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Analysis of Circular Strategies for Waste Electrical and Electronic Equipment: A Chilean Case Study

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Abstract

The rapid growth of Waste Electrical and Electronic Equipment (WEEE) has become a global environmental and management concern. In the present study, the status of WEEE in Chile, including the regulations, stakeholders, and the management process, is analyzed, with the inclusion of the circular approach followed in Switzerland, Colombia, and Japan. The PESTEL analysis method is used to identify the main factors affecting the sustainable management of WEEE, based on international best practices. On the other hand, a comprehensive circular approach has been proposed that meets the specific requirements of the Chilean context, in accordance with the Extended Producer Responsibility (EPR) Law. The approach includes the improvement of the collection system (fixed and mobile), the modernization of pretreatment through advanced technologies, the use of financial instruments (differentiated recycling rates and tax incentives), and the importance of educating citizens. The results discuss the expected environmental, social, and economic benefits of this strategy, such as increased material recovery, reduced hazardous waste in landfills, and the integration of recyclers and conclude with policy recommendations and actions to consolidate circular WEEE management in Chile.

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1. Introduction

In the last few decades, rapid advancements in technology and increased consumerism have significantly increased the rate of Waste Electrical and Electronic Equipment (WEEE) generation. This includes a wide range of electronic devices, from home appliances and computer systems to mobile phones and batteries. Even though this waste is rich in valuable materials such as metals and polymers, it also carries hazardous materials such as lead, mercury, cadmium, and other heavy metals [23][26]. If these materials are not handled properly, they may lead to severe environmental and health hazards by polluting the soil, water, and other ecosystems [23]. As a result, the world is now increasingly concerned about electronic waste management, as stated by international organizations that only a small percentage of the millions of tons of electronic waste generated each year is being recycled [11].

Chile is a clear case of this universal problem. The country is estimated to generate about 200,000 metric tons of waste every year, with only 5% being recycled [30]. According to the Ministry of the Environment, only 3.4% of this electronic waste is recycled at present, which translates to about 320 grams per person annually [7]. Most of this waste is at the household level, while some is mismanaged, mainly because of poor recycling infrastructure, economic factors, and a lack of awareness and participation in recycling activities [20][12].

However, it is noteworthy that there have been some achievements through the creation of a regulatory framework aimed at fostering a circular economy in waste management. The enactment of Law No. 20,920 in 2016 to promote recycling and Extended Producer Responsibility (EPR) has been a major milestone for environmental legislation in the country. The EPR law provides extended responsibility to the producers and importers of products that are categorized as priorities for waste management, such as electrical and electronic equipment, for managing post-consumer waste [9][28]. The law thus provides a major impetus for the promotion of sustainable production and consumption patterns by giving priority to waste prevention, reuse, and recycling over final disposal [25][15]. It also provides important tools such as deposit-refund systems, eco-design concepts, selective collection systems, traceability systems, and specific collection and recycling targets for different waste streams [29]. Overall, the legislation provides a legal basis for a transition from a linear economy of ‘take, use, and dispose’ to a circular economy where products at the end of their useful life can be reused or recycled to join the production cycle again.

Nevertheless, the implementation of this model continues to face significant challenges. Close to a decade after the EPR Law in Chile was enacted, Chile does not yet boast a wide network of collection points and treatment facilities for WEEE [16][27]. Furthermore, it has been identified that there are regional differences in the options available to users and businesses in different parts of the country to properly dispose of their obsolete electrical devices [16][3]. Even though the EPR Law in Chile holds producers accountable for their share in the management of WEEE, the level of citizen involvement remains limited. The rates of source-separated waste and citizen awareness about collection points and the benefits of electrical recycling remain low in Chile [5][1].

