

Evaluation of Circular Economy Practices for Management of the Reverse Chain of Electronic Waste in Brazil

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ABSTRACT

The increasing production of Waste Electrical and Electronic Equipment (WEEE) in Brazil is driving the adoption of circular economy (CE) practices related to the management of the WEEE reverse chain. Thus, the adoption of CE becomes essential for strategic management that promotes environmental preservation, and economic and social development. This study, which employed a survey as the research method, aims to evaluate the importance of CE practices related to the management of the WEEE reverse chain in Brazil. To achieve this, we employed the Kruskal-Wallis and Holm-Sidak multiple comparison tests. Based on the obtained results, the most significant practices are related to legislation and regulations, and effective consumer participation. These are followed by practices related to the management of outsourced recycling companies, and the involvement of logistics operators, treatment, and recycling strategies. The least representative practices were simulations and optimization strategies for logistics transportation, collection centers, and recycling centers. This study contributes to managerial practice by suggesting trends related to environmental management practices and material circularity, as well as compliance with the National Solid Waste Policy. For society, the research highlights the need for consumer education regarding the disposal of WEEE, as well as the necessity for governments and companies to collaborate in forming cooperatives.

Keywords: WEEE, Circular Economy, Reverse Logistics, Reverse chain

1. INTRODUCTION

Waste Electrical and Electronic Equipment (WEEE) is globally increasing at a rate of 3-5% per year [1]. Ranked second as a WEEE producer in the Americas, with an annual output of 1.5 million tons, Brazil demands critical attention for the management of this type of waste [2]. WEEE is a significant source of waste due to the scarcity and value of the materials it contains [1]. Reverse logistics (RL) emerges as a solution for reintegrating WEEE into the production cycle. It encompasses the planning, implementation, and control of reverse flows involving raw materials, finished products, rejects, or discards. The goal is to achieve a final destination that minimizes environmental impact and complies with legal requirements [3]. According to [1], RL of WEEE is crucial for achieving a circular economy (CE) and promoting resource efficiency.

Despite the lack of implementation of CE focusing on WEEE RL, the main goal of CE is to create a regenerative system that ensures the optimal reuse, renewal, remanufacturing, and recycling of products, materials, and waste, keeping them in a closed loop [4]. Effective RL management contributes to achieving the expected economic, environmental, and social benefits through the adoption of CE practices [4]. Considering the EEE segment and its corresponding WEEE reverse chain, RL practices related to CE are crucial for generating environmental, economic, and social value through the integration of these practices. The more CE-related practices are employed, the greater the value creation for organizations, the reverse chain, and the respective products and materials [5].

In this context, it is crucial for players in the WEEE reverse chain to adopt CE practices. These practices enable the collection, segregation, remanufacturing, reuse, and recycling of WEEE, creating a closed loop with economic, environmental, and social benefits. Consequently, the integration of the WEEE reverse chain with CE is a vital strategic aspect for ensuring the efficiency of operations.

In the systematic literature review, no study was identified that evaluates, using the non-parametric Kruskal-Wallis test, the CE practices related to the reverse chain of WEEE suitable for Brazil, highlighting the research gap addressed in this study. In this context, the present study aims to address the following research question: what is the degree of importance of CE practices related to WEEE reverse chain management in Brazil? Therefore, the objective of this study is to assess the degree of importance of CE practices related to WEEE reverse chain management in Brazil.

This work is justified by the limited number of research studies in Brazil despite its significant role in WEEE production. By identifying the degree of importance of the main CE practices, this pioneering study contributes to both the theory (scientific literature) and organizational practice, highlighting the need for the formulation and adoption of strategies that address both implemented and theoretical practices. By implementing strategies linked to CE-favoring practices in reverse chain management, society benefits from economic outcomes and job creation.

2. LITERATURE REVIEW

In this study, a systematic literature review was conducted on the relationship between RL and CE. Twenty-one scientific publications defining 13 CE practices were identified, as shown in Table 1. The countries with the highest number of publications were India (3), Italy (3), Brazil (3), and Denmark (2).

