazil (IBGE, 2018). This fact suggests that these states have a higher potential to generate WPCB given the direct relationship between GDP and e-waste generation (KUMAR et al., 2017) and that these WPCB recyclers are distributed in a more favourable way considering these potential hotspots.

Therefore, as shown in Figures 2 (a) and (b), SP (and São Paulo city) can be considered the main identified pole in terms of the estimated values on daily WPCB generation and the localization of the recyclers, which might indicate the biggest market interests and infrastructure for WPCB processing. Currently, the WPCB flow generated in the country is mostly drained to SP and some other states in the coastal portion of the country with the purposes of exportation by sea transport to the smelters and refineries in Europe, Canada, and Japan, that perform the WPCB advanced recycling, as already stated in previous studies (DIAS et al., 2018; LOPES DOS SANTOS, 2020; OTTONI, 2021; SOUZA, 2019). The state of SP is the most populous and with the highest concentration of economic activities in Brazil (DALMO et al., 2019), which possibly contributes to this favourable scenario for e-waste processing in the state.

4.2. Assessment of best municipalities and units' size

Considering SP as the main adequate pole for WPCB processing, the total of 5570 municipalities in Brazil were filtered to a list of 645 municipalities of SP. From this new scope, the ones with WPCB generation lower than 0.1 t/d (very low generation) were excluded from the analysis, resulting in 56 available municipalities. The cities without a municipal waste management plan, municipal financial incentives for industry, and the ones out of the reverse logistics system's official list were also discarded from the sample, which reduced the list to 35 possible municipalities. As further cut-off criteria, the municipalities with BEDI lower than 4.1 were also excluded, for ensuring cities with higher education levels, and GDP per capita higher than US$ 7,000. The remaining 17 municipalities were individually assessed, and those with at least three low values in comparison to the others in any of the indicators presented in **Table 1** were excluded. The results pointed to eight final cities with the potential to attract recycling units, according to the selected sustainability criteria, as presented in **Table 2**.

The indicator values were measured or identified according to the respective data source and city specificities, while the score values were assigned according to the relative importance of the indicator value in the set of indicators analyzed. In the WPCB generation, for example, São Caetano do Sul received the lowest value according to the generation among the evaluated cities, and Campinas received the best score in the same set.

As highlighted in **Table 2**, the eight municipalities were ranked in a scoring system, according to the values of each adopted indicator, from weight 8 (highest score) to 1 (lowest score), in the absence of tied values.

The biggest WPCB generators from the remaining sample were the municipalities of Campinas (0.91 t/d), São Bernardo do Campo (0.64 t/d) and Santo André (0.57 t/d). These three municipalities and São Caetano do Sul are close to São Paulo city, which was identified as the biggest WPCB generator in Brazil, and, therefore, can guarantee the daily supply of the recycling unit with collected WPCB. The stretch between Campinas and São Paulo can be done in about 1 hour and 30 minutes in normal traffic conditions (93.8 km), and this distance in terms of the time of transportation is even lower for São Bernardo do Campo and Santo André (approximately 50 min each, in 19.6 km and 21 km, respectively). Although São Caetano do Sul is the smallest generator in the selected group in **Table 2**, it is the closest municipality to São Paulo (14.2 km, or about 40 min of distance in normal traffic conditions), and, thus, could be considered a good option.

From the filtered list of the main WPCB primary logistics agents, eight of them are distributed in the eight selected municipalities. Other municipalities had WPCB primary logistics agents identified but were also cut off for not meeting the minimum criteria established in one or more indicators. Campinas was the municipality with more WPCB primary logistics agents identified (3 units), followed by Sorocaba (2 units), Jundiaí (1 unit), Barueri (1 unit) and Americana (1 unit). The three remaining municipalities did not have relevant WPCB recyclers identified, as consulted in the DAT4RE project list (CETEM, 2021). The proximity of the recycling unit to the primary logistics agents is important since such companies process or participate in other stages of WPCB management (collection, transport, storage), which is a positive criterion to be considered in logistics planning. Considering that the primary logistics agents are also mostly close to the generation hotspots for logistics and financial purposes, the proximity of the recycling units and the primary logistics agents is according to the study of ABALANSA et al. (2021), which has stated that waste management facilities should be installed closer to where the waste is generated to also avoid negative environmental impacts.