The objectives of this paper are to identify and analyze the strategies related to the sustainable management of WEEE in Chile by incorporating the principles of circular economy concepts. For this purpose, the current situation related to WEEE management in Chile at the national level will be evaluated in terms of the legal framework, flows of WEEE management, and major stakeholders involved in WEEE management in Chile, as well as the current limitations in the management of WEEE in Chile. Similarly, successful experiences in WEEE management in other countries will be evaluated and compared with the current situation in Chile. Finally, based on the results of the analysis of the current situation in Chile and successful experiences in other countries, an overall strategy will be proposed to manage WEEE in Chile in accordance with the EPR Law and improvements in terms of infrastructure, technology, finance, and education will be taken into account to close the WEEE life cycle.

Moreover, the methodology used in the analysis of the cases of Switzerland, Colombia, and Japan will be explained in the following sections of the paper, followed by the strategy proposed for Chile and the conclusions and recommendations of the study.

2. Related Work

Plastic has become a common commodity throughout the world, appreciated for the low cost of production as well as the versatility of the material to be molded for a multitude of purposes. Despite the widespread presence of plastic within almost every industry, however, less than 10% of the plastic produced is recycled every year [5]. Many organizations have not made recycling a top priority, not only because of a lack of knowledge about the management of wastes, but also because of the additional cost of recycling plastic wastes [6]. This is no longer the case as organizations are forced to look for strategies to help recycling through the implementation of EPR [7].

Among the various options, mechanical recycling is the most commonly used. This works effectively with thermoplastics and also requires less investment compared to the other processes. Nevertheless, with every cycle of recycling, the material becomes weaker. Additives are therefore necessary to achieve some of the mechanical properties of the material [8][9]. In comparison, chemical recycling, although effective, is far more energy-intensive and operationally challenging [10]. The other processes, such as energy recovery and biological recycling, are not feasible due to environmental concerns [11] and are also too expensive [12].

Studies have also been conducted on the properties of the recycled materials when used in the 3D printing process. Not all materials can be recycled, and fewer materials can be used to create the filament necessary for the 3D printer [13][14][15]. Some materials, when melted, release harmful chemicals, which can be detrimental to the environment and the user. This contradicts the concept of sustainability, which is a major factor.

Nevertheless, some of the most popular polymers used in daily life, such as PET (Polyethylene Terephthalate), Despite the challenges, a small number of commonly used polymers such as PET, HDPE (High-Density Polyethylene), PP, ABS (Acrylonitrile-Butadiene-Styrene), and HIPS (High-Impact Polystyrene) show good properties when recycled and reprocessed, which is why they are commonly used for recycling.

However, polymers like PET, HDPE, PP, ABS, and HIPS have shown promising results when they are recycled and processed properly. They are considered common polymers for recycling into recycled filaments.

3. Methodology

The methodological framework for this research has combined elements of description and proactivity through the use of documentary research and a comparative assessment. The rationale for this research has a number of different elements, including: (1) undertaking a comprehensive review of the literature; (2) undertaking a PESTEL analysis (Political, Economic, Social, Technology, Environmental, and Legal) of the context in which WEEE management has to be carried out in Chile; (3) undertaking case studies of the experiences of other countries with regard to WEEE management; and (4) developing a proposal based on a conceptual evaluation of the potential benefits of the research. The process will follow a series of five phases:

- **Phase 1:** We define the current status of WEEE management in Chile. In order to achieve this, we will rely on secondary data collected from government publications, previous studies conducted on this particular topic, and academic journals related to WEEE management.
- **Phase 2:** We will carry out a PESTEL analysis in order to comprehend the overall context of WEEE management in Chile [10].
- **Phase 3:** An international analysis will be conducted by comparing WEEE management in three countries: Switzerland, Colombia, and Japan. For the purpose of gathering data on WEEE management in these countries, technical literature and publications of relevant organizations will be relied upon.
- **Phase 4:** A proposal will be formulated on how to implement the Circular Economy concept in WEEE management in Chile. It is based on the particular problems that Chile faces in WEEE management, as well as lessons learned from Switzerland, Colombia, and Japan. The strategy was captured in a flowchart that integrates improvements at each stage of the process (collection, pretreatment, recycling, etc.) and incorporates new components into the current Chilean system (mobile point network, regional plants, traceability systems, among others), refer to **Fig. 1**.