2.1 RESEARCH RELATING WEEE RL WITH CE

Regarding studies from India, the authors of [1] developed a survey to assess the state of WEEE management and proposed regulation and policies, manufacturer accountability, and reduction of informality as practices for promoting CE. By proposing an extended producer responsibility model, the study [6] concluded in their case study that the exchange of experiences between formal and informal sectors of WEEE recycling adds human development to CE. In a systematic literature review conducted by authors of [7] to evaluate emerging themes and research directions regarding WEEE reuse, it was concluded that the practice linked to the adoption of WEEE remanufacturing strategies is one of the best options for end-of-life EEE, promoting material circularity and contributing to environmental impact mitigation and socio-economic benefits.

In the studies from Italy, a case study conducted in [8] evaluated the economic and environmental contributions of WEEE management, concluding that recycling and recovery of metals promote CE. Also, in a case study to evaluate alternatives for promoting CE, the authors of [9] concluded that industrial symbiosis in RL management plays an important role in this process. In a case study conducted by [4] to evaluate how WEEE RL and regulations support the goals defined by the European Union (EU) for collection and recycling, the conclusion was that environmental legislation and policies are favorable factors for CE.

Regarding studies from Brazil, the study presented in [10] analyzed the destination of WEEE and the social implications of reverse logistic of WEEE, concluding that recycling and

recovery of precious metals promote CE. Another case study conducted in [2] it was analyzed the generation, location of recycling centers, and reverse collection routes of WEEE, concluding that these factors and the disposal of end-of-life EEE promote CE. The authors of [11] developed a framework for analyzing WEEE management and remanufacturing practices, concluding that WEEE recovery and dismantling promote CE by generating revenue through collaboration between recovery centers and manufacturers.

In Denmark, a study presented in [12] assessed the necessary criteria for maximizing WEEE reuse in recyclers through a case study, concluding that recycling and recovery of precious metals promote CE. In [5] a systematic literature review identified gaps to guide research on WEEE disposal and also that strategic planning and the participation of all stakeholders involved in WEEE RL activities are essential to implement all CE-related practices.

In Ukraine, the authors of [13] conducted a case study to propose an intelligent WEEE RL system for managing collection services and connecting them to computerized networks, concluding that transportation strategy, circular product design, and consumer participation are important practices. The study presented in [14] evaluated challenges and opportunities in precious metal recovery and environmental impact reduction in a UK case study, concluded that environmental legislation and policies are favorable factors for CE. In a case study analyzing formal and informal recyclers and secondary material flows of WEEE in Mexico [15], it was concluded that hazardous substance mitigation, strategies to reduce the informal recycling sector, and remanufacturing strategies are favorable factors for CE. The authors of [16, 17] conducted case studies in Belgium to assess plastic recovery strategies, concluding that there is technical and economic viability in the recycling process for promoting CE. In Sweden, a case study conducted in [18] to analyze the environmental impacts and favorable economic advantages of reuse, recycling, and remanufacturing of laptops demonstrated that hazardous substance mitigation is achieved through these processes. In [19], a case study in China was conducted to analyze CE in relation to regulations and WEEE RL management in formal and informal recycling sectors, concluding that environmental legislation and policies to reduce the informal sector are favorable factors for CE. Another case study conducted in Chile and Finland by [20] to analyze interactions of CE practices in WEEE recyclers concluded that environmental legislation and policies are relevant in these interactions. The authors of [21] conducted a case study in Belgium and Germany to evaluate CE regulations adopted by WEEE recycling centers in the recovery of precious metals, concluding that environmental legislation and policies are favorable factors for CE. When studying the most relevant attribute

for integrating logistics operators into the WEEE reverse chain, a case study conducted in Malaysia [22] identified that the inclusion of outsourced logistics transportation is a favorable factor for CE.