Table 2 – The eight most favourable municipalities for implementing a WPCB advanced recycling unit in Brazil and their metrics

Municipality	Logistics						Economic					
	WPCB generation (t/d)	Score	Distance from São Paulo city (km)	Score	WPCB Primary logistics agents (unit)	Score	GDP per capita (US$)	Score	Incentive for Industry	Score	Electronics ITV (%)	Score
São Caetano do Sul	0.13	1	14.2	8	0	0	15,094.88	6	Yes	1	0.4	1
Jundiaí	0.31	4	59.0	4	1	1	18,933.78	7	N.I.	0	11.4	4
Campinas	0.91	8	93.8	3	3	3	9,255.14	3	Yes	1	22.2	5
São Bernardo do Campo	0.64	7	19.6	7	0	0	10,924.06	5	Yes	1	0.4	1
Barueri	0.20	3	31.2	5	1	1	33,548.82	8	N.I.	0	2.2	2
Sorocaba	0.49	5	101.0	2	2	2	9,390.44	4	Yes	1	10.2	3
Santo André	0.57	6	21.0	6	0	0	7,288.06	1	Yes	1	0	0
Americana	0.18	2	130.0	1	1	1	8,602.83	2	Yes	1	0	0

Municipality	Environmental				Social				TOTAL
	RLS	Score	MWMP	Score	HDI (0-1)	Score	BEDI (0-10)	Score	
São Caetano do Sul	Yes	1	Yes	1	0.862	7	4.9	6	32
Jundiaí	Yes	1	Yes	1	0.822	6	4.5	3	31
Campinas	Yes	1	Yes	1	0.805	3	4.1	1	29
São Bernardo do Campo	Yes	1	Yes	1	0.805	3	4.1	1	27
Barueri	Yes	1	Yes	1	0.786	1	4.6	4	26
Sorocaba	Yes	1	Yes	1	0.798	2	4.4	2	23
Santo André	Yes	1	Yes	1	0.815	5	4.1	1	22
Americana	Yes	1	Yes	1	0.811	4	4.7	5	18

Font: the authors, 2023.

The biggest GDP per capita on the list in **Table 2** was found in Barueri (US$ 33,548.82), followed by Jundiaí (US$ 18,933.78) and São Caetano do Sul (US$ 15,094.88). Higher municipal GDP per capita values indicate more developed municipalities, which would be more favourable locations for the recycling unit, especially considering the demonstrated intrinsic relationship between GDP and e-waste generation (AWASTHI et al., 2018; KUMAR et al., 2017; XAVIER et al., 2021).

Only two of the eight final municipalities did not inform the existence of incentives (such as reduction or exemption of Urban Property Tax) in the Brazilian Institute of Geography and Statistics (IBGE) database (Jundiaí and Barueri), but since these cities presented relevant values in the other indicators, they were not excluded from the detailed analysis. For this indicator, only the answers "no" were excluded from the sample.

The participation of the SP industry in the activities of computer, electronic and optical equipment has increased (from 44.0% to 50.1%) between 2003 and 2016 (SEADE, 2019), a fact that reinforces the idea that this state may be the main pole for the reverse electronics industry in the country. Campinas (22.2%), Jundiaí (11.4%) and Sorocaba (10.2%) were the cities with the highest electronics ITV in the entire state. Other municipalities in the state also contributed, as in the case of Hortolândia (8.9%), but were excluded because of lower values in other indicators.

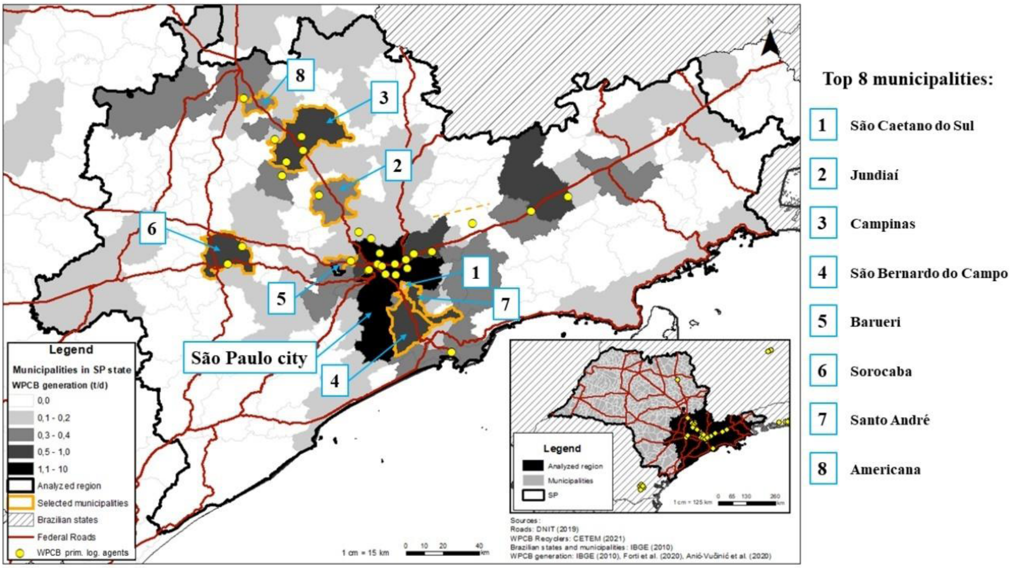
Regarding the environmental factors, only the municipalities considered in the official list of the Sectoral Agreement for post-consumer electronics products for reverse, as reinforced in Federal Decree No 10,240 (BRAZIL, 2020), and the ones with a published municipal waste management plan (MWMP) were selected. Since all the eight most favourable municipalities fulfilled these two requirements, they all received the same weight (1). These indicators were fundamental for pointing out the municipalities with minimum infrastructure related to waste management and reverse logistics, which might guarantee better conditions for a recycling plant. The cities listed in the Decree No. 10,240 as target municipalities of the e-waste reverse logistics system would be equipped with collection points for these wastes and specialized teams will be responsible for collecting and disposing of these materials for value recovery (BRAZIL, 2020). Regarding the waste management plans (WMP), according to Ottoni et al. (2021), these documents support the waste managers in organizing solutions for waste in a holistic context, and they can, therefore, prepare the municipalities for best practices to increase the value recovery potential of the generated waste.

