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Circular Economy in the Electronic Products Sector: Material Flow Analysis and Economic Impact of Cellphone E-Waste in Mexico

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Abstract: The circular economy (CE) model has become highly relevant in recent years, with the electronics industry being one of the sectors that has considered its application. Despite only a limited amount of literature being available on waste electric and electronic equipment (e-waste) in Mexico, the Mexican Government, academic institutions, and electronics industry have coordinated efforts to implement the CE in the country. This study evaluates the current technical and economic situation of cellphone e-waste generated in Mexico by surveying and analyzing the main actors that influence the management of this waste and using a material flow analysis. Extensive fieldwork was conducted in order to quantify the extent of cellphone e-waste processing in both formal and informal channels. The study of printed circuit boards in cellphones shows that the total value of cellphone e-waste materials ranges between $11.277 and $12.444 million USD per year in Mexico. However, a value of only $0.677 million USD is recycled through formal channels. After characterizing the remanufacturing and recycling CE loops, we conclude that the potential for improvement and advancing towards a CE model is significant

Keywords: circular economy; electronic products; material flow analysis; e-waste; cellphones; Mexico

1. Introduction

The circular economy (CE) is a concept that has been around for more than two decades and currently has many definitions. Some researchers state that the CE should target the following dimensions of impact: Environmental, economic, and social [1]. Other leading groups emphasize the need for new business models that facilitate the transition from open production systems towards closed systems that reuse resources and reduce energy consumption [2].

A generally accepted definition of the CE is still elusive, pushing academic research to analyze a wide range of related concepts and methods in search for such general definition [3]. In order to have a reference framework, we settled on the definition formulated by Kirchherr et al., which states that "A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling, and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks), and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations." [4].

In Latin America, particularly in Mexico, the concept of a CE for electronic products is relatively new. Public policy and supporting research related to implementing a circular economy model are recent considerations. Similarly, studies on e-waste generation, characterization of recycling facilities, and repair stores are limited in scope. Consequently, there is a need to analyze the different schemes and actors involved in waste electric and electronic equipment (WEEE) management in order to determine the degree of implementation in terms of a CE model for electronic products.

In 2006, the National Institute of Ecology of Mexico (INE for its acronym in Spanish) published a national e-waste management manual, which has since then been updated to 2010 through regional studies [5,6]. Subsequently, several studies on e-waste were published between 2012 and 2014, based on integral management guides and recycling programs [5–8]. The Federal Ministry of Environment and Natural Resources of Mexico (SEMARNAT), in cooperation with the United Nations Development Program (UNDP), currently carries out studies on integral e-waste management, and in 2017, SEMARNAT-UNDP published an inventory of e-waste generation in Mexico with the base year 2015 [9]. Within this framework, the CE is starting to be considered in the electronic products sector in Mexico and it is envisioned that the new e-waste law will include this new circular economic industrial model.

1.1. Literature Review

1.1.1. Circular Economy of Electronic Products

CE models for electronic products provide mechanisms for extending the life of the equipment and then recycling and recovering each material for reuse as a secondary raw material in another system. Several tools have been developed to identify, analyze, and evaluate these processes in a system [10]. Cellphone e-waste circulates through several processes, and its materials can be used in different stages or industrial processes. Table 1 presents a comparative analysis of the methodology used in the research reported here and studies conducted by Yu et al. [11], Ghosh et al. [12], Baldé et al. [13], and Kumar et al. [14], who evaluated the processes in electronic waste circulation—such as the generation of e-waste (based on the GDP of a country), repair, recycling, and the composition and flow of waste materials—using their highest economic value in the international market.

Table 1. Analysis of the processes for e-waste material flow from cellphones (comparison of reported research in this work vs. selected international studies).

Process	Methodology	Current Study	Yu et al. [11]	Ghosh et al. [12]	Baldé et al. [13]	Kumar et al. [14]
Generation	Gross domestic product analysis of cellphone waste generation	✓	✓		✓	✓
Repair	Literature review and database analysis	✓	✓		✓	✓
	Field investigations and employee interviews	✓				
	Analysis of facilities, equipment, and tools	✓				
	Analysis of the academic level of the employees	✓				
	Analysis of environmental procedures and health and safety conditions	✓				
Recycling	Literature review and database analysis	✓	✓	✓	✓	✓
	Field investigations (interviews)	✓				
	Analysis of facilities, equipment, and tools	✓				
	Technical evaluation of the employees	✓				
	Determination of e-waste composition	✓	✓	✓	✓	✓
	Analysis of manual and mechanical separation processes	✓		✓	✓	
	Analysis of end-processing technologies: physical, chemical, and/or biological separation			✓	✓	
Material flow analysis	Cellphone manual disassembly tests	✓				
	Mass balance calculations	✓	✓			✓
	Commodities	✓	✓		✓	✓

Source: Prepared by the authors based on the fieldwork and a literature review [11–14].

The generation of e-waste is directly related to the GDP of a country. The studies of Yu et al. [11], Baldé et al. [13], and Kumar et al. [14] showed that the consumption of cellphone equipment is between 1 and 1.1 cellphones per person, and that as the GDP of a country increases, the waste generation increases at a similar rate. Similarly, Baldé et al. [13] correlated the total e-waste generated in 50 countries with their GDPs and the sizes of their populations and confirmed that these three factors are correlated.

Published CE models in the electronic products sector have analyzed the actors and scenarios involved in electrical and electronic equipment flow (Table 1). Different authors have evaluated the reparability and recycling of electronics to determine the feasibility of migrating toward a CE model [11–13]. Analyzing the generation, repair, management, and recycling processes for electronic equipment in a particular country allows for the determination of its technological capabilities to enable a CE model.

Most countries with emerging economies have basic recycling processes, such as manual separation of components, crushing machines, metal separators, and compactors, and very few recyclers recover valuable components such as gold, copper, cobalt, and tin. Baldé et al. [13] and Ghosh et al. [12] analyzed the electronic recycling industry and its final processing through physical, chemical, and/or biological separation to determine the technological recycling level of a country and establish whether it is possible to recover materials locally by means of manual, mechanical, physical, chemical, and/or biotechnological processes (Table 1). Their studies showed that emerging countries do not have the end-processing technologies to recover all the materials from printed circuit boards (PCBs).