2.2 CE PRACTICES RELATED TO WEEE REVERSE CHAIN

Table 1 presents CE practices (P1 to P13) related to the reverse chain of WEEE. Initially, it is necessary to understand the legislation and regulation of WEEE to promote CE, as they both encourage good practices and standardize them within the EEE sector. They also provide viable alternatives [2], adapt territorial scales [4], and identify sectors that require greater attention or professionalization [14, 23]. The way that legislation and regulation are understood and implemented in the industry determines the approaches, whether they are command and control or educational. Based on the chosen approach, companies are led to build strategies that are part of their business decisions. The strategic decision to outsource logistics processes and recycle WEEE results in increased WEEE circularity [22], potentializing the indicators to be reported or covering larger territorial extensions with the same agent [2], and adding economic benefits.

However, not all options for promoting CE in the reverse chain can be outsourced. Decisions that favor extended producer responsibility models as a way to minimize environmental and human health damage, such as the reduction or elimination of substances that can be hazardous in the disposal or reuse of WEEE [24] and the structuring of a closed-loop reverse chain [18], may be considered exclusive to the EEE-producing company, establishing production processes that differentiate it from its competition.

Table 1 – CE Practices Related to WEEE Reverse Chain

Nevertheless, the dissemination of best practices can be a form of cost savings for the producing companies. By organizing themselves into sector groups, EEE producers can promote strategies for the return and treatment of WEEE, influencing other actors in the reverse chain towards environmentally sound disposal of this type of waste [1] and enhancing material circularity [12, 16, 17, 20, 21]. This sectoral collaboration can also act on reducing the informal sector of WEEE. For example, by contracting companies with established best practices, the EEE manufacturer also seeks to reduce negative exposure to social and human issues related to informality [15].

In this context, the development of strategies to put a certain condition into action is suggested before its implementation. An example is simulation, which points to best practices and cost savings in choosing viable paths for promoting CE. This includes the establishment of recycling centers for more effective waste reuse [2], evaluation of the most suitable location for WEEE collection centers [23], and the use of information technology (IT) tools to determine how WEEE transportation and collection should be carried out [13].

It is also important to consider other actors (players) in the construction and implementation of a company's strategy for promoting CE, such as the inclusion of retailers and end consumers in executing part of the process of returning WEEE to the production chain, which are examples of practices that bring effective results.

Thus, the effective inclusion of retail companies in the WEEE chain is necessary given their important role in the reverse chain, whether as collection points for WEEE or as educators for end-of-life EEE users [5]. Measures such as extending the lifespan or recycling alone or in combination cannot mitigate the scarcity of metals as raw materials [18]. The consumer is a crucial link in the reverse chain, as the decision on what to do with end-of-life EEE, whether for proper disposal [1], extending the lifespan through maximum personal use [18], donation [5], or sending it for remanufacturing [7], is exclusive to them and depends on their level of awareness and conviction regarding the best options [4]. Thus, consumer education amplifies other practices that benefit the industry and the country, as it facilitates the return of precious metals as secondary raw materials to the production cycle [14], minimizes the importation of these geopolitically sensitive resources [8], and adds value to the reverse chain and the consumer market [21].

Seventeen case studies and two surveys identified (Appendix 1) in the literature report thirteen CE practices that promote the management of the WEEE reverse chain and reduce impacts on human health and the environment. These studies emphasize that these practices need to be adopted within a context that considers the challenges of WEEE management, the complexity of this type of waste, and the participation of all actors in the chain, including public agencies, private companies, cooperatives, and consumers.

3. METHODOLOGY

A descriptive and exploratory research was conducted to understand the degree of importance of CE practices for the management of the WEEE reverse chain in Brazil. Data collection involved multiple participants selected through statistical sampling techniques,

making it a survey-type research [25]. The study was conducted in a cross-sectional manner, meaning data sources were surveyed only once [26].

The research employed a combination of qualitative and quantitative approaches. According to [27], integrating quantitative and qualitative studies can enhance understanding of the phenomenon under study. Access to documentary data, such as the National Solid Waste Policy – Law number 12.305/10 and the "Settlement Agreement for the Implementation of the Reverse Logistics System for Electrical and Electronic Products in Brazil," characterized the research as exploratory and documentary in nature. This approach seeks to provide a comprehensive overview of a subject that is still underexplored and includes hypotheses [28].

