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QUANTIFICATION AND CHARACTERIZATION OF WASTE ELECTRICAL AND ELECTRONIC EQUIPMENT DISPOSAL: A CASE STUDY FROM BRAZIL

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Abstract

This work presents a survey conducted in a middle-class region of the city of Caruaru (Brazil) in 2018/2019. In this study, questionnaires addressing consumer habits, characterization of electronic products, and socioeconomic data were received from 380 families. The characterization of electrical and electronic equipment considered the following eight devices: desktop computer, laptop, printer, tablet, mobile phone, CRT TV, LCD/Plasma TV, and LED TV. Descriptive statistics, Chi-square and Spearman's correlation tests, and Robinson's approach method were used in evaluating and analyzing the data obtained. The analysis of the questionnaires resulted in some important findings: (i) the interviewed families have between 5 and 16 electrical and electronic equipment (EEE) (in use and not in use) in their homes; the amount of EEE is strongly linked to the family income ranges; (ii) an average of 292,015 kg (4.70 kg/capita) of e-waste is generated from those eight devices each year by Caruaru households; and (iii) obsolescence and failure are the two main reasons for the end of the EEE' useful life, with obsolescence being the main reason for discarding mobile phones. The results of this survey, together with data collection made by the municipality itself, should assist in developing and implementing e-waste management actions that consider the collection, reuse, and recycling of electronic equipment.

Key words: Brazil, developing countries, E-waste management, quantification, WEEE characterization

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1. Introduction

Modern life has led to a growing use of electrical and electronic equipment and this has increased concern about the huge generation of e-waste (waste electrical and electronic equipment). With an increasing generation flow, e-waste ranges from large and small household appliances (such as fridge, air conditioner, TVs, laptops, mobile phones, toys, etc.) to automatic dispensers, which include all appliances that automatically deliver all types of products, such as hot drinks, bottles, cans, or money (see the complete and comprehensive definition in EU (2012)). A large part of e-waste is composed of printed circuit boards (PCBs) that are rich in valuable metals (Abdelbasir et al., 2018). Tunali et al. (2021) characterized heavy metals, precious metals and rare-earth elements of PCBs and screens from three sources of e-waste (old mobile phones, smartphones and laptops). The results showed that (i) copper (Cu), iron

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(Fe), zinc (Zn), nickel (Ni), lead (Pb) and aluminum (Al) were the main heavy metals; (ii) neodymium (Nd), silver (Ag) and gold (Au) were the main precious metals; and (iii) platinum (Pt), lanthanum (La), dysprosium (Dy), praseodymium (Pr) and cerium (Ce) were the main rare-earth elements found. PCBs of all samples showed higher amounts of elements compared to screens.

In recent years, several recycling techniques have been developed to recover valuable metals present in waste printed circuit boards, contributing to the reduction of pollution caused by this type of e-waste. According to Awasthi et al. (2017), these techniques involve the following processes: physical (manual dismantling, physical crushing or mechanical processes), chemical (usually using nitric acid, sulfuric acid and hydrogen peroxide as a chemical pretreatment agent), hydrometallurgical leaching separation (cyanide, thiourea, thiosulphate, halide and biological leaching) and pyrometallurgical separation (pyrolysis, vacuum pyrolysis and direct smelting). The first three processes are more sustainable and ecofriendly (Awasthi et al., 2017). According to Kaya (2019), pyrometallurgical treatment methods are used more commonly than hydrometallurgical methods, and aqueous recovery methods are gaining prominence in e-waste recycling. The main full-scale industrial e-waste recycling plants are Umicore’s Integrated Smelters-Refineries in Belgium (hydrometallurgy, electrometallurgy and pyrometallurgy); Aurubis Recycling Center in Germany (pyrometallurgy); DOWA Group in Japan (hydrometallurgy and pyrometallurgy); PCB Manufacturing Waste Recycling in Taiwan (hydrometallurgy and electrochemical process); and Rönnskar Smelter in Sweden (hydrometallurgy and pyrometallurgy).

Some elements present in e-waste are in great demand in illegal recycling markets in developing countries (Awasthi et al., 2016, 2018; Umair et al., 2015). However, e-waste has dangerous substances in its composition and its correct management is a cause for environmental and health concerns in some countries in Asia, Africa, and Latin America (Borthakur, 2020; Puangprasert and Prueksasit, 2019).

In the last decades, technological advances and the evolution of electronic products were unpredictable (Gurauskiene and Stasiskiene, 2018;Parajuly et al., 2020). In addition to the fast technological obsolescence of electronic devices, there is the perceived obsolescence that brings together a set of values attributed to the product that impels the consumer to change it, even when the product is still in perfect working order (Conceição et al., 2014). Some countries have been looking for solutions to minimize the problems caused by obsolescence. In the European Union, the Ecodesign Directive (Directive 2009/125/EC) established the extension of lifetime (expressed through minimum guaranteed lifetime, minimum time for availability of spare parts, modularity, upgradeability and reparability) as a parameter to minimize environmental impact (EU, 2009). In 2019, Directive 2009/125/EC was updated with the introduction of resource efficiency requirements. In 2020, the European Community approved the Circular Economy Action Plan, which, among other aspects, promises to restrict single-use technology and combat premature obsolescence (EU, 2020). The remanufacturing market, in which remanufactured products have a lower price, is an important approach to tackling obsolescence by developing countries. When formalized, this network for the recovery and production of manufactured goods can contribute to reducing environmental impacts and creating new jobs (Rivera and Lallmahomed, 2015).