1.1.2. Waste Electric and Electronic Equipment Management Strategies

During the last decade, several studies have focused on e-waste management, with the purpose of mitigating social, environmental, and economic problems involved in the rapid growth of WEEE [2,15]. These studies have developed several tools for a proper WEEE management, all of which consider the evaluation of potential socio-environmental impact. Among the most relevant tools, we can find the following:

- Life cycle assessment (LCA) is a decision-making tool which is widely used to evaluate economic aspects in the design and development of a product as well as energy and environmental impact, such as climate change, ozone layer, eco-toxicity, carcinogens, acidification, and eutrophication [11]. This tool has been use to determine the impact of WEEE and evaluate strategies for a proper e-waste management, leading to economic benefits for material recovery of some materials such as glass, iron, copper, aluminum, and plastic [1,2,16–18].
- Materials flow analysis (MFA) is a decision-making tool for an adequate environmental management of waste. It is used to study the route of the components/materials that flow through different processes (repair, re-conditioning, re-manufacture, recycling) until their final destinations, such as recovery of materials, landfills, and incineration [1,11,17]. MFA is applied to e-waste management to characterize electronic product stages and to develop an adequate management of e-waste, all while considering environmental, economic, and social indicators [19,20].
- Multi-criteria decision analysis (MCDA) is a strategic decision tool which helps solve complex multiple criteria scenarios that include qualitative and quantitative variables of the problem in question [20]. This tool has been applied to environmental management schemes, such as the development of e-waste management strategies, thus providing a positive socio-environmental impact [15,18].
- Extended producer responsibility (EPR) is an environmental tool that assigns additional responsibilities to manufacturers [7]. These responsibilities extend until the product is collected at the end of its useful life and is based on the principles of the United Nations Environment Programme (UNEP) [21,22]. It is defined as an environmental policy approach which includes the material and financial responsibility of the manufacturer about the product. This policy has

two fundamental characteristics: a) Transfer responsibility to the producer (collection, treatment, reuse, and recycling), and b) provide incentives to producers for improving product design that facilitates treatment, reuse, and recycling [8,23].

Electric and electronic equipment (EEE) is composed of a combination of hazardous and non-hazardous materials which require specialized separation processes. Depending on the purpose of the recycler, the end of the useful life of EEE can be divided into material recovery (repair, re-conditioning, disassembling) or power generation (incineration) [24]. Figure 1 shows the recovery processes of EEE [16,17]. It shows that the useful life of an EEE can be extended by means of the reuse, repair, updating its hardware and operating system, or replacement of some of its parts (reconditioning). In case the equipment no longer works, the recycler will opt for manual/mechanical disassembly and will take advantage of the functional components and use them to remanufacture other products. Regarding recycling, companies use almost all parts and materials of electronic waste in order to sell them in local markets or abroad. If the materials cannot be recovered locally/abroad by end-processing technologies, they pass to destruction stage, either by means of incineration to generate energy or to final disposal (depending on national environmental laws) [8,22,24].

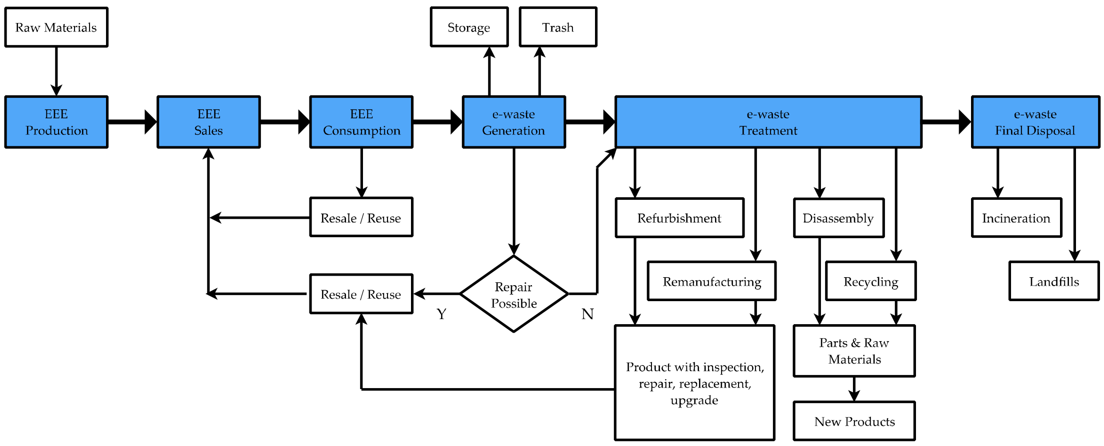

Figure 1. Life cycle of electric and electronic equipment. Source: Prepared by the authors based on fieldwork and literature review [6,8,9,16,17].

1.2. Research Question and Objective

The literature review shows the lack of in depth information about the state of the circular economy of electronic products in Mexico. In this context, the research question is what are the processes and conditions that promote or limit the implementation of a circular economy model for cellphones in Mexico. Therefore, the objective of this study is to characterize the processes and conditions involving the generation and processing of e-waste in Mexico, with a particular focus on cellphones.

The research included the characterization and evaluation of the actors that are involved in the repair and recycling processes and an examination of the fate of each component out of cellphones. More particularly, the processes involved in e-waste generation and processing were characterized by fieldwork involving a survey of recycling facilities and a survey of repair stores for cellphones, as well as a detailed study of cellphone disassembly. In order to evaluate the conditions that promote or limit the implementation of a circular economy model for cellphones in Mexico, a material flow analysis and an economic impact analysis were conducted.

2. Materials and Methods

The materials and methods used in this research are derived from the most generally accepted definitions of a CE. Urbinati et al. indicate that closed systems that reuse resources and reduce energy consumption are fundamental elements of the CE [2]. Kirchherr et al. and Homrich et al. are emphatic in considering environment quality, economic prosperity, and social equity as the ultimate goals of the CE [3,4]. In this context, the proposed materials and methods in this research aim at characterizing the maturity of the loops (closed systems) in regards to reuse, remanufacturing (repair), and recycling. In addition, the economic assessment of cellphone e-waste provides an indication of the current environmental, economic, and social impact involving these products.

2.1. Outlook of Repair and Recycling

First, the field research reported here took place between the second half of 2015 and the first half of 2016, with a survey of twelve recycling companies involved in electrical and electronic waste recycling. The methodology for the characterization of these facilities was through personal interviews with the Chief Executive Officer or the Chief Operating Officer at each company.

A questionnaire was sent to each company before the personal interview. The questionnaire was developed based on previous research by the Federal Ministry of Environment [9,25] and the National Institute of Ecology of Mexico [5], and it covered factors such as company size (number of employees), presence in other countries, types and quantities of waste, recycling processes and technologies, quality and environmental certifications, and health and safety. The twelve recycling facilities were classified by city and coded for confidentiality purposes (for example, C: Mexico City, M: Monterrey, and G: Guadalajara). These field data were then compared with the findings of Yu et al. [11] in China, estimations of the gross domestic product (GDP) in China and Mexico, and data from SEMARNAT's studies on national e-waste generation in Mexico [9]. Subsequently, 66 formal and informal electronic repair stores were evaluated. The focus of the study was to understand their technical, academic, labor (child labor), and environmental standards, as well as their health and safety conditions.

2.2. Material Flow Analysis of Cellphone Waste

A material flow analysis of cellphone e-waste was conducted that considered the mass balance and disassembly efficiency in Mexican facilities. The recycling facility Proambi provided all of the logistical and technical support for this study and donated 80 cellphones. First, a cellphone data sheet, detailing materials, tools, and personal protection equipment, was filled out,. A technician supported the manual disassembly process. Each cellphone component was weighed using an analytical balance (Model PPN-40S, TecnoCor, Santiago Miahuatlán Puebla, México), and every disassembly step was timed. The following brands and models of cellphones were analyzed (with the number of units in parentheses): Alcatel 6045 (10), BTE (15), Huawei Y520-U03 (15), Huawei G527-U081 (15), BLU Star4.5 (2), BLU Life (2), ZTE Blade A475 (2), ZTE V6 (2), ZTE Blade L3 (2), Samsung SMJ1000MU (10), Samsung J1 (1), Samsung J3 (2), and Samsung Grand Prime (2). The number of disassembled parts ranged from 13–15 components, depending on the type of cellphone.