The social dimension analysis included two main indicators. From **Table 2**, the values of the human development index (HDI) of the eight most favourable municipalities were all close to 0.8, which is considered a high level and indicates more developed cities. However, the basic education development index (BEDI) for all eight and other municipalities in SP presented values below 7.0 on a scale from 0 to 10, in which the better the performance of students and approved students, the higher the BEDI (INEP, 2018). Thus, basic education seems to be a challenge at a national level, which, as stated by Schwartzman (2003) might be related to quality, equity, and inappropriate use of resources in the country. Of the top eight municipalities in **Table 2**, São Caetano do Sul

(4.9), Americana (4.7) and Barueri (4.6) presented the highest BEDI values.

The total sum of the weights for each indicator in **Table 2** pointed to the order of the most favourable municipalities in Brazil for implementing an advanced recycling unit from WPCB, as geographically illustrated in **Figure 3**.

Figure 3 – The most favourable municipalities for implementing a WPCB advanced recycling unit in Brazil



Font: the authors, 2023

The map in **Figure 3** highlighted the geographic distribution of the most favourable municipalities, besides the main primary logistics agents, main roads and the municipal WPCB generation for each alternative in greyscale, considering that the biggest generators have a darker colour. Therefore, the municipality of São Caetano do Sul was identified as possibly the best option in terms of logistics and sustainability for implementing the WPCB processing unit, followed by Jundiaí, Campinas, São Bernardo do Campo, Barueri, Sorocaba, Santo André and Americana.

The sum of the WPCB estimated generation of the biggest generators in a ratio of 190 km from São Caetano do Sul indicates the potential daily capacity of about 24 t/d, considering a simplified scenario in which almost 100% of the generated WPCB amount is collected and transported to the processing unit in São Caetano do Sul. However, since such collection rates are not a reality in Brazil, the considered daily capacity of a first advanced recycling unit should be smaller to avoid economic losses and guarantee that the minimum quantities supply continuous recycling processing. On the other hand, these recycling plants might consider receiving other types of feed material from industrial waste, by-products from other non-ferrous industries and consumer recyclables besides the WPCB, such as car exhaust catalysts (HAGELÜKEN, 2006).

Therefore, the determination of the recycling unit's capacity might consider the local availability of other inputs to increase the potential gains and benefits generated from such plants. Also, the e-waste advanced recycling in Brazil must be necessarily linked to the development of the RLS in the country (OTTONI, 2021), aiming at achieving higher rates of collected e-waste to supply the reverse chain. The public policies to encourage the recycling chain, as well as the legal mechanisms for assigning responsibility to producers to properly pay for investments in reverse logistics systems are basic requirements for the completion and expansion of the formal recycling market, especially in developing countries.

4.3. Limitations and practical implications of the methodology

Even though the adopted methodology for assessing the best locations for e-waste processing applied to the Brazilian case has considered varied aspects of economic, social, environmental and logistics dimensions, some limitations should be highlighted as possible topics to be addressed in future related research, namely:

• **Estimated e-waste generation data:** As the values of e-waste/WPCB generation data were estimated due to the lack of an official database in Brazil, the results might not represent the real context of the country's e-waste urban mines. This can also be a problem in other developing countries without an official e-waste database. Therefore, future studies that repeat this method with realistic e-waste generation quantities might have different conclusions on the best locations for e-waste processing.