This consumption trajectory has led to the generation of large amounts of e-waste and to the export of this waste from developed countries to poorer countries (Baidya et al., 2020; Baldé et al., 2017; Kiddee et al., 2013). In this sense, it is important to characterize and forecast the generation of e-waste so that this group of waste can be managed effectively and sustainably. Studies have been carried out in several countries to estimate the generation of e-waste, using methods generally based on sales/stock estimates, useful life, and average weight of the equipment, in addition to market conditions. Other studies, such as those by Baldé et al. (2017) and Forti et al. (2020), are based on two of the main global inventories: (i) the Global E-waste Statistics Partnership, which represents substantial efforts to expand national and regional capacities in e-waste statistics in several countries (GESP, 2021) and (ii) the Organization for Economic Co-operation and Development (OECD, 2021), the United Nations Statistics Division (UNSD, 2021) and the United Nations Economic Commission for Europe (UNECE, 2021), which used the measurement framework in pilots to collect global data on e-waste. Table 1 shows the details of some of the main studies on estimating waste production (location of research, methods used and main findings).

Brazil is the largest producer of e-waste in Latin America, with 2.14 Mt/year and 10.2 kg/inhabitant (Forti et al., 2020). However, the availability of qualitative and quantitative data on e-waste is still limited in Brazil. The Brazilian Electrical and Electronics Industry Association (ABINEE), a non-profit civil society that represents the electrical and electronic sectors in Brazil, publishes an annual document named “Economic Overview and Performance of the Sector” (ABINEE, 2020). This document provides performance indicators for the electrical and electronic industry, considering the sales and import and export markets for electronic equipment by area (industrial automation, electrical and electronics components, industrial equipment, IT products, telecommunications, household appliances, electrical material for installations and generation and transmission and distribution of electrical energy). The last “Economic Overview and Performance of the Sector” (ABINEE, 2020) showed that, from 2012 to 2019, there was a 62.53% drop in sales of desktops/laptops and a 3.12% and 177.46% increase in tablets and smartphone sales, respectively. Due to their multiple functions, the preference for smartphones is growing. In Brazil, data from CETIC (2020) shows that computers were responsible for 80% of access to the internet in 2015; in 2020, this share dropped to less than 40%. Smartphone internet access for shopping, work and academic activities is even greater for lower-income classes. The sale of smartphones has grown worldwide (Statista, 2021a), while PC sales are decreasing (Statista, 2021b). Tamimi et al. (2018) highlighted social (the need to follow the latest trends and influences), technical (easy usage, lightweight, design and functionality) and dependency factors (communication, study, work and social networks) as main factors of the preference for smartphones over PCs in Abu Dhabi (United Arab Emirates).

Table 1. Studies using methods for estimating e-waste production

Reference	***Location***	***E-waste Legislation***	***Method***	***Data Required***			***Main Findings***
				Sales	***Stock***	***Lifetime***	
Ravindra and Mor (2019)	Chandigarh (India)	The E-waste Management Rules (India, 2016)	*Questionnaire-based analysis*			✓	An annual generation of 4100 tons (17 kg per household) of e-waste was estimated from all the households of Chandigarh; results also indicated that about 63 tons of valuable heavy metals could be extracted annually, having the potential for urban mining, and may reimburse benefits of over \$65,000 per annum^{-1}.
Araujo et al. (2017)	Fernando de Noronha Island (Brazil)	BNPSW (Brazil, 2010)	*Robinson's approach*			✓	(i) Refrigerators were the most frequent EEE in homes; (ii) 1.3 tons of e-waste were estimated to be generated in a period of 1 year (2014–2015).
Cabral Neto et al. (2016)	Recife (Brazil)	BNPSW (Brazil, 2010)	*Time series model*	✓		✓	The study forecasted annual lead acid battery (LAB) scrap from 2016 to 2020; the number of vehicle sales grew at a relatively low rate (~8%) compared to the growth of generation of LAB scrap (~52%).
Alavi et al. (2015)	Ahvaz City (Iran)	-	*Consumption and use*		✓	✓	(i) The total number of discarded electronic items was 2,157,742 units (in 2011); (ii) the total generation of e-waste was 9952.25 metric tons per year (9.95 kg per capita per year); (iii) air conditioners were the most generated e-waste, followed by refrigerators and freezers, washing machines and televisions.
			Robinson's approach			✓	
Wang et al. (2013)	Netherlands	WEE Directive (EU, 2012)	*Time step*	✓	✓		The results demonstrated a significant disparity between different estimation methods arising from the use of data with distinct qualities.
			Simple delay	✓		✓	
Araújo et al. (2012)	Brazil	BNPSW (Brazil, 2010)	*Consumption and use*		✓	✓	A production of 709,012 tons per year (3.77 kg/capita/year) of e-waste was estimated.
			Time step	✓	✓		
Chung et al. (2011)	Hong Kong	Hong Kong Waste Reduction & Recycling (Hong Kong, 2013)	*Robinson's approach*			✓	A production of 80,443 tons (11.5 kg/capita) of e-waste was estimated in a period of 1 year.
Robinson (2009)	Global	-	*Robinson's approach*				(i) The global production of e-waste estimated was 20–25 million tons per year; (ii) Europe, the United States and Australasia stood out as the main producers of electronic waste; (iii) by 2020, China, Eastern Europe and Latin America will become major producers of e-waste.