Once this information had been recorded, a mass balance analysis of each cellphone and its components was performed, based on the methodologies proposed by Yu et al. [11] and Badiru et al. [10]. The variation in material during the manual disassembly process (ΔM) was determined by calculating the difference between the initial weight of the cellphone (Σf_{in}) and the sum of the weight of all components that left the process (Σf_{out}) (Equation (1)). In addition, the percentage variation of the material during disassembly (Em) was calculated to determine the efficiency of the process and the percentage of material losses (Equation (2)).

$$\Delta M = \Sigma f_{\text{in}} - \Sigma f_{\text{out}} \text{ (Material balance equation)} \tag{1}$$

$$Em = \left[\left(\frac{\Sigma f_{\text{out}}}{\Sigma f_{\text{in}}} \right) \right] * 100 \text{ (Disassembly efficiency equation)} \tag{2}$$

2.3. Economic Impact of E-Waste Materials in Printed Circuit Boards of Cellphones

For the economic calculation, the study focused only on the printed circuit boards (PCBs). Weight concentrations of metals, non-metals, and rare earths were calculated using information from Ogunniyi et al. [26], Oguchi et al. [27], Yamane et al. [28], Kumar et al. [14], and Holgersson et al. [29]. The economic value of the materials was calculated using the average national and international prices for the year 2015 through marketers such as Kitco [30], Trading Economics [31], and the Integral System on Mining Economics from Mexico [32].

2.4. Mass Analysis E-Waste Materials in Cellphones

No material flow analyses or mapping data are currently available for the content of cellphone waste in Mexico. Consequently, published studies from other regions were used as a reference, such as that of Yu et al. [11]—who analyzed the materials that are used in cellphones in China and determined the average contents of copper, aluminum, iron, lead, tin, gold, silver, and palladium—and Baldé et al. [13], who determined the contents of 18 materials that are used in cellphones in a study conducted at the United Nations University in Bonn, Germany. Based on the findings of these studies, the weight and percentage of cellphone waste materials generated in Mexico were calculated, with an emphasis on common metals (copper, aluminum, iron, lead, tin, and zinc), precious metals (gold, silver, and palladium), rare metals (cobalt and gallium), plastic, and glass.

3. Results

3.1. Outlook of Repair and Recycling

This section presents the results of the survey on recycling facilities and repair stores in Mexico, along with the analyses of e-waste generation and material flow. First, e-waste generation in recycling facilities is characterized and analyzed. Then, the generation of cellphone waste and its relationship with the GDP, as well as the findings of other studies carried out in China [11] and Mexico [9], are examined. This is followed by the analysis of formal and informal cellphone repair stores.

3.1.1. Waste Electrical and Electronic Equipment in Recycling Facilities

The field study of recycling facilities in Mexico showed that component separation was based on both manual operations and mechanical systems (see Table 2.) Additional detail is included in the Figure A1 of the Appendix A. However, none of these facilities had end-processing technologies for recovering materials. The interviews showed that 42% of e-waste can be reused and enters a second-hand market, while the remaining 58% goes through manual separation. All of the facilities followed this procedure, but only 67% of them had mechanical separation processes, which included crushers, magnetic separators, and metal compactors.

Table 2. Characterization of the 12 recycling facilities surveyed in Mexico, 2015.

Surveyed Companies				Separation Processes		Reuse and Recycling		
Size	**Number of Employees**	**Total E-Waste Processed (ton/year)**	**Code: M: Mexico City G: Guadalajara M: Monterrey**	**Manual**	**Mechanical**	**Second Hand Sale**	**PCB Export**	**Local Materials Recycling**
Small	<35	<100	C2, C4	Y	N	Y	Y	Y
			C5, G3, M2	Y	N	Y	N	Y
Medium	35–59	100–499	G2, G4	Y	N	Y	Y	Y
Large	>60	500–1200	C1, C3, C6, G1, M1	Y	Y	Y	Y	Y

Source: Prepared by the authors based on fieldwork.

At all recycling companies, the disassembled parts of a piece of electrical and electronic equipment (e.g., plastic, steel, PCB, metals) are inspected for later reuse, local trade, or sale in international markets to recover precious metals. These results are consistent with findings reported by Namias [33], who analyzed the U.S. recycling industry and determined that, similarly to Mexico, the U.S. recyclers sell components to Europe or Asia to recover precious metals. Since the Mexican recycling facilities investigated here did not have the end-processing technologies to recover precious metals, PCBs were the main component they exported, being sold to countries such as China, Japan, and Belgium. The next section will provide more details about the material flow and disassembly of PCBs

National and international certifications for health and safety, quality, environmental impact, and social responsibility varied between recycling facilities, depending on their e-waste processing volume [8,15,34]. National permits are granted to all recycling facilities in Mexico (large, medium, and small) by government institutions such as SEMARNAT, Ministry of Health, and Ministry of Labor and Social Prevention. By contrast, international certifications, such as ISO 9001 and ISO 14001, are only given to medium and large recycling facilities that handle e-waste volumes of more than 500 tons per year. High-capacity recyclers also have certifications that ensure correct e-waste recycling processes are in place, such as R2 (Responsible Recycling) and/or e-Stewards® (Responsible Recycling and Reuse of Electronic Equipment®).

The 12 recycling facilities processed a total of 4488 tons of e-waste in 2015. Figure 2 shows the source of this e-waste, which mostly consisted of domestic appliances (or white goods) and printers (47%), followed by computers and televisions (12%–19%), and, finally, a small amount of cellphones, tablets, and smaller equipment (additional detail is included in Table A1 of the Appendix A). The proportion of cellphones was found to be only 7%, equivalent to 301 tons/year.

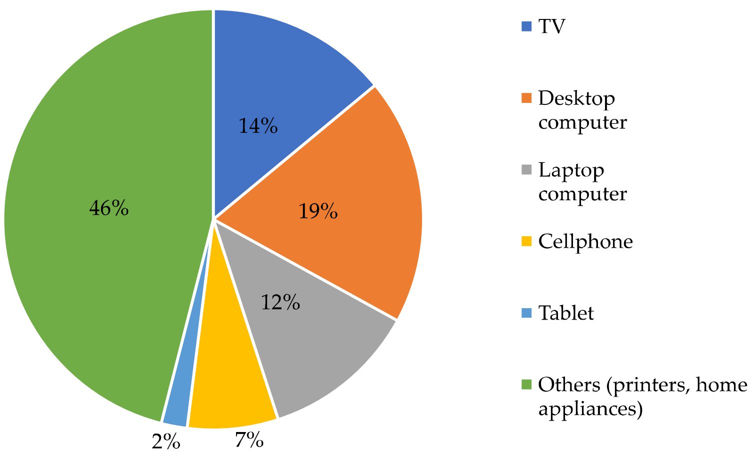

Figure 2. Sources of the e-waste generation processed by the 12 recycling facilities interviewed, 2015.