- **Phase 5:** A qualitative evaluation of the potential benefits of the proposed strategy was conducted. Given the limited availability of detailed quantitative data, the evaluation focused on a qualitative cost-benefit analysis and a comparison of scenarios with and without the strategy's implementation. Impacts were considered in five areas: environmental (reduction of hazardous waste disposal, increased material recovery), social (creation of green jobs, formalization of recyclers), economic (resource savings, secondary market development), technological (recycling transfer and innovation), and legal (better compliance with EPR targets).

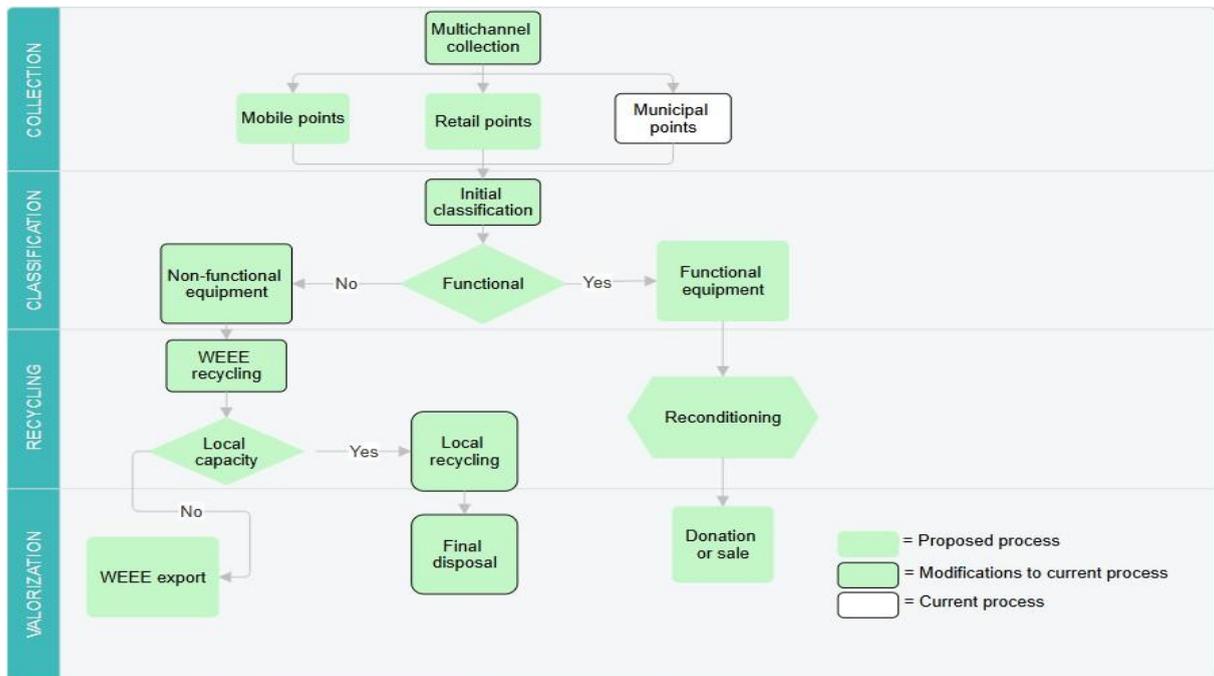


Fig. 1. Flowchart of the proposal for Chilean WEEE management.

4. Results

4.1. National context – Chilean situation

Chile's legal framework in dealing with electronic waste is well established, with Law 20,920 on extended producer responsibility (EPR). However, in terms of implementation, Chile's performance is not impressive. The law established a system of shared responsibility, with producers and importers establishing and funding recycling programs, distributors and retailers collecting used and unused electronic devices, and consumers delivering their used electronic devices to collection points instead of throwing them away with regular trash [1]. Nevertheless, the development of required infrastructure to support this system has not grown sufficiently to meet the objectives outlined in this law. Huge areas across the country, especially rural areas, are still without access to proper WEEE disposal and treatment facilities [16]. There are currently many management companies authorized to collect and treat electronic waste across the country. However, these management companies are limited in number and are mainly located in the Metropolitan Region and some mining areas [27].