Nevertheless, the speed of e-waste production in Brazil is not accompanied by an increase in management efficiency or by the production of technical-scientific data. There is still a limitation of national data on the production, sale and useful life of EEE, and consequently, there are few studies estimating the production of e-waste in Brazil. In this sense, estimating the generation potential of e-waste is an important step to better understand the reality and plan the actions necessary for the proper management of this type of waste. Most of the few studies estimating e-waste production in Brazil used data from the Brazilian Institute of Geography and Statistics (IBGE) to collect information about EEE present in households. This information is limited to determining the existence of EEE, not the amount of equipment present in each household. Examples of these studies include (i) Araújo at al. (2012), showing an estimate of e-waste generation for the whole of Brazil, and (ii) Franco andLange (2011) and Rodrigues (2015), who estimated the generation for Belo Horizonte and São Paulo, two capitals of highly developed states in the Southeast region of Brazil. Cabral Neto et al. (2016) estimated the generation of lead acid battery scrap in Brazil using data from the National Association of Vehicle Manufacturers. Araújo et al. (2017) estimated the production of e-waste for Fernando de Noronha, an island environment classified as an area of environmental preservation on the coast of Brazil, through data collection in situ.

The Brazilian National Policy on Solid Waste (BNPSW) obliges manufacturers, importers, distributors, and resellers of electronic products and their components to structure and implement a reverse logistics system, by returning products after disposal by consumers (Brasil, 2010). Mexico, Costa Rica, Colombia and Peru have the most advanced e-waste management systems in Latin America, while Chile and Brazil are still establishing the basis of a policy for e-waste management (Forti et al., 2020). In October 2020, Brazil took an important step toward the implementation of BNPSW by publishing the Sectoral Agreement for the Implementation of the Reverse Logistics System for e-waste from households (MMA, 2021). In addition to implementing existing legislation, the promotion of reverse logistics contracts and the development of the recycling industry are important e-waste management challenges in Brazil (Oliveira Neto et al., 2019). Besides the characterization of waste, research on demographic and socioeconomic factors has proved to be important management guidelines for e-waste, as shown by Gutierréz et al. (2011) and Li et al. (2012) (who correlated the management of these residues with schooling), and Song et al. (2012) (who correlated purchasing power with age).

In this context, this research presents a quali-quantitative characterization of e-waste produced in a middle-class neighborhood from Caruaru, a Brazilian city.Robinson's approach (Robinson, 2009) was chosen for estimating e-waste generation due to the limited data on sales and imports of electronic equipment in Brazil, especially on a local scale. The results show estimates of generation rates of eight types of e-waste, and clearly reinforce the correlation between purchasing power and access to consumer electronics goods.

This study makes a new contribution to studies on estimating e-waste generation in Brazil. First, the study was carried out in a medium-sized city (100,000 to 500,000 inhabitants) located in the Northeast region of Brazil, where socioeconomic and environmental characteristics are quite different from those studied by Brazilian authors. Medium-sized cities have been playing a special role in the economy of Brazil; for instance, the average economic growth index measured by the gross domestic product (GDP) of medium-sized cities was 153% between 2004 and 2010, compared to a 94% growth in national GDP in the same period, and formal employment has increased 70% in these cities (IBGE, 2010). Second, the study considers a set of e-wastes widely found in Brazilian households, not a single type of waste. Finally, this work is also differentiated by the use of primary data, collected in situ, to estimate e-waste production.

2. Materials and method

This research was performed following the research design and methodology shown in Fig 1 and is divided into four main phases: (i) preliminary research assessment and gap identification, (ii) data collection, (iii) data analysis and (iv) conclusions. The first phase (presented in the Introduction section) is dedicated to the literature survey, identification of literature gaps, problem justification and motivation for the study. The second phase comprises the definition of the population and study area, data collection tool preparation (questionnaire), sample size determination, sampling method used and the data cleaning and entry to the statistical software. The third phase is related to the data analysis, which includes quantitative and qualitative approaches. Finally, the fourth phase provides some conclusions and recommendations based on the results of the present study.

2.1. Study area description

The area of interest was the neighborhoods of Maurício de Nassau and Universitário from the city of Caruaru, Brazil. These locations were selected based on the dominance of middle-class families, and similarity in terms of consumption of electronics equipment and production of e-waste. The whole study area occupies 6.72 km^2 of the city and has 20,681 properties ranging from apartments to bare lands (Caruaru, 2017). The city of Caruaru has an approximate area of 920.6 km^2, 291,371 inhabitants, and gross domestic products (GDP) of R$ 3,003.6 million (IBGE, 2017).