3.1.2. GDP-Related Estimation of E-Waste Generation in Mexico

Baldé et al. [13] showed that e-waste generation is directly related to the GDP and population size of a country, while Yu et al. [11] and Kumar et al. [14] demonstrated that the consumption of cellphone waste is between 1 and 1.1 cellphones per person and that the generation of e-waste in a country increases in a similar proportion to the increase in GDP. Based on these findings, and given that the last data set available is from 2010 [9], we proceeded to estimate cellphone e-waste in Mexico.

First, the weight of cellphone e-waste generation was estimated based on the cellphone e-waste generated in China for 2008 ($N_{CH\text{-}2008}$) as reported by Yu et al. (77 million units) [11] and the average weight of the cellphones analyzed in the field research (W_{CH}: 150 grams/unit). We estimated 11,550 tons of cellphone e-waste were generated in China for 2008 ($CW_{CH\text{-}2008}$), as described in Equation (3).

$$CW_{CH-2008} = W_{CH} * N_{CH-2008}\ (\text{cellphone e}-\text{waste generation in China 2008},\ [\text{ton/y}]) \quad (3)$$

The growth of cellphone e-waste is assumed to be proportional to GDP. Therefore, we estimated that cellphone e-waste increased from $CW_{CH\text{-}2008}$ = 11,550 tons in 2008 to $CW_{CH\text{-}2015}$ = 27,795 tons in

2015, as indicated in Equation (4) through the consideration that $GDP_{CH\text{-}2008}$ = $4598 billion USD and $GDP_{CH\text{-}2015}$ = $11,065 billion USD [27].

$$CW_{CH-2015} = CW_{CH-2008} * \left(\frac{GDP_{CH-2015}}{GDP_{CH-2008}}\right) \text{(cellphone e} - \text{waste generation in China 2015, [ton/y])} \quad (4)$$

Following the same logic, we then estimated the cellphone e-waste generation in Mexico as a proportion of the GDP between China and Mexico. The reference data are $GDP_{CH\text{-}2015}$ = $11,065 billion USD (China), $GDP_{MX\text{-}2015}$ = $1,173 billion USD (Mexico), and 27,795 tons of cellphone e-waste in China for 2015 ($CW_{CH\text{-}2015}$), as indicated in Equation (5). Therefore, we estimated a generation of 2947 tons of cellphone e-waste in Mexico. Table 3 summarizes these estimations.

$$CW_{MX-2015} = CW_{CH-2015} * \left(\frac{GDP_{MX-2015}}{GDP_{CH-2015}}\right) \text{(cellphone e} - \text{waste generation in Mexico 2015, [ton/y])} \quad (5)$$

Table 3. Relationship between the gross domestic product (GDP) and cellphone waste generation in China and Mexico in 2015.

Indicator/Calculated Data	Unit	China (2015)	Mexico (2015)
Population	(million)	1371.3	125.9
GDP	(billion USD)	11,065	1173
Total e-waste generation	(ton/year)	N/A	1,103,570 [25]
Total cellphone e-waste generation, CW	(ton/year)	27,794 ***	2947 ***
Cellphone e-waste formally recycled in Mexico (based on 10.8% [25])	(ton/year)	N/A	316.85 ***
Field survey of cellphone waste formally recycled in Mexico (7%)	(ton/year)	N/A	301 +++
Percentage of cellphone waste in total e-waste	(%)	N/A	0.3 ***

*** Estimated data. +++ Field data. Source: Prepared by the author based on [8,11,13,25,35].

According to studies carried out by SEMARNAT [25] and Cruz [8], the formal recycling market in Mexico only captures 10.8% of e-waste at a national level. Therefore, it was estimated that 316.85 tons of cellphone waste were formally recycled in Mexico in 2015 (Table 3). Finally, the proportion of cellphone waste from the total e-waste generated was estimated to be 0.3% for Mexico. The field study showed that only 7% of cellphone waste from 12 recycling facilities (301 tons of the 4,488 tons generated per year) stemmed from formal recycling. Therefore, we proceeded to analyze formal/informal electronics repair stores in Mexico in order to understand how these shops work and what do they do with their e-waste (see Section 4.3).

3.1.3. Repair Store Characterization

The field study of 66 repair stores in Mexico focused on finding the main differences between formality and informality in working conditions, environmental standards, and health and safety conditions. The results indicated that the formal repair market competes against the informal market in an uneven manner, with large differences in safety standards, environmental standards, and basic conditions of the employees between the two.

Employees in the formal market have higher levels of academic achievement than those in the informal market (see Table 4 and Figure 3 for more details). In addition, formal stores have almost double or even triple the number of workers compared with informal stores, while the presence of child labor was confirmed in the informal stores, with the ages of those involved ranging from 8 to 15 years old.

In terms of health and safety conditions, the formal repair stores fulfill the regulations of each municipality and the permits granted by the Civil Protection and Firefighters governmental office. Thus, formal stores have signage, smoke detectors, and fire extinguishers. By contrast, informal repair stores only partially fulfill these standards. The generation of e-waste is insignificant in both types of stores (in average less than 1 kilogram per year), with most components or electronic materials being reused. However, where e-waste is generated, it is most likely to be thrown into the garbage in both types of stores (100% informal stores and 72% formal stores); 13% of formal stores donate, and 15% give it to recycling companies [8,9,25].

Table 4. Characteristics of formal and informal repairing stores in Mexico.

General Characteristics	Formal	Informal
Number of surveyed stores	33	33
Total number of employees	103	56
Percentage of child labor	0%	21%
Academic Level		
Elementary school	0	2
Middle school	8	16
High school	30	22
Associate degree	24	11
Bachelor's degree (in progress)	31	5
Bachelor's degree	10	0
Health and Safety Conditions		
First aid kit	67%	27%
Fire extinguishers	100%	52%
Smoke detectors	100%	18%
Safety signage	100%	42%

Source: Prepared by the authors based on fieldwork.

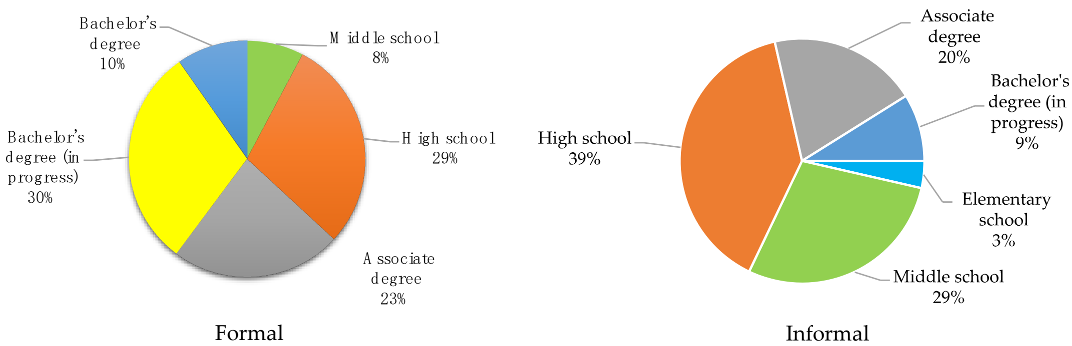

Figure 3. Academic level of formal and informal employees of repair shops in Mexico, 2015. *Source*: prepared by the authors based on fieldwork.