• **Scoring system for each criterion:** The adopted scoring system for the sustainability assessment of best municipalities considered that the final score is obtained by a simple sum of the scores for each metric, and, therefore, some metrics contribute more to the final score than others, as in the case of the logistics, economic and social aspects over the environmental ones. This choice was taken given the lack of practical and available ways to measure the quality performance of the environmental criteria (municipality considered in the Sectoral Agreement for electronics reverse logistics system – RLS, existence of Municipal Waste Management Plan - MWMP). In these indicators, the values were measured as YES/NO answers instead of a qualitative numerical gradation, as in the other indicators. Future adaptations of this method might consider adding new criteria that could be measured in a qualitative numerical range to better compare and equally influence the final score. Also, next studies could test other different metrics for weighting the indicators instead of assuming values based on the total number of municipalities analyzed, as this could generate an imbalance in the case of assessing a larger number of cities.

• **Correlation between the indicators' dimensions:** some of the chosen indicators from different dimensions (e.g., 'logistics', 'environmental', 'economic', 'social') can be related and, then, influence the final results of other metrics. For instance, the distance from each municipality to São Paulo city (logistics) may also be related to less fuel consumption and also to lower emissions, therefore contributing positively to environmental metrics. Therefore, a more in-depth look at this aspect of the correlation between indicators of this method should be a possible subject for future research.

As practical implications of the application of this methodology in developing countries, this study showed that strategic planning for effective reverse logistics in the long term is essential for implementing complete e-waste urban mining in these nations. Besides, the challenges of establishing more realistic methods for assessing the best e-waste processing locations were highlighted.

The methodology for identifying the most favourable e-waste processing locations adopted in this case study in Brazil can also be implemented in other developing countries, especially those with greater e-waste generation. This can be seen as a strategy to improve economic, environmental and social development, reduce informal and primitive e-waste treatment, and, therefore, address the e-waste problem in the developing world.

5. Conclusion

The present study addressed the problem of e-waste value transferring by exporting WPCB from developing countries to processing industries in developed countries overseas. For this purpose, this study proposed a methodological procedure for logistics and sustainable assessment to identify the main potential e-waste/WPCB processing favourable locations. The application of this methodology in Brazil, which has the potential to generate about 64 kt/year of WPCB, indicated the eight most suitable locations to implement WPCB advanced recycling units through sustainability and logistics criteria, highlighting the municipalities of São Caetano do Sul, Jundiaí and Campinas. This study also pointed out a potential generation of 24 t/d of WPCB in this hotspot adjacencies and expressive GDP values that might indicate higher e-waste consumption. These facts justify the concentration of processing units in the region to supply the high local demand and can be the initial spot for e-waste value recovery planning and integrated management in the country.

Finally, the findings suggested that e-waste facilities are feasible to be located in Brazil to improve the value recovered from e-waste streams. It was also indicated that the location of WPCB facilities in a specific region of São Paulo state (considering three main municipalities) would absorb production from the surrounding region and, in this way, make processing in small-scale units viable.

The consideration of decentralized and smaller units (as in the case of the micro-factories, for instance) in strategic locations for WPCB processing can be another possible solution to be assessed. From a managerial perspective, this decentralized strategy can represent reduced costs and environmental impacts related to transportation given the short distances from hotspots to recyclers. However, it needs to be studied in more detail in future research.

The limitations of this study were mainly based on the estimated values of e-waste/WPCB generation data due to the lack of an official database in Brazil for such purposes, which can also be a problem in other developing countries without an official e-waste database. Also, the adopted scoring system for the sustainability assessment of best municipalities could be improved with other indicators as more information is added to an official database, and other different weighting methods could be further tested, analyzed and compared in the following steps. Since this paper focused on a logistics feasibility approach, an agenda for future studies should include a more detailed analysis of centralized and decentralized units' sizes, besides an economic and technical feasibility assessment of the best metallurgical routes for WPCB value recovery in Brazil and other developing countries to help improve sustainability and circularity levels of the electronics sector in these nations.

This study contributed to the understanding that complete e-waste urban mining is possible and desirable for increasing the levels of circularity and sustainability in developing countries. Nonetheless, it depends on strategic planning for effective reverse logistics in the long term, besides public policies to encourage waste value recovery options.

Acknowledgement

The authors would like to thank the Brazilian Council for Scientific and Technological Development (CNPq) for the scholarship No 132388/2020-0 to the first author.

References

ABALANSA, S., MAHRAD, B. El, ICELY, J., *et al.* "Electronic waste, an environmental problem exported to developing countries: The good, the bad and the ugly", **Sustainability (Switzerland)**, v. 13, n. 9, p. 1–24, 2021. DOI: 10.3390/su13095302. .