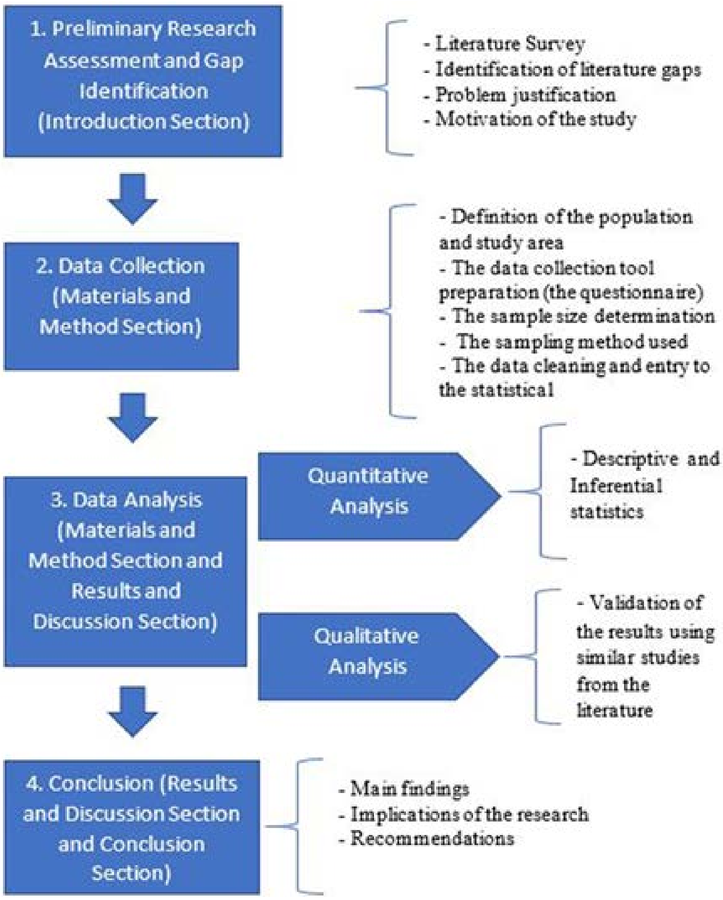

Fig. 1. Research design

Over the last 15 years, the city has been in a fast-paced economic growth, which attracted many local, regional, national, and international enterprises. Its main sources of income are services (74.4% of the GDP of 2010), trade, industry, and tourism. Caruaru is one of the largest clothing centers of Northeast Brazil, producing clothes sold on a national scale and in a few South American countries, with monthly total revenue exceeding 144 million Brazilian reals (about 28 million US dollars) (Caruaru, 2018).

2.2. Sampling design

All evaluations were performed with one sample per neighborhood. To correctly represent all 20,681 current households from the neighborhoods in the study, the size of these samples was calculated using the following equation (Eq. 1):

$$n = \left[\left(\frac{Z_{\alpha/2} x \delta}{E} \right) \right]^2 \qquad (1)$$

where: n is the sample size, $Z_{\alpha/2}$is the critical value for the desired degree of confidence, E is the standard error, which must be equal to α, and δ is the standard deviation of a given target variable.

In this study, for $Z_{\alpha/2} = 1.96$, $\delta = 0.25$ and $E = 0.05$, the equation provided $n = 380$ households. A random sampling technique was used to select a sample containing the recommended 380 households of the study area. In statistics, a simple random sample is a subset of individuals chosen from a larger set (a population). Each individual is chosen randomly and entirely by chance, such that each individual has the same probability of being chosen at any stage during the sampling process, and each subset of k individuals has the same probability of being chosen for the sample as any other subset of k individuals (Yates et al., 2008).

2.3. Data collection

As a data collection tool to support the analysis, a semi-structured questionnaire was applied to each target group to acquire and verify information about (*i*) the type (desktop computer, laptop, printer, tablet, mobile phone, CRT TV, LCD/Plasma TV, and LED TV) and number of electronic products currently in use and not in use (due to non-functioning or obsolescence) by the families; (ii) the time that each electronic product, in use or not in use, remains at home; (iii) the time of use for the electronic product before its replacement; and (iv) socioeconomic and demographic data of families. The reason for including socioeconomic and demographic variables in this study is that these variables have attracted special attention by scholars in e-waste recycling

(Wang et al., 2011): gender (Saphores et al., 2006), age (Nnorom et al., 2009; Song et al., 2012), educational level (Gutiérrez et al., 2011; Li et al., 2012; Nixon and Saphores, 2007; Song et al., 2012) and family income (Darby and Obara, 2005; Song et al., 2012).

The questionnaires were distributed from November 2018 to September 2019. With respect to the use and preparation of the questionnaire to obtain reliable data in the study area, this research considered that in Brazil, there are no official consolidated data on the production of e-waste or reverse logistics systems for this type of product (Oliveira et al., 2016; Araujo et al., 2017). Moreover, illegally imported goods should also be considered important factors in these results because they are quite common in Brazil (Araujo et al., 2017). Considering these data constraints, Robinson's approach was used to forecast e-waste generation because it requires a minimum amount of data (Chung et al., 2011; Robinson, 2009). Data preparation and cleaning were performed using Microsoft Excel (2019).