3.2. Material Flow Analysis of Cellphone E-Waste

The study of 80 cellphones in the field shows that the manual disassembly process was highly efficient (98–99%, see Table 5). The Huawei brand showed the highest efficiency for manual separation (99%), while all other brands had efficiencies of 98%. Separation time ranged from 3.24–4.22 minutes, with the Samsung brand requiring the shortest time for disassembly, and the Blu brand requiring the longest. The weight of some components varied depending on the cellphone brand, but most components had similar weights across all brands.

One of the most important components of cellphones is the PCB or motherboard. Studies worldwide have indicated that the PCB has the highest economic value and contains precious metals [8,14,26–29]. The field research showed that, on average, the PCB represented 9% of the total weight across the 80 cellphones analyzed, having the greatest weight in Huawei (16 grams), the lowest weight in Samsung (11 grams), and an intermediate weight in the remaining three brands (13 grams).

Table 5. Weight and efficiency of cellphone components obtained from manual disassembly.

Item	Cellphone Component	Average Weight of Cellphone Components (g)				
		Samsung (20 units)	Huawei (20 units)	Alcatel (15 units)	BLU (15 units)	ZTE (10 units)
1	Cover case	15.0	16.0	17.0	11.0	16.0
2	Speaker	2.0	1.0	1.4	2.0	2.0
3	Touch Pad	13.0	15.0	***	18.0	22.0
4	Display	21.0	20.0	33.0	21.0	24.0
5	Battery	42.0	35.0	44.0	30.0	44.0
6	Printed circuit board	11.0	16.0	13.0	13.0	13.0
7	Charging	5.0	5.0	6.0	5.0	1.0
8	Frontal camera	0.2	0.5	0.5	0.5	0.5
9	Rear camera	0.6	0.1	0.1	0.1	0.1
10	Horn	0.4	0.5	0.5	0.5	0.5
11	Buttons (home, vibrator)	0.2	0.2	0.2	0.2	0.2
12	Audio	0.6	1.0	1.0	1.0	1.0
13	Case	18.0	20.0	18.0	20.0	16.0
14	SIM tray	0.0	0.0	0.5	0.0	0.5
15	Other (screws, flexors, cables, buttons, plastics)	18.0	8.0	21.0	8.0	11.0
	Initial weight (g)	150	140	160	133	155
	Final weight (g)	147	138	156	130	152
	Efficiency (%)	98	99	98	98	98
	Disassembly time (min)	3.24	3.95	4.11	4.22	3.67

*** Touch pad attached to display. Source: Prepared by the authors based on field research.

The average percentage of materials that make up the printed circuit board (PCB) was also estimated from the literature. Table 6 shows the composition of the PCB, which contains 10 materials with high commercial value. Precious metals are present at concentrations of <0.1%, whereas there were higher concentrations of materials that provide structure to the PCB, such as copper (40.34%) and steel (3.5%). Other materials that are vital for the integration of all circuits in the PCB are also present at low concentrations, such as gallium (0.022%)—a semiconductor metal that is used for the integrated network circuits—and neodymium, which is a rare earth that serves as a magnet [36]. The economic analysis presented next shows that although some of these elements are present at only small concentrations, they nonetheless have high commercial interest worldwide due to their unit cost. The PCB is the only component that is exported by most Mexican recycling facilities.

Table 6. Percentage of materials in the printed circuit boards (PCB's) of cellphones.

Item	Element	PCB (% by Weight)	Price (USD/ton)	Item	Element	PCB (% by Weight)	Price (USD/ton)
1	Copper	40.340	5490	6	Gold	0.0488	40,919,295
2	Tin	4.118	16,000	7	Silver	0.028	553,086
3	Steel	3.494	361	8	Gallium	0.022	317,000
4	Nickel	2.598	11,788	9	Neodymium	0.028	54,614
5	Titanium	0.350	55,556	10	Palladium	0.00564	24,395,944

Source: prepared by the authors based on [14,16–18,20–24].

3.3. Economic Impact of E-Waste Materials in Printed Circuit Boards of Cellphones

The value of the materials that can be recovered from cellphone waste and are of commercial interest was calculated from the weight of each cellphone and its components. Table 7 shows the average percentage of materials contained in the PCB followed by the estimated cost per ton of each of these materials. The weight of each material was calculated from the cellphone waste generation calculated by SEMARNAT [9], Baldé et al. [13], and the field study of 12 recycling facilities for 2015.

Table 7. Economic value of materials in cellphone printed circuit boards in Mexico in 2015.

Item	Material	Composition	Market Price	Total Cellphones in Mexico				Formal Recycling in Mexico	
				Cellphones: 5517.9 ton/y (S)		Cellphones: 5000 ton/y (B)		Cellphones: 301 ton/y (F)	
				PCB: 496.6 ton/y (S)		PCB: 450 ton/y (B)		PCB: 27 ton/y (F)	
		(%) +++	(USD/ton) ***	W	Value	W	Value	W	Value
				(ton/y)	(USD)	(ton/y)	(USD)	(ton/y)	(USD)
Metals									
1	Copper	40.340	5490	200.33	1,099,803	181.53	996,600	10.89	59,796
2	Nickel	2.598	11,788	12.90	152,085	11.69	137,814	0.70	8269
3	Steel	3.494	361	17.35	6264	15.72	5676	0.94	341
4	Tin	4.118	16,000	20.45	327,200	18.53	296,496	1.11	17,790
5	Titanium	0.350	55,556	1.74	96,562	1.58	87,501	0.09	5250
6	Gallium	0.022	317,000	0.11	34,633	0.10	31,383	0.01	1883
Precious Metals									
7	Palladium	0.006	24,395,944	0.030	726,902	0.027	658,690	0.002	39,521
8	Silver	0.028	553,086	0.139	76,906	0.126	69,689	0.008	4181
9	Gold	0.0488	40,919,295	0.243	9,916,415	0.221	8,985,877	0.013	539,153
Rare Earths									
10	Neodymium	0.028	54,614	0.139	7594	0.126	6881	0.008	413
	Total				12,444,362		11,276,607		676,596

S: SEMARNAT [9], B: Baldé et al. [13], F: Field study with 12 recycling facilities. +++ Estimated data from Table 6. *** Data from 2015. Source: Prepared by the authors based on fieldwork and literature [9,13].

Studies carried out by SEMARNAT indicated that 496.6 tons of PCBs were generated from cellphones in Mexico in 2015—representing 9% from 5517.9 tons total e-waste—with an estimated total value of approximately $12.444 million USD. Similarly, values obtained from the studies conducted by the United Nations University [13] gave an estimated economic value of $11.277 million USD for Mexico. Finally, the field study conducted at 12 recycling facilities in the present study showed that 27 tons of PCBs were generated, equating to an estimated value of almost $676,596 USD for these companies.

3.4. Mass Analysis of E-Waste Materials in Cellphones

This section presents the results of the mass analysis of the materials that comprise cellphone waste, which used the e-waste generation data for 2015 provided by SEMARNAT [9] and the United Nations University [13] as references (1103.57 and 1000 kilotons, respectively). Studies carried out by Baldé et al. [13] indicated that only 0.5% of the total e-waste generated contained cellphone waste, giving weights of 5517.9 and 5,000 tons in cellphones, respectively.