AFONSO, J. C. "Waste electrical and electronic equipment: The Anthropocene knocks on our door", **Revista Virtual de Quimica**, v. 10, n. 6, p. 1849–1897, 2018. DOI: 10.21577/1984-6835.20180121.

ARAUJO, R. A. de, XAVIER, L. H. "Banco de dados e estudo geoespacial de organizações do segmento de resíduos eletroeletrônicos no Brasil.", **Série Jornada de iniciação Científica**, p. 199–203, 2019. Available at: https://www.cetem.gov.br/jornadas/jornada-de-iniciacao-cientifica/itemlist/category/108-2019?start=10.

AWASTHI, A. K., CUCCHIELLA, F., D'ADAMO, I., *et al.* "Modelling the correlations of e-waste quantity with economic increase", **Science of the Total Environment**, v. 613–614, p. 46–53, 2018. DOI: 10.1016/j.scitotenv.2017.08.288.

AWASTHI, A. K., LI, J. "Sustainable Bioprospecting of Electronic Waste", **Trends in Biotechnology**, v. 37, n. 7, p. 677–680, 2019. DOI: 10.1016/j.tibtech.2019.03.004.

BRAZIL. **Federal Decree No. 10,240, of February 12, 2020. Regulates item VI of the caput of art. 33 and art. 56 of Law No. 12,305, of August 2, 2010, and complements Decree No. 9,177, of October 23, 2017, regarding the implementation of a reverse logistics system**. 2020. Available at: http://www.planalto.gov.br/ccivil_03/_ato2019-637 2022/2020/decreto/D10240.htm (accessed on: 13 Dec. 2020).

CETEM – CENTER FOR MINERAL TECHNOLOGY. **Recicladores (Recyclers)**. 2021. Available at: https://www.cetem.gov.br/reminare/recicladores (accessed on: 10 Feb. 2021).

CHEN, M., OGUNSEITAN, O. A., WANG, J., *et al.* "Evolution of electronic waste toxicity: Trends in innovation and regulation", **Environment International**, v. 89–90, p. 147–154, 2016. DOI: 10.1016/j.envint.2016.01.022.

DA SILVA, J. R. A., AUGUSTO, J., BEZANA, T., *et al.* "Rematronic: Project to recovery precious metals from electronic waste", **7th International ACM Conference on Management of Computational and Collective Intelligence in Digital EcoSystems, MEDES 2015**, n. June 2016, p. 221–227, 2015. DOI: 10.1145/2857218.2857268.

DALMO, F. C., SIMÃO, N. M., LIMA, H. Q. de, *et al.* "Energy recovery overview of municipal solid waste in São Paulo State, Brazil", **Journal of Cleaner Production**, v. 212, p. 461–474, 2019. DOI: 10.1016/j.jclepro.2018.12.016. .

DEMAJOROVIC, J., AUGUSTO, E. E. F., DE SOUZA, M. T. S. "Reverse logistics of E-waste in developing countries: Challenges and prospects for the Brazilian model", **Ambiente e Sociedade**, v. 19, n. 2, p. 117–136, 2016. DOI: 10.1590/1809-4422ASOC141545V1922016.

DIAS, P., MACHADO, A., HUDA, N., *et al.* "Waste electric and electronic equipment (WEEE) management: A study on the Brazilian recycling routes", **Journal of Cleaner Production**, v. 174, p. 7–16, 2018. DOI: 10.1016/j.jclepro.2017.10.219. .

DNIT – BRAZILIAN DEPARTMENT OF INFRASTRUCTURE OF TRANSPORT. **Sistema Nacional de Viação (Brazilian National Road System)**. 2019. Available at: http://servicos.dnit.gov.br/vgeo/ (accessed on: 13 Feb. 2021).

DOAN, L. T. T., AMER, Y., LEE, S., *et al.* "E-Waste Reverse Supply Chain : A Review and Future Perspectives", **applied sciences**, v. 9, n. 5195, p. 1–28, 2019. DOI: 10.3390/app9235195.

FORTI, V., BALDÉ, C. P., KUEHR, R., *et al.* **The Global E-waste Monitor 2020: Quantities, Flows, and the Circular Economy Potential**. [S.l: s.n.], 2020.

GHIMIRE, H., ARIYA, P. A. "E-Wastes: Bridging the Knowledge Gaps in Global Production Budgets, Composition, Recycling and Sustainability Implications", **Sustainable Chemistry**, v. 1, n. 2, p. 154–182, 2020. DOI: 10.3390/suschem1020012. .