2.4. Data analysis

As stated previously, a quantitative and qualitative approach to the analysis of the collected data was adopted. This approach was necessary to establish relationships between the variables from the content analysis obtained through the questionnaire and comprises three main techniques: descriptive and inferential statistics for the quantitative analysis as well as validating the results using similar studies from the literature for the qualitative analysis.

Therefore, first, a descriptive analysis was conducted, comprising the socioeconomic and demographic variables to characterize the interviewed families and the relation between family income and EEE stock. Second, Spearman's tests ($\alpha = 0.05$) were performed using Eq. (2)to identify correlations between family income, EEE stock and e-waste generation, in which x and y are the variables to be tested for covariance, d is the difference between each pair of values, and n is the total number of pairs. To evaluate its statistical significance, a t-test was applied when the data population was greater than 20 pairs; otherwise, a simple p-value was acquired using critical theoretical values.

$$r_s = 1 - \left[\frac{6\sum d^2}{n(n^2-1)} \right] \tag{2}$$

Third, to verify the existence of an association between educational level, family income and residents' behavior regarding the management of e-waste, correlations using Chi-square tests were analyzed. All statistical analyses were done using BioStat 5.3.

Fourth, in this study, the Robinson method (Robinson, 2009) was applied to the data obtained to forecast e-waste generation in the study area. The method requires only data from stock of the products, and the e-waste generation can be estimated using Eq. (3).

$$E = \frac{Wx(O+S)}{L} \tag{3}$$

where E is the e-waste generation (kg year^{-1}), W stands for unit weight of an electrical and electronic equipment (EEE) (kg), O and S are the number of electronics in use and stocked respectively, and L is the approximate life span of these products (years). O and S were obtained through the questionnaires. As for W it was adopted values from other studies and products' technical sheets and values for L were obtained using a mix of both methods. Finally, results were validated using a qualitative analysis of previous studies in the literature.

3. Results and Discussion

3.1. General characterization of the interviewed families

Table 2 shows a brief sociodemographic profile of the respondents. The study covered a population of 1196 people, distributed in 380 households, and the results showed (i) higher participation among women (58%) and people between 18 and 30 years (69%); (ii) most of the respondents belonged to the most populous neighborhood, Mauricio de Nassau; (iii) 78% of participants attended or had already completed higher education; and (iv) most households had two, three or four people (73%). Most respondents were considered middle class or above in Brazil, with an income greater than 2.4 times the minimum wage (MW) (Lameiras, 2019).

Table 3 shows family income per household and EEE stock. The higher the income, the greater the amount of EEE in the household. Most households had an income ranging from 1 to 8 MW, with an average number of EEE ranging from 9 to 16 (in/out of use). Rodrigues et al. (2015) found an average of 18.2 EEE per household and 5.3 EEE per inhabitant, taking into account the 26 types of EEE most present in households in the city of São Paulo, whose GDP is 100 times higher than that of the city of Caruaru (IBGE, 2017).

Most of the EEE (percentage above 77%) were in use in homes. Forti et al. (2020) evaluated the presence of 6 types of EEE (including fridges, laptops / tablets, washing machines, microwaves, mobile phone, and lamps) according to the income level of several countries, measured by the average purchasing power parity per capita. Excluding the lighting equipment, the authors observed an average number of the selected EEE per household ranging from 3.62 EEE (low-income level countries) to 12.6 EEE (high income level countries), with mobile phone and laptop / tablet among the most present for any income level. The authors conclude that the greater the country's purchasing power, the greater the number of appliances owned per capita.

To confirm the existence of an association between household income and the production of e-waste, correlations between quantitative variables were verified. Initially, the normality of each data set was checked using the Kolmogorov-Smirnov test, with 95% confidence, and it was found that none of them had a normal distribution. Thus, Spearman's correlation test was used to verify the existence of an association between them. Table 4 shows the 380 pairs of variables considered for family income, EEE stock per household and generation of e-waste per households, as well as eight pairs of variables for the average stock and generation values for each income group. All variables tested showed considerable correlation, as they resulted in high values of Rs accompanied by significant values of the statistical probability of correlation (| t_0 |>t_{tab} or p-value <0.05).