The data obtained in the present study from the field research in recycling facilities in Mexico were also used, which showed that the 12 companies recycled a total of 301 tons of cellphone waste. Focusing on the total e-waste generation from SEMARNAT [S], Baldé [B], and the fieldwork [F], each material was calculated based on the compilation of the cellphone composition from Kumar et al. [14], Zeng et al. [19], Ouguchi et al. [27], Yamane et al. [28], and Holgersson et al. [29]. For example: Aluminum, with 2.35% of composition, represents 129.67 tons from the cellphone waste of SEMARNAT (5517.9 ton).

Cellphones are generally composed of 18 chemical elements and other materials that cannot be recovered, such as porcelains, flexors, plastic parts, and glue [13]. Table 8 presents the cellphone waste compositions that were determined by Baldé et al. [13] across 50 countries and the estimated weights of each element in cellphone waste in Mexico based on the cellphone waste data calculated by SEMARNAT, Baldé et al., and the field research carried out at 12 Mexican recycling facilities in the present study [9,13].

Table 8. Weight estimation of the materials in cellphone e-waste in Mexico in 2015.

Item	Material	Cellphone Composition (%) ***	Weight of Materials in Cellphone Waste (Estimated Data) (ton/year)		
			Total E-waste in Mexico: 5517.9 ton/y (S)	Total E-waste in Mexico: 5000 ton/y (B)	Formal Recycling E-waste in Mexico 301 ton/y (F)
			Metals		
1	Aluminum	2.35	129.67	117.50	7.07
2	Cobalt	5.00	275.90	250.00	15.05
3	Copper	9.94	548.48	497.00	29.92
4	Indium	0.00006	0.003	0.003	0.00
5	Lead	0.004	0.22	0.20	0.01
6	Lithium	0.35	19.31	17.50	1.05
7	Nickel	1.6	88.29	80.00	4.82
8	Steel	9.74	537.44	487.00	29.32
9	Tantalum	0.018	0.99	0.90	0.05
10	Tungsten	0.31	17.11	15.50	0.93
11	Zinc	0.4	22.07	20.00	1.20
			Precious Metals		
12	Gold	0.02	1.10	1.00	0.06
13	Palladium	0.008	0.44	0.40	0.02
14	Silver	0.24	13.24	12.00	0.72
			Rare Earths		
15	Neodymium	0.04	2.21	2.00	0.12
16	Praseodymium	0.0079	0.44	0.40	0.02
			Non-metals		
17	Glass	3.8	209.68	190.00	11.44
18	Plastics	45.03	2484.71	2251.50	135.54
19	Other	21.15	1167.04	1057.50	63.66
	TOTAL	100	5518	5000	301

S: SEMARNAT [9], B: Baldé et al. [13], F: Field study with 12 recycling facilities, *** Hard data Baldé et al. [13]. Source: Prepared by the authors based on fieldwork and literature [9,13].

The 18 elements that comprise cellphones were classified into metals, non-metals, precious metals, and rare earths. There were 11 elements in the metals category, among which copper had the highest representation (9.94%), followed by steel (9.74%) and cobalt (5%), while aluminum (2.35%), nickel (1.6%), zinc (0.4%), and lithium (0.35%) were present at lower levels. Precious metals, such as gold (0.02%), palladium (0.008%), and silver (0.24%), were mainly found in the PCBs, and their recovery has great commercial importance. Rare earths, such as neodymium (0.04%) and praseodymium (0.0079%), serve as magnets in cellphones. Finally, plastic has the highest representation in cellphones (42.03%).

3.5. Interconnection of Research Results in the Context of the Circular Economy

The CE is normally represented by four loops: a) Product-life extension, b) redistribution/reuse, c) remanufacturing (repair), and d) recycling [2]. The results shown in this section characterize the third (repair shops) and fourth loops (recycling facilities and material flow analysis) in order to assess their degree of development. In addition, the ultimate goal of a CE is measured in terms of the associated environmental, economic, and social impact [1,4]. On the one hand, the analysis of valuable materials in PCBs and cellphones provides a basis for appraisal of the economic and environmental impact of this type of e-waste. On the other hand, the survey of informal repair shows provides a unique look at the social impact of the remanufacturing loop. The following discussion section will provide more detail into all the aforementioned dimensions of CE.

4. Discussion

4.1. Outlook of Repair and Recycling

The field study findings in regards to sources of e-waste in Mexico are consistent with that of Cucchiella et al. [37], who showed that the e-waste flow is primarily made up of household appliances. Similarly, the United Nations University determined that large equipment and cooling and freezing equipment have the represent the highest volume in the e-waste flow [13].

Furthermore, the reported finding that cellphone waste has one of the lowest representations at 7% (equivalent to 301 tons/year) is also consistent with the results of Baldé et al. [13], who confirmed that small and telecommunications equipment constitute the lowest proportion of e-waste flow. Given an estimation of cellphone e-waste in the order of $2633 tons/year, this outlook highlights the need for public policy incentives and further regulations in order to capture a higher proportion of cellphone e-waste through formal channels and therefore harness the potential economic benefits derived from valuable materials.

Fieldwork results in Mexico showed that recycling processes are basic, based on both manual operations and mechanical systems. This finding is consistent with studies by SEMARNAT [25], Cruz et al. [8], Ghosh et al. [12], and Kumar et al. [14], as it shows that recycling processes in Mexico and in emerging economies are elemental, simple, and do not include end-processing technologies. Similar work of Parajuly et al. [15] studied the processing techniques used on recycling companies in Europe, including medium and small recyclers used rudimentary tools and equipment, which pose significant health and safety risks to the workers. Nonetheless, the recovered material streams from manual disassembly are of high purity and cleanliness, and makes it possible to recover even small valuable components and material e-waste.

In this study, we found that informal repair shops compete in an inequitable way compared to formal shops. However, informality was identified as a self-organized workforce that offers the customer similar quality of work in less time and at a lower price. In Mexico, it is clear that consumers prefer the most economic and efficient solution, regardless if it is a formal or informal shop. Studies undertaken by Atlason et al. [38] and Perez-Belis et al. [39] showed that consumers look for formal repair stores based on the type and quality of customer service but often prefer the most economic and efficient solution in terms of repair time and price, regardless of the academic level or working conditions of the people working there.

4.2. Material Flow Analysis of Cellphone E-Waste

After material flow analysis, the fieldwork reported here confirmed that recycling companies in Mexico export all PCBs extracted from cellphones. These findings are congruent with those of Ghosh et al. [12], who defined the different routes of recycling and end-processing technologies by analyzing more than 150 articles; they also confirmed that few countries have this type of recovery technology, and that these materials are generally shipped to Asian and European countries. Similarly, Cucchiella et al. [37] determined that Europe has unresolved issues related to recycling processes, particularly in regards to materials recover from PCB components because of incorrect disassembly.

In order to justify the installation of this kind of end-processing technology for materials discovery in Mexico, there has to be a solid case in terms of return on investment. Furthermore, the economic impact study and mass analysis provide some elements for such a business case.