3.1 Data collection procedure

The development of the conceptual model was supported by a systematic literature review to identify the research gap as well as to develop the questionnaire. To achieve this, we employed the PRISMA method, which consists of an approach designed to improve the transparency and completeness of reporting in systematic reviews and meta-analyses [29]. Following PRISMA, the review was organized into four phases: identification, screening, eligibility, and inclusion. Initially, articles were identified in research databases and downloaded, followed by screening through content analysis to determine relevance to the research terms. This facilitated the eligibility phase, where articles were selected based on predefined criteria, with reasons documented for exclusions. This method ensured transparency in presenting the selected articles [29]. The review encompassed databases such as Scopus, Science Direct, Web of Science, Scielo, Emerald, Wiley, Proquest, Ebsco, and Taylor & Francis (Table 2). Ninety-three articles were initially identified from high-impact publications, and following PRISMA guidelines [29], a systematic literature review was conducted to construct the conceptual model, formulate hypotheses, and clearly delineate the research gap [30, 31]. Ultimately, 21 articles were validated and included in the systematic literature review.

Table 2 – Databases and Research Terms Used in the Systematic Literature Review

Figure 1 presents the PRISMA flow diagram indicating the four phases for conducting systematic literature review and the number of articles related to each phase.

Figure 1 – Steps for Applying PRISMA in this Study. Source: [29]

3.1.1 Development of the research model with hypothesis

Electronics manufacturers have increasingly adopted CE practices to enhance the management of the WEEE reverse chain, particularly in the realm of WEEE reverse logistics, whether managed internally or outsourced [13, 22]. This trend underscores the importance of simulation for optimizing transportation routes [2] and strategically locating collection centers [23], all while adhering to environmental legislation governing WEEE management [1]. Furthermore, these practices include WEEE recycling initiatives [18, 24] aimed at fostering WEEE circularity [12, 16, 17, 20, 21], which incorporates processes like remanufacturing [7]. The adoption of CE practices also aims to mitigate informal labor within the sector [15] and promote socio-environmental education throughout the chain [14]. Therefore, the accumulating scientific evidence suggests that electronics manufacturers are embracing CE practices to advance the management of the WEEE reverse chain, leading to the following hypothesis:

H1: The adoption of CE practices by electronics manufacturers has a positive impact on the management of the WEEE reverse chain in Brazil.

In this context, Figure 2 presents the research model, which considers the 13 CE Practices in relation to the management of the WEEE reverse chain in Brazil.

Figure 2 - Research Model

3.1.2. Survey Research Method

The statistical software G*Power version 3.1.9.7 was utilized to estimate the sample size, guided by the study of [32] for F-statistical analysis (F-test). This analysis evaluates the relationship between the variation of sample means and their internal variation. Effect sizes (f^2) of 0.02, 0.15, and 0.35 were considered to represent small, medium, and large effects, respectively. For this study, an effect size (f^2) of 0.35 was selected, indicating that a minimum sample size of 84 responses is necessary.

The present study follows the recommendations outlined in [25], starting with a pilot test conducted with experts in the field to validate the questionnaire. This phase aims to assess the experts' comprehension of the questionnaire and make necessary adjustments such as corrections, additions, deletions, or modifications of terms that are unclear to them. The pilot test involved a group of ten respondents, consisting of professionals representing

manufacturers and importers of Electrical and Electronic Equipment (EEE) with extensive knowledge of WEEE reverse chain management and experience in complying with the "Agreement for the Implementation of the Reverse Logistics System for WEEE".

Following the pilot test, the validated questionnaire (Appendix 2) was distributed via email to a larger group of respondents. The questionnaire utilized a Likert scale ranging from 1 to 7, where respondents indicated the "Degree of Importance" they assigned to each CE practice in managing the WEEE reverse chain in Brazil. A score of 7 denoted the highest importance, with subsequent scores indicating decreasing levels of importance, down to 1 which signified no importance. The study successfully collected 91 completed questionnaires.