The current treatment system for WEEE in Chile is mainly manual. The current system of pretreatment involves disassembling electronic devices to retrieve reusable parts, separating base materials like metals and plastic, and separating hazardous waste like batteries and monitor screens. However, the system under focus has low levels of automation and technology, which are a challenge in terms of efficiency, traceability, and recovery rates. This is due to the discrepancy between the lofty goals set in the pro-recycling legal framework and the realities on the ground. This discrepancy can only be bridged by stepping up investment, incentives, and education to increase the collection and recovery rates of WEEE.

4.2. PESTEL Analysis – Key Factors in Chile

Several interrelated factors are relevant to the opportunities and challenges in the management of WEEE in Chile. These factors are political, economic, social, technological, environmental, and legal. From an overall perspective, it is possible to identify that the various elements of PESTEL analysis create a complex scenario, where advances in terms of regulation are accompanied by obstacles related to structure, technology, and human behavior. The main findings of the PESTEL analysis are shown in **Fig. 2** – National context – Chilean situation.

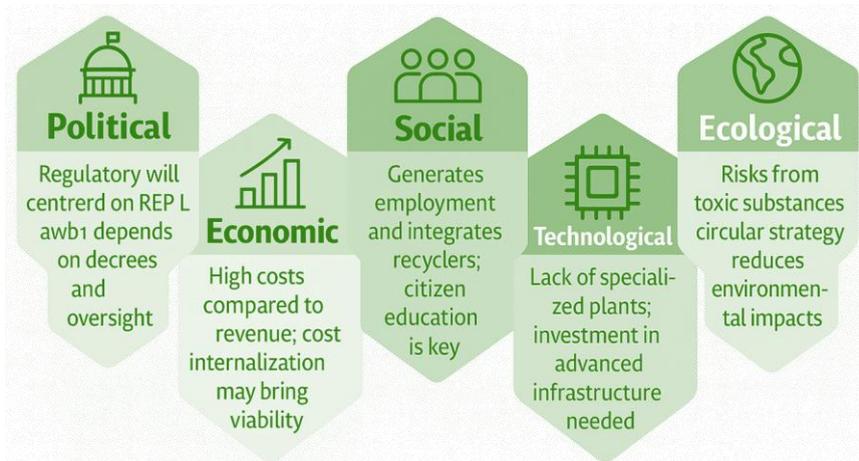


Fig. 2. PESTEL Analysis, Key Factors in Chile.

4.3. International Experiences

The three case studies on WEEE management in Switzerland, Colombia, and Japan provide valuable insights into how countries have addressed WEEE management through the circular economy concept. Each of the vignettes occurs in its own distinct context of institutions, economies, and cultures; however, as a whole, the three studies provide valuable lessons on how Chile can create a better WEEE management system.

- 1) **Switzerland:** As one of the pioneers in WEEE management in the context of a national WEEE management system based on the concept of Extended Producer Responsibility, Switzerland has mandated the funding and operation of WEEE management by manufacturers and importers and distributors of electrical and electronic equipment since the end of the 1990s. Of particular importance in the context of WEEE management in Switzerland is the so-called Advanced Recycling Fee (ARF) component of the cost of new electrical and electronic products and appliances purchased by consumers and paid at the point of sale. This allows consumers to return obsolete WEEE at no additional cost at designated WEEE take-back locations and/or at retail stores throughout the country, effectively removing the economic disincentive to WEEE disposal and creating a strong funding model for WEEE management in general. Indeed, in 2016, the country collected 22.2 kg of WEEE per capita, one of the highest rates in the world, with collection rates as high as 95%. For Chile, the Swiss model illustrates the importance of combining regulatory requirements with clear and transparent economic incentives to encourage participation in WEEE management and support the long-term viability of WEEE management systems.
- 2) **Colombia:** The past ten years have seen significant advances by this country in implementing EPR for WEEE, adapting it to the Latin American context. The National WEEE Policy and Law 1672 of 2013 established mandatory requirements for producers/importers of electronic equipment to develop Selective Collection Systems (SCS) and environmental management plans for this waste. This gave rise to three main collective systems operated by business consortia: EcoCómputo, Red Verde, and Lúmina. Together, they are responsible for the collection and management of the WEEE in Colombia. Moreover, one aspect that needs to be improved in