GHOSH, B., GHOSH, M. K., PARHI, P., *et al.* "Waste Printed Circuit Boards recycling: An extensive assessment of current status", **Journal of Cleaner Production**, v. 94, p. 5–19, 2015. DOI: 10.1016/j.jclepro.2015.02.024.

HABIB, A., BHATTI, H. N., IQBAL, M. “Metallurgical Processing Strategies for Metals Recovery from Industrial Slags”, **Zeitschrift fur Physikalische Chemie**, v. 234, n. 2, p. 201–231, 2020. DOI: 10.1515/zpch-2019-0001.

HAGELÜKEN, C. “Recycling of Electronic Scrap At Umicore Precious Metals”, **Acta Metallurgica Slovaca**, v. 12, n. June 2006, p. 111–120, 2006.

HAO, J., WANG, Y., WU, Y., GUO, F. “Metal recovery from waste printed circuit boards: A review for current status and perspectives”, **Resources, Conservation and Recycling**, v. 157, 104787, 2020. https://doi.org/10.1016/j.resconrec.2020.104787.

HONDA, S., KHETRIWAL, D. S., KUEHR, R. **E-WASTE MONITOR**. . [S.l: s.n.], 2016.

IBGE - BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS. **Basic Municipal Information Survey - MUNIC (Pesquisa de Informações Básicas Municipais - MUNIC)**. 2019. Available at: https://www.ibge.gov.br/estatisticas/sociais/educacao/10586-pesquisa-de-informacoes-basicas-municipais.html?=&t=resultados (accessed in: 10 Feb. 2021).

IBGE - BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS. **Census 2010**. 2010. Available at: https://censo2010.ibge.gov.br/materiais/guia-do-censo/operacao-censitaria.html (accessed on: 10 Feb. 2021).

IBGE - INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA. **Sistema de Contas Regionais (Regional Accounts System: Brazil 2019)**. **Ibge**. [S.l: s.n.], 2018. Available at: https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9054-contas-regionais-do-brasil.html?=&t=o-que-e.

IBGE – BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS. **Cidades@ - Produto Interno Bruto dos Municípios (Cities@ - Gross Domestic Product of Municipalities)**. 2017. Available at: https://cidades.ibge.gov.br/ (accessed in: 10 Feb. 2021).

ILANKOON, I. M. S. K., GHORBANI, Y., CHONG, M. N., *et al.* “E-waste in the international context – A review of trade flows, regulations, hazards, waste management strategies and technologies for value recovery”, **Waste Management**, v. 82, p. 258–275, 2018. DOI: 10.1016/j.wasman.2018.10.018.

INEP - BRAZILIAN INSTITUTE OF EDUCATIONAL STUDIES AND RESEARCH ANÍSIO TEIXEIRA. Índice de Desenvolvimento da Educação Básica – IDEB 2017 (Basic Education Development Index). 2018. Available at: http://portal.inep.gov.br/artigo/-/asset_publisher/B4AQV9zFY7Bv/content/id/1511536 (accessed in: 10 Feb. 2021).

KAYA, M. **Current WEEE recycling solutions**. [S.l.], Elsevier Ltd, 2018. Available at: http://dx.doi.org/10.1016/B978-0-08-102057-9.00003-2.

KAYA, M. **Industrial-Scale E-Waste / WPCB Recycling**. [S.l: s.n.], 2019.

KAYA, M. **Waste Printed Circuit Board (WPCB) Recovery Technology: Disassembly and Desoldering Approach.** [S.l.], Elsevier Ltd., 2020a. Available at: http://dx.doi.org/10.1016/

B978-0-12-803581-8.11246-9.

KAYA, M. **Waste Printed Circuit Board (WPCB) Recycling: Conventional and Emerging Technology Approach**. [S.l.], Elsevier Ltd., 2020b. Available at: http://dx.doi.org/10.1016/B978-0-12-803581-8.11296-2.

KHALIQ, A., RHAMDHANI, M. A., BROOKS, G., *et al.* "Metal extraction processes for electronic waste and existing industrial routes: A review and Australian perspective", **Resources**, v. 3, n. 1, p. 152–179, 2014. DOI: 10.3390/resources3010152.

KIDDEE, P., NAIDU, R., WONG, M. H. "Electronic waste management approaches: An overview", **Waste Management**, v. 33, n. 5, p. 1237–1250, 2013. DOI: 10.1016/j.wasman.2013.01.006.

KUMAR, A., HOLUSZKO, M., ESPINOSA, D. C. R. "E-waste: An overview on generation, collection, legislation and recycling practices", **Resources, Conservation and Recycling**, v. 122, p. 32–42, 2017. DOI: 10.1016/j.resconrec.2017.01.018.