3.2 Procedure for Data Analysis

After receiving the completed questionnaires, the data were tabulated, formatted, and analyzed using statistical tests [33]. Specifically, the degree of importance of CE-favorable practices was assessed using the Kruskal-Wallis test, followed by the Holm-Sidak multiple comparisons test. These statistical analyses were conducted with the software "Action Stat 3.7," which is developed on the R platform, a leading statistical programming language globally. This tool integrates with Microsoft Excel, providing a user-friendly interface for performing advanced statistical analyses. It is particularly suited for non-parametric tests like the Kruskal-Wallis and Holm-Sidak tests, offering practical and intuitive capabilities within the familiar environment of Excel.

The Kruskal-Wallis test is used when there is a need to compare three or more independent groups with ordinal variables, aiming to evaluate if there are significant differences between the groups and present them under ranking levels after conducting the analyses. When rejecting the null hypothesis, it is necessary to perform multiple comparisons to identify which groups have statistically significant different means and which do not. For this purpose, the complementary Holm-Sidak test was used to locate which groups exhibit significantly different means through multiple comparisons [34].

In the application of the Holm-Sidak statistical test, the classification criteria prove to be fundamental for understanding the significant differences between the CE practice groups [a] to [e]. Statistical significance is established when all possible combinations between these groups present P-values lower than 0.05 (5%) [34]. This means that the variations between the means of the groups are statistically relevant, providing a solid basis for the ordered classification of the groups according to their degrees of importance. Therefore, following this

classification, we can infer that CE practices allocated in groups with lower P-values have a statistically more significant influence than those in groups with higher P-values.

On the other hand, comparisons within each group do not exhibit statistically significant differences, as all associated P-values are greater than 5% [34]. This indicates that practices within the same group are statistically similar, demonstrating internal consistency without significant differentiation. Therefore, when analyzing practices within a specific group, there is no statistical evidence supporting significant preferences or distinctions between them. The ordered classification of the groups based on their statistical significance reveals the relative degree of importance of each evaluated element. Importantly, comparisons within the same groups consistently show no statistically significant differences, underscoring the uniformity and coherence of CE practices within each group. As a result, adhering to practices classified under group A, for instance, yields a higher degree of importance compared to group B, and so forth.

4. RESULTS

The analysis of responses related to CE practices, depicted in Figure 3, highlights that practices associated with legislation and regulations of WEEE (88%) and consumer participation in the reverse chain (80%) received the highest scores, indicating their significant importance with scores ranging between 5.6 and 6.16 on the Likert scale. Following closely, practices related to the management of third-party WEEE recycling companies, involvement of logistics operators in the WEEE reverse chain, and strategies for treatment and recycling of WEEE received relatively high scores, ranging between 65% and 67%. Conversely, practices with the lowest scores were associated with simulation strategies for logistic transportation of WEEE (35%), collection centers (31%), and WEEE recycling centers (24%). These low scores suggest a lack of implementation of these CE practices, with responses falling between 1.68 and 2.45 on the Likert scale. Practices with intermediate scores included the recovery of precious metals from WEEE (60%), involvement of retailers in the WEEE reverse chain (58%), reduction or elimination of hazardous substances from WEEE (55%), adoption of remanufacturing strategies (repair, reuse, and recirculation) of WEEE (49%), and strategies to reduce the informal WEEE sector (45%). These practices indicate varying levels of implementation and perceived importance among respondents.

Overall, the analysis underscores varying degrees of implementation and importance of CE practices in the management of the WEEE reverse chain in Brazil, providing insights into areas of strength and potential improvement.

Figure 3 - Descriptive Assessment of CE Practices (P1 to P13)

The non-parametric statistical analysis (related to questions numbered 1 to 13), presented in Figure 4, shows a P-value of 2.2626×10^{-174} for the Kruskal-Wallis test, which is less than 0.05. This indicates the rejection of the internal null hypothesis, suggesting that there are statistically significant differences with 95% confidence in at least two compared groups. Therefore, it was necessary to perform the Holm-Sidak multiple comparisons test to assess, pair by pair, the null hypothesis that the means of the groups are equal, meaning that there are no statistically significant differences.