Colombia is technological: there are not yet industrialized plants to fully process all WEEE, so after an initial manual disassembly, certain components (electronic cards, metal, and plastic fractions) are exported to other countries for refining. Even so, the Colombian experience stands out for managing to articulate the industry in collective schemes that have increased territorial coverage and annual recollection of WEEE (collection goals increase every year). For Chile, Colombia offers lessons on the creation of sector-based post-consumer systems in the Latin American context, the importance of specific regulations (resolutions) that encourage producers to join forces and submit plans, and the need to complement local management with international alliances for the final recycling of certain materials.

- 3) **Japan:** Japan has one of the strictest and most structured frameworks for recycling e-waste, centered on the “user pays” principle and full traceability. Japanese legislation is primarily composed of two laws: The Household Electrical Appliance Recycling Act of 1998 and the Small Electrical Appliance Recycling Act of 2012. The former established a mandatory recycling system for four types of mass-produced household appliances (televisions, refrigerators, washing machines, and air conditioners), defining shared but differentiated responsibilities: consumers must hand in their used equipment and pay a recycling fee per appliance; retailers must accept unused appliances when a customer buys a new one, or even if the customer does not buy one (as long as it is an equivalent product), and take them to designated collection centers; and manufacturers must be responsible for recycling the collected appliances, meeting minimum material recovery rates. This system offers dedicated funding through user-paid tickets at the collection point and also keeps a detailed record for every recycled item. The traceability is thorough, covering every discarded appliance from the point it is collected by the retailer (through receipt issued) to its arrival at the recycling facility operated by the manufacturer, thus allowing for continuous monitoring for compliance. Japan has also built upon this system through its strict enforcement and sanction measures. If retailers or manufacturers do not comply with their collection/recycling duties or attempt to falsify records, they face severe fines and prosecution. The end result is an effective system that ensures almost every approved appliance is collected from consumers who discard them, thus ensuring high rates of material recycling, for example, by law, over 70% of an appliance by weight is recycled. In relation to the Chilean scenario, Japan offers an example for developing a recycling ticket/fee system for funding, defining roles for every actor within the chain (with legally binding obligations), and developing documentary tracking systems for transparency and ensuring compliance with recycling targets.

Through the different international experiences, a consensus has been observed regarding the need for a robust regulatory framework, achieved through the implementation of specific WEEE regulations or the integration of these regulations into the EPR regulations, to be accompanied by adequate infrastructures and economic incentives to change the behavior of producers and consumers. This is demonstrated by the experiences in Switzerland, Colombia, and Japan, where the need for the collaboration between the government and private actors is emphasized, as the former can achieve greater efficiency in the collection and management of WEEE through the collective systems organized by the latter. Moreover, the importance of traceability and flow control, as observed in the Swiss reporting systems and the ticket system in Japan, is also emphasized as a means to professionalize the management of WEEE. All these aspects have been taken into consideration for the proposed strategy for Chile, as discussed in the next section.