LOPES DOS SANTOS, K. "The recycling of e-waste in the Industrialised Global South: the case of Sao Paulo Macrometropolis", **International Journal of Urban Sustainable Development**, v. 00, n. 00, p. 1–14, 2020. DOI: 10.1080/19463138.2020.1790373.

LUNDGREN, K. **The global impact of e-waste: Addressing the challenge**. [S.l: s.n.], 2012.

MAGODA, K.; MEKUTO, L. "Biohydrometallurgical Recovery of Metals from Waste Electronic Equipment: Current Status and Proposed Process", *Recycling* 2022, 7, 67. https://doi.org/10.3390/recycling7050067

MISHRA, G., JHA, R., RAO, M. D., *et al.* "Recovery of silver from waste printed circuit boards (WPCBs) through hydrometallurgical route: A review", **Environmental Challenges**, v. 4, n. March, p. 100073, 2021. DOI: 10.1016/j.envc.2021.100073. .

MOTTA, L. B., BARRETO, R. da C. "Indicadores para análise da gestão de resíduos eletroeletrônicos em instituições públicas e privadas", **XXVIII Encontro Nacional de Tratamento de Minérios e Metalurgia Extrativa**, n. July, 2019. DOI: 10.13140/RG.2.2.23009.04963. Available at: http://www.entmme2019.entmme.org/trabalhos/156.pdf.

NILSSON, A. E., ARAGONÉS, M. M., TORRALVO, F. A., *et al.* "A review of the carbon footprint of Cu and Zn production from primary and secondary sources", **Minerals**, v. 7, n. 9, 2017. DOI: 10.3390/min7090168.

NING, C., LIN, C. S. K., HUI, D. C. W., *et al.* "Waste Printed Circuit Board (PCB) Recycling Techniques", **Topics in Current Chemistry**, v. 375, n. 2, 2017. DOI: 10.1007/s41061-017-0118-7. .

OTTONI, M. de S. O. **ASSESSMENT OF A REVERSE LOGISTICS FRAMEWORK FOR WASTE PRINTED CIRCUIT BOARDS (WPCB) IN BRAZIL**. 2021. 173 f. 2021. Available at: http://www.ppe.ufrj.br/images/publicações/doutorado/Dissertação_Marianna_Ottoni.pdf.

OTTONI, M., DIAS, P., XAVIER, L. H. "A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil", **Journal of Cleaner Production**, v. 261, p. 120990, 2020. DOI: 10.1016/j.jclepro.2020.120990.

OTTONI, M., FONSECA, D. L., PERTEL, M. "Circularity and sustainability within waste management in universities: case study of waste management plans (WMPs) in Brazilian public universities", **International Journal of Sustainability in Higher Education**, 2021. DOI: 10.1108/IJSHE-02-2021-0064.

PETRIDIS, N. E., PETRIDIS, K., STIAKAKIS, E. "Global e-waste trade network analysis", **Resources, Conservation and Recycling**, v. 158, n. March, p. 104742, 2020. DOI: 10.1016/j.resconrec.2020.104742.

SAHAJWALLA, V., GAIKWAD, V. "The present and future of e-waste plastics recycling", **Current Opinion in Green and Sustainable Chemistry**, v. 13, p. 102–107, 2018. DOI: 10.1016/j.cogsc.2018.06.006.

SCHWARTZMAN, S., "The challenges of education in Brazil". **Oxford Studies in Comparative Education**, Oxford, UK., [s.n.], 2003. p. 44. Available at: http://www.schwartzman.org.br/simon/oxford/1_simon.pdf.

SEADE - STATE SYSTEM OF DATA ANALYSIS FOUNDATION (SÃO PAULO STATE). **Map of the Industry of São Paulo State 2003-2016**. 2019. Available at: https://www.seade.gov.br/wp-content/uploads/2019/04/MapaIndustria_abril2019.pdf. Acesso em: 10 fev. 2021.

SILVA, M. F., DUTRA, A. J. B., MANSUR, M. B. "Enrichment of copper, lead, and tin by mechanical dry processing of obsolete printed circuit board residues", **Materials Research**, v. 22, n. 5, p. 0–6, 2019. DOI: 10.1590/1980-5373-MR-2019-0341.

SILVAS, F. P. C., JIMÉNEZ CORREA, M. M., CALDAS, M. P. K., *et al.* "Printed circuit board recycling: Physical processing and copper extraction by selective leaching", **Waste Management**, v. 46, p. 503–510, 2015. DOI: 10.1016/j.wasman.2015.08.030.