Table 2. Sociodemographic profile of the household respondents

Variable	***Frequency***	***Percentage***
Gender		
Male	160	42%
Female	220	58%
Age		
18 - 30	262	69%
31 - 40	42	11%
41 - 50	46	12%
> 50	30	8%
Neighborhood		
Mauricio de Nassau	262	69%
Universitário	118	31%
Education		
Incomplete elementary school	8	2%
Complete elementary school	4	1%
Incomplete high school	4	1%
Complete high school	60	16%
Technical	8	2%
Incomplete higher education	136	36%
Complete higher education	103	27%
Postgraduate studies	57	15%
Number of people per household		
Up to 2 people	110	29%
3 – 4 people	205	54%
Above 5 people	65	17%
Family income		
Up to 1 MW	60	16%
1 - 2 MW	76	20%
2 - 3 MW	57	15%
3 - 4 MW	46	12%
4 - 6 MW	53	14%
6 - 8 MW	42	11%
8 - 10 MW	19	5%
Above 10 MW	27	7%

Table 3. Family income per household and EEE stock

Income (Minimum wage – MW)	***Number of households***	***% of households***	***EEE stock***			
			Total units	***Number of units per household* (average)***	***% in use (average)***	***% out of use (average)***
Up to 1 MW	58	15	352	5.00	90	10
1 - 2 MW	76	20	530	9.29	87	13
2 - 3 MW	58	15	524	9.28	87	13
3 - 4 MW	46	12	424	11.58	84	16
4 - 6 MW	54	15	620	11.48	89	11
6 - 8 MW	42	11	690	16.43	77	23
8 - 10 MW	20	5	333	16.65	83	17
Above 10 MW	26	7	420	16.15	84	16
Total	380	***Total***	3893	-	-	-

**Outliers were not considered*

Table 4. Results of the Spearman correlation test

Variables	*Parameters*	*Significant correlation*
Family income x EEE stock per household*	$Rs = 0.6788$ $t_0 = 17.9699$ $t_{tab} = 1.96$	Yes
Family income x generation of e-waste per household*	$Rs = 0.4316$ $t_0 = 9.3017$ $t_{tab} = 1.96$	Yes
Family income x average EEE stock per household**	Rs = 0. 0.9636 *p-value* = 0.0001	Yes
Family income x average EEE stock in use per household**	Rs = 0.9880 *p-value* <0.0001	Yes
Family income x average EEE stock out of use per household**	Rs = 0.8556 *p-value* = 0.0067	Yes
Family income x average generation of e-waste per household**	Rs = 0.9698 *p-value* <0.0001	Yes

**Considering n = 380 data pairs; **Considering n = 8 data pairs*

The results of the Spearman correlation test (Table 4) show the existence of a significant correlation between family income and the EEE stock. The analysis of the correlation coefficient (Rs) shows a stronger association when considering the average values of EEE stock and the generation of e-waste. The analysis also showed a strong positive correlation between income and stocks in use and out of use. The correlations with the EEE stock showed higher values of the coefficient Rs in relation to the correlations with e-waste generation. This is because other factors also have an influence on generation, such as the useful life and weight of EEE. Nevertheless, all correlations were considered significant.

According to Nowakowski (2019), the storage of e-waste in households is one of the most damaging factors to the circular economy because it reduces the number of items that can be recycled. The trend of e-waste storage found in this study, especially in higher-income families, shows that a significant portion of e-waste produced can be recycled, reducing the impacts of inappropriate disposal. However, for this possibility to materialize, awareness campaigns, selective collection programs and mechanisms that encourage the population to correctly dispose of this waste will be necessary.

Correlations using the Chi-square test were performed ($\alpha = 0.05$) to verify the existence of an association between social aspects and residents' behavior regarding the management of e-waste. Table 5 shows the observed frequency values and the results of the Chi-square test between the education of the respondents and the method of e-waste disposal, education of the respondent and family income and family income and method of e-waste disposal.

The correlations between respondents' education and e-waste disposal methods and between household income and e-waste disposal methods show that the higher the income and/or educational level, the higher the chance of such waste to be stored in households or remain in circulation as "used goods" when it reaches the end of its useful life. Handayani et al. (2018) pointed out that education level is directly proportional to the management of domestic solid waste. Milovantseva and Saphores (2013) showed that the higher the household income, the higher the chances of e-waste to be stored or reused by third parties.

The relationship between education and family income may be an important parameter for policymakers to expand environmental education actions in informing the population about environmental risks and human health, as well as the benefits of proper e-waste management. Yin et al. (2014) showed that education and income influence the behavior of Chinese consumers regarding the proper management of e-waste, specifically mobile phones. They also pointed out that it is possible for consumers to pay fees for e-waste recycling through environmental education.

3.2. Inventory of electrical and electronic equipment in households

Table 6 shows the inventory of EEE in households. For the eight types of equipment surveyed, the total inventory was 3893 EEE (85% in use and 15% out of use). The mobile phone was the EEE present in 99% of the households with an average of 5 devices per household. Laptop was the second most present EEE in homes. LCD / Plasma / LED TVs were the EEE with the lowest out of use stock, probably due to the difficulty of storage at home. CRT TVs appear among the most frequent out of use equipment, with an average of 1 out of use equipment per household. CRT TVs have become obsolete due to emerging technologies, such as LCD, plasma, and LED, increasing the stock of e-waste worldwide (Baldé et al., 2017). However, the National Household Sample Survey (PNAD), an annual survey to monitor the information necessary for the study of Brazilian socioeconomic development, also shows that about 66.6% of Brazilian households use a converter to receive digital television signals in CRT TVs (PNAD, 2018).