4.3. Economic Impact of E-Waste Materials in Printed Circuit Boards of Cellphones

Figure 4 shows the relative value of cellphone PCB materials based on the field data presented in Table 7. For this type of e-waste, it is clear that the most significant opportunity in terms of end-processing technologies centers on recovery of gold (with 79.7% of the total value in cellphone PCB materials). In terms of materials value, 97.0% is given by potential local recovery of gold, copper, palladium, and tin.

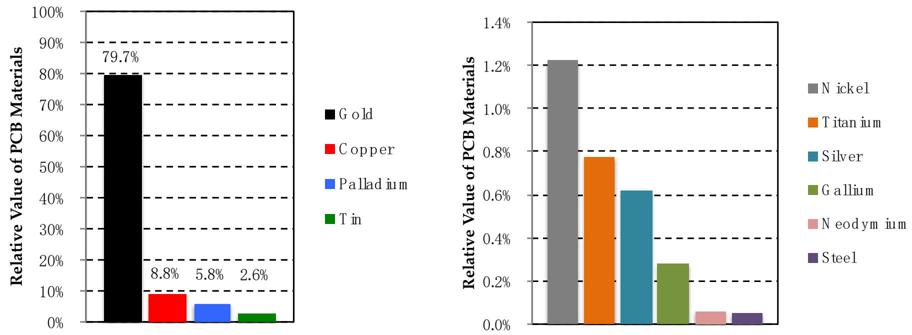

Figure 4. Relative value of cellphone PCB materials processed through formal channels in Mexico (source: based on filed data collected by authors and estimations reported in Table 8).

Although the market value of copper and tin is not nearly as high as that of gold and palladium ($40.9 and $24.4 million USD per ton, respectively), the relatively large proportion of these metals in cellphone PCBs makes them attractive in terms of value. Therefore, potential investment in end-processing technologies for recovery should be focused on those chemical elements.

Yu et al. [11] showed that, in China, the economic benefit of recycling one ton of cellphone waste per year was $10,860 USD, while Baldé et al. [13] determined that the economic value of gold, silver, and palladium in e-waste was $15.12 million USD per year in Latin America. Furthermore, Cucchiella et al. [37] suggested that the recovery of critical materials and precious metals (particularly gold) would generate half of the profits within a recycling economy.

If e-waste is correctly recycled, and the recovery of materials is carried out locally, there will be an immediate economic benefit to a country. Kumar et al. [14] explains that if electrical and electronic waste were recycled locally and efficiently, the recovery of materials in Europe such as gold, copper, silver, and palladium would be worth approximately $48 billion USD. Furthermore, Cucchiella et al. [37] concluded that such recycling of e-waste might generate income equivalent to $2.50 billion USD in 2015.

Based on the research reported here, we show that in Mexico there is a great potential for economic benefit from proper recycling and local processing of PCB materials from cellphones. Only an estimated value of $0.677 million USD in materials is recovered through formal means (see Table 7). However, the estimates show that the total value of cellphone PCB materials ranges between $11.277 and $12.444 million USD per year (see Table 7). These results highlight the importance of investing in end-processing technologies for materials recovery as well as developing strategies for better and more efficient e-waste collection which prevent the informal channels and unsafe disposal from taking almost 90% of this e-waste. Furthermore, the analysis of the complete cellphone (as opposed to analyzing only the PCB), as shown before, highlights the significance of precious metals such as gold, palladium, lithium, and nickel.

5. Conclusions

The circular economy is a relatively new concept for the electronic products sector in Mexico but has high potential for impact. There are limited investigations of e-waste in this country, so the present study provides useful and necessary insights for planning and establishing strategies that will benefit the society, environment, industry, and economy of Mexico. Some of these strategies should focus on improving the technological abilities of electronic waste recyclers, enhancing the repair and reuse of parts, and investing in end-processing technologies for materials recovery.

The material flow analysis indicates that Mexico captures a value of $0.679 million of materials for cellphone PCBs through formal recycling. The total value of these materials is estimated in the range of $12.485 million USD per year. Under these conditions, from the industry point of view, a proper case for return on investment for end-processing technologies is difficult. Therefore, complete PCBs will probably continue to be exported, with the corresponding loss of national economic benefit.

On the other hand, the informal processing of cellphone e-waste provides another affordable channel for repair and reuse, with the associated reduction of environmental impact, which could aid in advancing Mexico towards a circular economy model. However, this study has identified areas of improvement for the informal repair shops in terms of safety and compliance with labor regulations, especially in regard to working and health conditions for the workforce.

In terms of the circular economy paradigm, as related to e-waste of cellphones, our study shows some progress in terms of closing the loops of remanufacturing (repair) and material recycling. Therefore, we have addressed only two out the four loops involved in a complete CE scenario. Further research is necessary in order to look into the companies and their policies in terms of product design for extended use (related to the first loop of the CE). Additional research is also envisioned regarding the social impact of informal repair shops. In this topic, there is much to discover given the fact that customers are satisfied with the service provided and this kind of repair shops also provides a source of employment.

Author Contributions: Conceptualization, D.C.; data curation, D.C.; formal analysis, D.C.; funding acquisition, C.A.R. and D.R.; investigation, D.C.; methodology, D.C., I.A., C.A.R., and D.R.; project management, D.C., I.A., C.A.R., and D.R.; supervision, D.C., I.A., C.A.R., and D.R.; validation, D.C., I.A., C.A.R., and D.R.; visualization, D.C.; writing—original draft, D.C.; writing—review and editing, D.C., I.A., D.R. and C.A.R.

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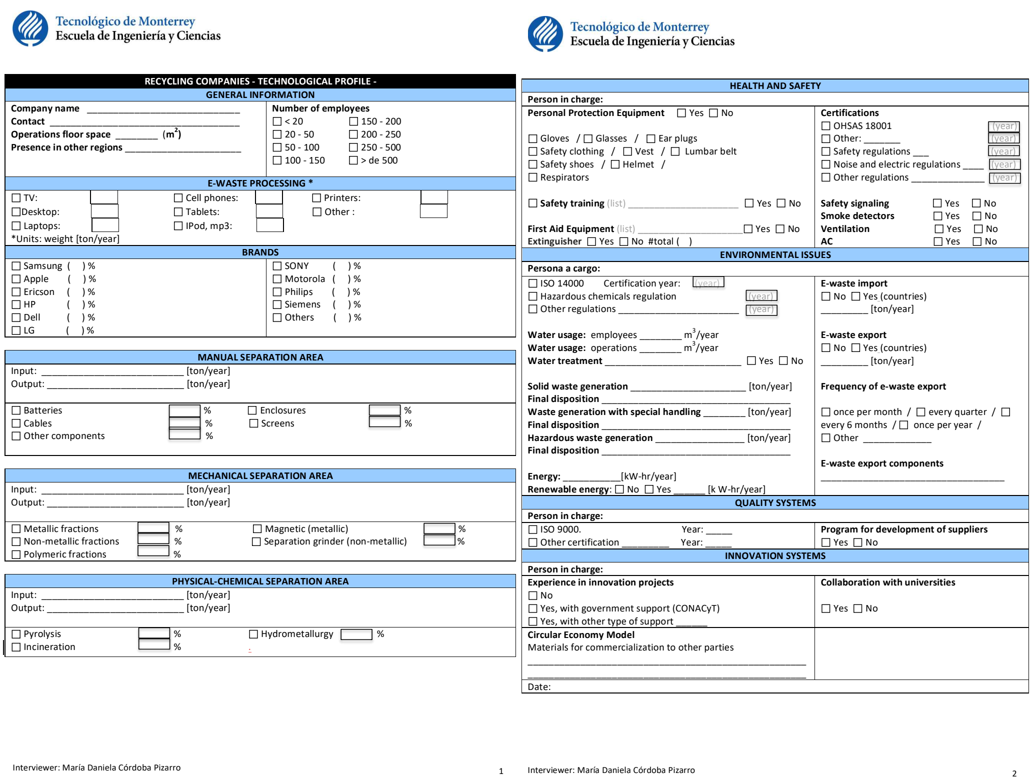
Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Appendix A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Escuela de Ingeniería y Ciencias