Based on the results of the P-values from the Holm-Sidak test, as illustrated in the "P-Value" column of the multiple comparisons in Figure 4, the rejection of the null hypothesis confirms the presence of statistically significant differences among certain combinations. It is important to note that numbers in red indicate P-values greater than 0.05, indicating non-significant differences in non-parametric statistics. Therefore, these comparisons do not show significant distinctions between the CE practices. Conversely, numbers in blue denote P-values less than 0.05, signifying statistically significant differences in non-parametric statistics [33, 34]. This indicates meaningful variations between these comparisons of CE practices.

Additionally, the grouping criteria align with the comparisons conducted using the Kruskal-Wallis test, followed by the Holm-Sidak multiple comparisons test, as outlined in [33, 34]. This approach ensures robust statistical analysis to differentiate the degrees of importance among the evaluated CE practices in managing the WEEE reverse chain in Brazil.

Figure 4 - Non-Parametric Statistical Assessment

Thus, in the ordered classification of the "Groupings Table" in Figure 5, the ranking of the means for each analyzed practice is presented, considering that elements allocated in the same group have means that are not statistically significant from each other. On the other hand, elements allocated in different groups have means that are statistically significant from each other.

Figure 5 presents the ordered ranking of practices favorable to CE and their respective groups. Practices allocated in Group [a] have higher means than the practices in Groups [b], [c], [d], and [e], which suggests a greater degree of importance for the practices in the first group. However, statistically, it is not possible to assert that Practice 1 (P1) has a higher degree of importance than Practice 13 (P13) because both belong to Group [a]. On the other hand, both P1 and P13 have higher representativeness in terms of the degree of importance when compared to the other practices allocated in different groups.

The highest ranking of the practice "implementation of legislation and regulations for WEEE" is likely due to the obligations prescribed by the "National Solid Waste Policy" and the "Sector Agreement". These regulations act as agents that enforce the fulfillment of targets for the environmentally appropriate return and destination of WEEE through the establishment, implementation, operation, and management of the electronic waste reverse logistics system in Brazil. These measures play a crucial role in promoting responsible disposal and recycling practices, which contribute to the circular economy and environmental conservation efforts in the country.

Figure 5 - Classification of CE Practices

At its most critical level, effective consumer participation in the WEEE Reverse Chain is indispensable for the success of the WEEE reverse logistics system and achieving material circularity, thereby advancing CE. Consumer involvement is pivotal as consumers direct WEEE to collection points, initiating the reverse cycle. Without this active participation, WEEE cannot undergo environmentally sound treatment, which hampers efforts to enhance CE within the Brazilian context.

With regard to the practices of Management of Outsourced WEEE Recycling Companies and Insertion of Outsourced Logistics Operators in the Reverse WEEE Chain, which are well classified in the ranking results, this attribution refers to the fact that, according to the Sectoral Agreement, only admitted for the management of WEEE in the reverse chain, companies that prove technical capacity for implementation and operationalization and expansion of this reverse chain in Brazil. For this, it is necessary to establish partnerships with duly qualified and structured companies to meet the increase in demands, since WEEE return targets must be met and proven.

Another well-ranked practice refers to the Adoption of WEEE Recycling Strategies, which represents the need for investments in new recycling technologies in order to implement

CE, given the complexity of treating electronic waste. Converging with the above, the Recovery of Precious Metals from WEEE stands out for its importance related to the practices of processing and recovery of materials such as gold, silver, platinum and palladium contained in printed circuit boards (PCBs). Therefore, the reverse chain of WEEE in Brazil, as it does not have mastery over this technology, is obliged to send PCBs to companies located abroad.

Also, very representative in terms of importance for the CE, the practice of Inserting Retailers in the WEEE Reverse Chain stood out. In the WEEE reverse logistics system, the retailer is considered a great partner that can bring benefits to the WEEE reverse chain, since it can also be used as a point of receipt of electronic waste.