Fig. 2 shows that obsolescence and failure are the two main reasons for the end of the EEE' useful life. Gutierréz et al. (2011) and Li et al. (2012) also point to malfunction and obsolete technology as reasons for the disposal of electronic products, in

Spain and in China, respectively. Mobile phones are the most out of use EEE and obsolescence is the biggest obstacle to its use. Desktop computers and CRT TVs also have obsolescence as a major reason for disuse. LED TVs were the EEE that has less technical problems.

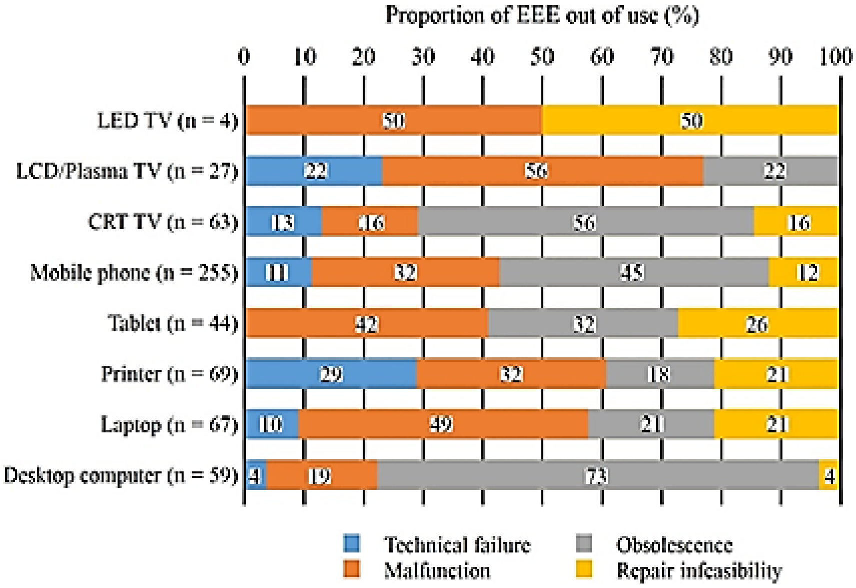

Fig. 2. Main reasons for EEE end of life (n = amount of EEE out of use)

Table 5. Observed frequencies between studied variables

Education of the respondent	***Method of e-waste disposal*** Chi^2 = 59.97; Coef. C = 0.36 (p-value < 0.05)					***Total***
	Non-selective	***Selective***	***Home storage***	***Sale***	***Donation***	
IES	4	0	0	0	4	8
CES	0	0	2	0	2	4
IHS	2	0	0	2	0	4
CHS	16	8	22	6	10	62
Tech	0	0	6	0	0	6
IHE	20	12	54	16	34	136
CHE	34	10	32	6	22	104
Post-Grad.	14	4	22	0	16	56
Total	90	34	138	30	88	380

Education of the respondent	***Number of minimum wages*** Chi^2 = 176.36; Coef. C = 0.56 (p-value < 0.05)								***Total***
	<1	***1–2***	***2–3***	***3–4***	***4–6***	***6–8***	***8–10***	***>10***	
IES	2	6	0	0	0	0	0	0	8
CES	2	0	0	2	0	0	0	0	4
IHS	0	0	0	0	2	0	2	0	4
CHS	4	16	16	12	8	2	0	4	62
Tech	2	0	2	2	0	0	0	0	6
IHE	40	28	22	14	24	2	4	2	136
CHE	8	20	10	8	10	22	10	16	104
Post-Grad.	0	6	8	8	10	16	4	4	56
Total	58	76	58	46	54	42	20	26	380

IES – Incomplete elementary school / CES – Complete elementary school / IHS – Incomplete high school / CHS – Complete high school / Tech – Technical / IHE – Incomplete higher education / CHE – Complete higher education / Post-Grad. - postgraduate studies

Method of e-waste disposal	***Number of minimum wages*** *Chi^2 =96.37; Coef. C =0.44(p-value < 0.05).								***Total***
	<1	***1–2***	***2–3***	***3–4***	***4–6***	***6–8***	***8–10***	***>10***	
Non-selective	10	20	8	8	10	14	4	16	90
Selective	2	6	10	4	4	2	4	2	34
Home storage	26	26	28	16	18	16	8	0	138
Sale	6	8	6	2	2	2	2	2	30
Donation	14	16	6	16	20	8	2	6	88
Total	58	76	58	46	54	42	20	26	380

3.3. Potential for e-waste generation

The e-waste generation estimate was performed using the Robinson approach. The EEE stock was obtained in the field survey. Lifetime data were obtained from studies by Robinson (2009) and Oguchi et al. (2008), or obtained in the field survey (questionnaire). The average weight data for the equipment was based on the works of Robinson (2009), Oguchi et al. (2008), and ABDI (2013), as shown in Table 7.