RECYCLING COMPANIES - TECHNOLOGICAL PROFILE -

GENERAL INFORMATION

Company name ___
Contact ___
Operations floor space ___ (m^2)
Presence in other regions ___

Number of employees
☐ < 20 ☐ 150 - 200
☐ 20 - 50 ☐ 200 - 250
☐ 50 - 100 ☐ 250 - 500
☐ 100 - 150 ☐ > de 500

E-WASTE PROCESSING *

☐ TV: ☐ Cell phones: ☐ Printers:
☐ Desktop: ☐ Tablets: ☐ Other :
☐ Laptops: ☐ IPod, mp3:
*Units: weight [ton/year]

BRANDS

☐ Samsung ( ) %
☐ Apple ( ) %
☐ Ericson ( ) %
☐ HP ( ) %
☐ Dell ( ) %
☐ LG ( ) %
☐ SONY ( ) %
☐ Motorola ( ) %
☐ Philips ( ) %
☐ Siemens ( ) %
☐ Others ( ) %

MANUAL SEPARATION AREA

Input: ___ [ton/year]
Output: ___ [ton/year]
☐ Batteries % ☐ Enclosures %
☐ Cables % ☐ Screens %
☐ Other components %

MECHANICAL SEPARATION AREA

Input: ___ [ton/year]
Output: ___ [ton/year]
☐ Metallic fractions % ☐ Magnetic (metallic) %
☐ Non-metallic fractions % ☐ Separation grinder (non-metallic) %
☐ Polymeric fractions %

PHYSICAL-CHEMICAL SEPARATION AREA

Input: ___ [ton/year]
Output: ___ [ton/year]
☐ Pyrolysis % ☐ Hydrometallurgy %
☐ Incineration %

Interviewer: María Daniela Córdoba Pizarro 1

Tecnológico de Monterrey
Escuela de Ingeniería y Ciencias

HEALTH AND SAFETY

Person in charge:

Personal Protection Equipment ☐ Yes ☐ No
☐ Gloves / ☐ Glasses / ☐ Ear plugs
☐ Safety clothing / ☐ Vest / ☐ Lumbar belt
☐ Safety shoes / ☐ Helmet /
☐ Respirators
☐ Safety training (list) ___ ☐ Yes ☐ No
First Aid Equipment (list) ___ ☐ Yes ☐ No
Extinguisher ☐ Yes ☐ No #total ( )

Certifications
☐ OHSAS 18001 (year)
☐ Other: ___ (year)
☐ Safety regulations ___ (year)
☐ Noise and electric regulations ___ (year)
☐ Other regulations ___ (year)
Safety signaling ☐ Yes ☐ No
Smoke detectors ☐ Yes ☐ No
Ventilation ☐ Yes ☐ No
AC ☐ Yes ☐ No

ENVIRONMENTAL ISSUES

Persona a cargo:

☐ ISO 14000 Certification year: (year)
☐ Hazardous chemicals regulation (year)
☐ Other regulations ___ (year)
Water usage: employees ___ m^3/year
Water usage: operations ___ m^3/year
Water treatment ___ ☐ Yes ☐ No
Solid waste generation ___ [ton/year]
Final disposition ___
Waste generation with special handling ___ [ton/year]
Final disposition ___
Hazardous waste generation ___ [ton/year]
Final disposition ___
Energy: ___[kW-hr/year]
Renewable energy: ☐ No ☐ Yes ___ [k W-hr/year]

E-waste import
☐ No ☐ Yes (countries)
___ [ton/year]
E-waste export
☐ No ☐ Yes (countries)
___ [ton/year]
Frequency of e-waste export
☐ once per month / ☐ every quarter / ☐ every 6 months / ☐ once per year /
☐ Other ___
E-waste export components
___

QUALITY SYSTEMS

Person in charge:

☐ ISO 9000. Year: ___
☐ Other certification ___ Year: ___
Program for development of suppliers
☐ Yes ☐ No

INNOVATION SYSTEMS

Person in charge:

Experience in innovation projects
☐ No
☐ Yes, with government support (CONACyT)
☐ Yes, with other type of support ___
Collaboration with universities
☐ Yes ☐ No
Circular Economy Model
Materials for commercialization to other parties
___
Date:

Interviewer: María Daniela Córdoba Pizarro 2

Figure A1. Questionnaire used for the survey of recycling companies.

Table A1. E-waste collection of electrical and electronic equipment by each recycling facility interviewed, 2015.

Company	Total E-Waste	TV	Desktop Computer	Laptop Computer	Cellphone	Tablet	Others
	(ton/year)	Percentage (%) and Weight (ton/year)					
			Small				
C2	60	6% 3.6	2% 1.2	2% 1.2	3% 1.8	0% 0	87% 52.2
C4	96	24% 23.0	18% 17.3	15% 14.4	9% 8.6	2% 1.9	32% 30.7
C5	60	17% 10.2	18% 10.8	12% 7.2	10% 6.0	5% 3.0	38% 22.8
G3	72	20% 14.4	25% 18.0	17% 12.2	12% 8.6	1% 0.7	25% 18
M2	84	4% 3.4	28% 23.5	21% 17.6	7% 5.9	1% 0.8	39% 32.76
			Medium				
G2	120	19% 22.8	30% 36.0	16% 19.2	9% 10.8	0% 0.0	26% 31.2
G4	360	7% 25.2	18% 64.8	21% 75.6	4% 14.4	5% 18.0	45% 162
			Large				
C1	540	15% 81.0	24% 129.6	8% 43.2	6% 32.4	1% 5.4	46% 248
C3	636	2% 12.7	18% 114.5	2% 12.7	2% 12.7	0% 0.0	76% 483.36
C6	720	15% 108.0	17% 122.4	15% 108.0	6% 43.2	3% 21.6	44% 316.8
G1	600	15% 90.0	16% 96.0	10% 60.0	10% 60.0	3% 18.0	46% 276.0
M1	1140	20% 228.0	18% 205.2	10% 114.0	5% 57.0	3% 34.2	44% 501.6
Total	4488	14% 622	19% 839	12% 485	7% 261	2% 104	46% 2176

Source: prepared by the authors based on field work.

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