The next highlighted practice, Reduce or Eliminate Hazardous Substances from WEEE, is represented by the importance of environmentally appropriate disposal of WEEE, through the operation of the reverse chain, avoiding possible environmental impacts on nature. By operationalizing the reverse chain in a broad way in the Brazilian territory, the risks of contamination and pollution levels are minimized, which contributes to CE in terms of preventing the degradation of nature and damage to the ecosystem.

With regard to the importance of the practice of Adoption of Remanufacturing Strategies (Repair, Reuse, Recirculation) of WEEE for CE, the cooperatives stand out, which seek to reuse parts and modules for the recovery of electronic products, in addition to targeting of non-reusable materials for the reverse chain of WEEE, being another favorable link to CE in Brazil.

For the practice of Adoption of Strategies for Reducing the Informal WEEE Sector in the WEEE segment, its importance for the CE is linked to the need to create strategies, encourage and train informal workers, which depend on the government and entities legislative and environmental measures, which can contribute to income generation, reduction of environmental impacts and improvement of material circularity in the reverse WEEE chain.

Regarding the practices with lower ranking scores, which refer to mathematical simulations for the optimization of the transport system, collection points, WEEE recycling centers, such results refer to the lack of applications in operational practice, being only applied in the theory.

Therefore, in view of the non-parametric statistical results attributed to the evaluations of practices favorable to CE, the hypothesis formulated in this study (H1) was validated confirming that “the adoption of CE practices by electronics manufacturers positively influences the management of the WEEE reverse chain in Brazil”.

5. DISCUSSION

In the results from the analysis of CE practices influencing the management of the WEEE reverse chain in Brazil, it is highlighted that Brazil ranks second as a WEEE producer in the Americas, generating approximately 1.5 million tons annually, underscoring the critical need for effective waste management [2]. Among the identified practices, the Implementation of Legislations and Regulations of WEEE and Effective Participation of Consumers in the WEEE Reverse Chain emerged as leading practices in the first rank group [35]. The significant importance attributed to WEEE laws and regulations for CE aligns with Brazil's National Solid Waste Policy and Sectorial Agreement. These frameworks serve as crucial intermediaries, setting return goals and ensuring environmentally appropriate disposal of WEEE. They play a pivotal role in structuring, operationalizing, and managing the electronic waste reverse chain in Brazil [36, 37]. Also linked to the highest level as a favorable CE practice, the effective participation of the consumer in the reverse WEEE chain is essential for the reverse logistics system to have a positive result in obtaining material circularity, since, without the participation of the final consumer, that needs to direct the WEEE to the collection points, the reverse cycle and recycling of the WEEE does not start. Scientific publications on WEEE, which related WEEE legislation and regulations [14] and Effective Consumer Participation in the WEEE Reverse Chain [1,4,5], being an important stakeholder for the effectiveness of reverse logistics [38], despite indicating these practices as favorable to CE, do not assess their levels of influence in reverse chain management. Thus, the results innovate and corroborate with the “NSWP” and the “Electronics Sectorial Agreement in Brazil”, positioning WEEE legislation and regulations and the effective participation of the consumer in the reverse WEEE chain, at the highest levels of influence in terms of WEEE management, which act as enabling agents for the achievement of goals, mandatory structuring, implementation and operation of the reverse logistics system in the Brazilian reality with the aim of promoting CE. In the social aspect, the study points out that the effective participation of the consumer is essential for the viability and success of the WEEE reverse logistics system in Brazil, since the decision to correctly dispose of electronic waste is up to the final consumer. With this, it refers to the fact that companies need to invest in effective consumer awareness, without which the logistical flow of WEEE does not start, compromising the effectiveness of processes related to the treatment of electronic waste, which can lead to low effectiveness of CE.

Among the next best ranked CE-friendly practices are the management of Outsourced WEEE Recycling Companies and the Insertion of Outsourced Logistics Operators in the reverse WEEE chain. This result refers to the fact that EEE producing companies have their

focus directed at the core business and the consequent outsourcing of other processes. Despite the authors [2, 22] listed outsourced recycling companies and the insertion of logistics operators in the reverse chain as practices that promote CE in their research, but did not identify the level of influence of these practices in the management of the reverse chain to promote CE. The present study contributes to the existing literature by identifying that experienced partnerships between the manager, outsourced recycling companies and the insertion of logistics operators in the reverse chain are ranked among the highest scales in terms of the degree of importance to promote CE in the management of the WEEE reverse chain. It also shows that the efficiency of collection services, logistical transport, recycling processes and environmentally appropriate disposal not only meet legal requirements, but also contribute to the management of companies by seeking partnerships that address these issues.