Considering the most critical situation, the generation potential of e-waste was calculated for the shortest average lifespan and the highest average weight of each equipment, as shown in Table 8. Thus, the total estimated e-waste production is 5364.30 kg year^{-1}. Considering the total number of households in Caruaru for 2019 (20,681 households) and the average of 3 people per household, an estimated e-waste potential generation of 292,015.72 kg year^{-1} is expected for the entire city, with a *per capita* generation of 4.70 kg inhabitant^{-1} year^{-1}. That *per capita* generation is in line with estimates made in different Brazilian cities. Araujo et al. (2017) found a *per capita* generation of 4.54 kg inhabitant^{-1} year^{-1} on the island of Fernando de Noronha. Rodrigues et al. (2015) estimated a per capita generation for the city of São Paulo of 4.80 kg inhabitant^{-1} year^{-1}. Franco and Lange (2011) estimated a generation of 4.23 kg inhabitant^{-1} year^{-1} in the city of Belo Horizonte.

Table 6. Inventory and characterization of EEE per households

EEE	*Total Stock (unit)*	*Percentage of households with EEE (%)*	*Average EEE per household (unit) **	*In use*		*Out of use*	
				Stock (%)	*Average EEE per household (unit)*	*Stock (%)*	*Average EEE per household (unit)*
Desktop Computer	198	32	2.2	70	1.13	30	1.07
Laptop	746	87	3.24	91	2.06	9	1.18
Printer	285	53	2.17	76	1.07	24	1.10
Tablet	257	42	2.34	83	1.34	17	1.00
Mobile phone	1445	99	5.09	82	3.16	18	1.93
CRT TV	165	21	2.35	62	1.28	38	1.07
LCD/Plasma TV	325	48	2.79	92	1.62	8	1.17
LED TV	472	58	3.11	99	2.11	1	1.00
Total	3893	-	-	3305 (85%)		588 (15%)	

** Outliers were not considered*

Table 7. Lifespan and average weight of EEE

Equipment	*Average lifetime (year)*			*Average weight (kg unit^{-1})*		
	Robinson (2009)	*Oguchi (2008)*	*This work**	*Robinson (2009)*	*ABDI (2013)*	*Oguchi (2008)*
Desktop computer	3	6.6	4.5	25	24.3	15
Laptop	-	7.4	3.4	-	2.4	2.9
Printer	-	7.1	3	-	6.3	5.6
Tablet	-	-	3.4	-	-	-
Cell phone	2	4.3	2.7	0.1	0.1	0.1
CRT TV	5	12	6.5	30	37.2	31
LCD/Plasma TV	-	7.2	5	-	12	8
LED TV	-	-	6	-	-	-

** The average weight data for tablets and LED TVs were obtained from the technical data sheets of the equipment, among the main brands sold in Brazil: tablet (0.5 kg) and LED TV (4.6 kg).*

Table 8. Potential for e-waste production

Equipment	*Average lifetime (year)*	*Average weight (kg unit^{-1})*	*Production (kg year^{-1})*		
			In use	*Out of use*	*Total*
Desktop computer	3	25	1158.33	491.67	1650.00
Laptop	3.4	2.9	579.15	57.15	636.29
Printer	3	6.3	453.60	144.90	598.50
Tablet	3.4	0.5	31.32	6.47	37.79
Cell phone	2	0.1	59.50	12.75	72.25
CRT TV	5	37.2	758.88	468.72	1227.60
LCD/Plasma TV	5	12	715.20	64.80	780.00
LED TV	6	4.6	358.80	3.07	361.87
Total	-	-	4114.78	1249.52	5364.30

Table 9 shows the production of e-waste according to family income and the number of people per household. While households with an income of up to 1 MW tend to generate up to 5 kg year^{-1}, in households with the highest incomes, it exceeds 23 kg year^{-1}. The results of the Spearman correlation test (Table 4) also reinforce the existence of a significant correlation between family income and generation of e-waste. Ravindra and Mor (2019) found that the generation of e-waste has a positive correlation with family income in Chandigarh (India). Kumar et al. (2017) pointed out that the e-waste generated per inhabitant correlates with the per capita income of inhabitants in any country, suggesting that the quantity of e-waste generated per inhabitant increases according to their purchasing power.

Table 9. Production of e-waste according to family income

Income (MW*)	Total production per households (kg year^{-1})	Average production perhousehold** (kg year^{-1})
Up to 1 MW	496.68	5.00
1–2 MW	848.85	9.29
2–3 MW	695.78	9.28
3–4 MW	644.34	11.58
4–6 MW	767.58	14.21
6–8 MW	970.98	23.12
8–10 MW	467.99	23.40
Above 10 MW	472.11	23.66

**Minimum wage; **Outliers were not considered*

4. Conclusions

This study estimated that on average, 292,015 kg year^{-1} (4.70 kg per capita year^{-1}) of desktop computer, laptop, printer, tablet, mobile phone, CRT TV, LCD/plasma TV and LED TV waste will be generated by Caruaru households. It revealed an important correlation between socioeconomic variables (family income and education level) and variables associated with e-waste management (stock of EEE, e-waste generation and method of e-waste disposal).

In addition to joint disposal of common waste, the storage of e-waste in residences is an obstacle to the proper management of this type of waste. Therefore, estimating the qualitative and quantitative potential of e-waste generation is an important step towards knowing the reality and planning the management in a conscious and appropriate way.

In this sense, the results of this study may help governments and other stakeholders to improve e-waste management policies in regions with similar characteristics.

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