SOUZA, R. G. **E-waste situation and current practices in Brazil**. [S.l.], INC, 2019. Available at: http://dx.doi.org/10.1016/B978-0-12-817030-4.00009-7.

TURAGA, R. M. R., BHASKAR, K., SINHA, S., *et al.* **E-Waste Management in India: Issues and Strategies**. [S.l: s.n.], 2019. v. 44.

XAVIER, L. H., GIESE, E. C., RIBEIRO-DUTHIE, A. C., *et al.* "Sustainability and the circular economy: A theoretical approach focused on e-waste urban mining", **Resources Policy**, n. August, p. 101467, 2019. DOI: 10.1016/j.resourpol.2019.101467.

XAVIER, L. H., OTTONI, M., LEPAWSKY, J. "Circular economy and e-waste management in the Americas: Brazilian and Canadian frameworks", **Journal of Cleaner Production**, v. 297, p. 126570, 2021. DOI: 10.1016/j.jclepro.2021.126570.

YOSHIDA, A., TERAZONO, A., BALLESTEROS, F. C., *et al.* "E-waste recycling processes in Indonesia, the Philippines, and Vietnam: A case study of cathode ray tube TVs and monitors",

Resources, Conservation and Recycling, v. 106, n. 2016, p. 48–58, 2016. DOI: 10.1016/j.resconrec.2015.10.020.

ZENG, X., YANG, C., CHIANG, J. F., *et al.* "Innovating e-waste management: From macroscopic to microscopic scales", **Science of the Total Environment**, v. 575, p. 1–5, 2017. DOI: 10.1016/j.scitotenv.2016.09.078.

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Submitted on: 29/07/2021
Accepted on: 10/01/2023
2023;26:e01073

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AMBIENTE & SOCIEDADE
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SciELO

Avaliação de sustentabilidade para alocação de unidades de processamento de resíduos de placas de circuito impresso: o caso brasileiro

Marianna Ottoni
Emilio Lèbre La Rovere
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Resumo: Placas de Circuito Impresso Residuais (PCIR) possuem elementos valiosos. Nos países em desenvolvimento, as PCIR são exportadas para tratamento pela ausência de recicladoras apropriadas, transferindo o alto valor agregado para os países desenvolvidos. Este estudo propôs um método para identificar os melhores locais para implantação de usinas de reciclagem de PCIR considerando critérios de sustentabilidade. O método foi aplicado ao Brasil e consistiu na análise estadual e municipal com base em 11 indicadores relacionados às dimensões da sustentabilidade, critérios logísticos e geoprocessamento. Os resultados sugeriram o estado de São Paulo (SP) como o principal polo de processamento de PCIR no Brasil, com geração estimada de quase 24 t/d, e São Caetano do Sul e Jundiaí como os principais municípios favoráveis à reciclagem de PCIR. Este estudo demonstrou que a logística sustentável para recuperação de valor das PCIR em países em desenvolvimento é possível e desejável para alcançar padrões mais circulares.

***Palavras-chave*:** Resíduos eletroeletrônicos (REEE); Placas de circuito impresso residuais (PCIR); Reciclagem; Mineração Urbana; Países em desenvolvimento.

São Paulo. Vol. 26, 2023
Artigo Original

AMBIENTE & SOCIEDADE
25 anos años years

Evaluación de la sostenibilidad para la asignación de unidades de procesamiento de residuos de placas de circuito impreso: el caso brasileño

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São Paulo. Vol. 26, 2023
Artículo Original

Resumen: Las Placas de Circuitos Impresos Residuales (PCIR) tienen elementos valiosos. En los países en desarrollo, los PCIR se exportan para su tratamiento debido a la ausencia de unidades de reciclaje adecuadas, transfiriendo el alto valor agregado a los países desarrollados. Este estudio propuso un método para identificar las mejores ubicaciones para la implementación de plantas de reciclaje de PCIR considerando criterios de sostenibilidad. El método fue aplicado al caso brasileño y consistió en análisis por 11 indicadores relacionados con las tres dimensiones de sostenibilidad, criterios logísticos y geoprocesamiento. Los resultados sugirieron el estado de São Paulo (SP) como el principal centro de procesamiento de PCIR en Brasil, y São Caetano do Sul y Jundiaí como los principales municipios favorables al reciclaje de PCIR. Este estudio demostró que la logística sostenible para la recuperación de PCIR en los países en desarrollo es posible y deseable para lograr patrones más circulares.

Palabras-clave: Residuos eléctricos y electrónicos (RAEE); Placas de Circuitos Impresos Residuales (PCIR); Reciclaje; Minería Urbana; Países en desarrollo.