Therefore, for the proposed **Framework for Chile**, as informed by the lessons learned and the assessment, a comprehensive strategy has been proposed for the current study to ensure the optimal management of WEEE in Chile, in line with the objectives of the EPR Law. The pillars of the proposed circular strategy are as follows:

- **Expanded Collection Network:** The strategy also includes an expanded collection network of fixed and mobile collection points to ensure that all regions in the country are reached. For this purpose, in major cities, fixed collection points would be established in coordination with local authorities and retailers of electrical and electronic devices. This would allow residents to conveniently deposit their unused electrical and electronic devices. These collection centers would also carry out initial sorting of collected WEEE. Devices found to be in good working order and capable of being repaired would be reconditioned and donated, and those found to be inoperable would be temporarily stored under safe conditions. For rural and low-density regions, mobile eco-points would be established to periodically visit different cities and towns to collect WEEE at predetermined

times.

- **Technological Modernization and Strengthening Pretreatment:** The next pillar involves the modernization of specialized technological infrastructure through the creation of three regional pretreatment plants, one each in the north, center, and south regions. The facilities that will be developed as per the plan will operate as disassembly facilities where WEEE is disassembled into its major constituent parts for recycling while at the same time ensuring that the hazardous components are handled properly. The plan also contemplates the integration of technologies such as automation, optical, magnetic, density-based separators, and others, with the aim of increasing efficiency and safety and promoting transparency through digital traceability.
- **Financial Mechanisms and Economic Incentives:** The plan contemplates the development of various financial mechanisms and economic incentives, including the establishment of a differentiated eco-tax on various electronic devices. The tax will be charged at the point of purchase and used for maintaining existing facilities, developing new facilities, and training personnel. Additionally, the plan contemplates various forms of tax incentives, including exemptions and reductions, for businesses that integrate recyclable materials into their processes and achieve set targets for collected materials.
- **Education, Awareness, and Training: Moving into a circular economy** model entails a paradigm shift in culture. Therefore, the formulation of a National WEEE Education and Awareness Program is strongly encouraged. This program includes wide-ranging public awareness campaigns, curriculum development that incorporates the principles of recycling and circular economy, and the formulation of technical training programs for grassroots recyclers. Training programs for grassroots recyclers are designed to professionalize these stakeholders for eventual inclusion in the formal waste management system, with better working conditions and safety standards. At the same time, awareness programs are designed to improve public participation in WEEE management.
- **Expected Impacts:** The successful implementation of the strategy is expected to decentralize WEEE management, improve national collection rates, and reduce the export of untreated WEEE for downstream processing. It is also expected to promote the recovery of resources, reduce landfill disposal, and create a new class of environmentally friendly ‘green jobs.’ Additionally, technological and financial upgrading of the system is expected to result in greater efficiency, transparency, while environmental education is expected to result in a more informed citizenry. The strategy is expected to result in a comprehensive model that meets the requirements of the EPR Law while at the same time making Chile a regional leader.

5. Conclusion

This research has recognized the need and opportunity for improving the management of Waste Electrical and Electronic Equipment (WEEE) in Chile through the implementation of strategies that promote a circular economy. From the comparative analysis, it is evident that for WEEE management to be effective, it is not only important to have an appropriate legal framework but also to establish practices that ensure a coordinated approach among reuse, recycling, and shared responsibility among stakeholders. When coordinated appropriately, it is possible to realize positive outcomes for the environment, economy, and society. From the experiences of Switzerland, Japan, and Colombia, it is evident that a legal framework is important for ensuring effective WEEE management. However, it is also important to have appropriate and enough infrastructure, a financially viable system, and active participation from stakeholders who are involved in WEEE management.

In this context, it is evident that Chile has an appropriate legal framework for managing WEEE, as it has an Extended Producer Responsibility (EPR) Law. From a developmental perspective, it is evident that there is a lot to be done to improve WEEE management. In this regard, it is evident that there is an opportunity to improve WEEE management in Chile, despite some weaknesses. From this perspective, it is evident that it is possible to improve WEEE management through strategies that can be implemented through the appropriate application of the legal framework and increased awareness among institutions, business, and society regarding environmental concerns. If implemented, it is possible to improve WEEE recovery and shift from a linear approach to a more circular approach.

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