Still among the best ranked practices, the result of the high degree of importance of the Adoption of WEEE Recycling Strategies points out that Brazil finds it difficult to recover more complex waste, which denotes the need for investments in new WEEE recycling technologies to carry out the CE. In the scientific literature, although the publications by [12, 16, 17] related innovative treatment and recycling strategies as effective to CE, were restricted to European countries. Thus, this result corroborates the Sectorial Agreement, which emphasizes that, in the current scenario, due to technological unavailability, Brazil faces difficulties in the treatment of more complex waste, originating from electronic waste.

At the intermediate ranking level, the WEEE Precious Metal Recovery practice is highlighted due to its importance related to the processing and recovery practices of precious metals contained in PCBs. This result is important since it relates the recovery of precious metals to economic gains. Also, the research by [8,18, 20] indicate practices based on the recovery of precious metals in a closed cycle as contributors to CE. However, the present study shows that the reverse chain of Brazilian WEEE does not have the necessary technology to process and recover this type of waste. In this context, it suggests that Brazil needs investments in transfers of advanced recycling technology so that it can take advantage of secondary raw materials (gold, silver, platinum, palladium), promoting a more effective CE, in addition to retaining greater economic gains from country.

At the same intermediate ranking level, the practice of Insertion of Retailers in the WEEE Reverse Chain is favorable to CE in terms of the adhesion of electronics retailers to the reverse logistics system of the WEEE chain. The finding shows the importance of the retailer in this process, since it can, in addition to educating the final consumer, establish itself as a WEEE collection point. The research conducted by [5], despite relating the involvement of

retailers in the reverse WEEE chain as a benefit to material circularity and taking into account the competitiveness between retail companies and other WEEE collection point facilities, did not consider the assessment of the degree of importance of this practice in the reverse chain to promote CE. In this sense, the contribution of the present study was to point out that the partnership between retailers and management companies brings benefits in terms of receiving electronic waste, serving as additional options for WEEE collection points for the final consumer, contributing to collection targets and recycling advocated by the Electronic Sector Agreement in Brazil.

The practice of Reducing or Eliminating Hazardous Substances from WEEE, ranked in the intermediate level results, is of paramount importance for CE in the sense of ensuring the environmentally appropriate final destination of WEEE through the management and operation of the reverse chain, avoiding and minimizing possible environmental impacts. Although the study of [18] related the mitigation of hazardous substances as a necessary practice for the improvement of CE did not consider the assessment of its degree of importance in terms of management of the reverse chain of WEEE. The present research contributes by relating a well-operated WEEE reverse chain management system to the reduction of risks related to hazardous substances such as mercury, lead, cadmium, chromium with contamination of the soil and water resources. Thus, in addition to mitigating risks to human health, it favors CE in its environmental aspects.

For the WEEE Adoption of Remanufacturing Strategies (Repair, Reuse, Recirculation) practice, also related to the importance of an intermediate level in the ranking, it is favorable to the CE, with regard to the insertion of cooperatives in the reverse WEEE chain, the which dismantle the equipment they receive, seeking to reuse the parts and modules for the recovery of electronic products. In this dismantling stage, materials that are not reusable for remanufacturing are sent for recycling, contributing to the circularity of the secondary raw material. This strategy of inserting cooperatives in the reverse WEEE chain is consistent with the PNRS, which emphasizes the need for plans to Incorporate cooperatives in the reverse logistics system for waste in Brazil. The studies conducted by [5, 15] and Anandh et al. (2021), despite highlighting the strategies of remanufacturing practices in the reverse chain management system, did not report the importance of WEEE cooperatives to promote CE. In this way, the result of the present research contributes to highlighting the importance and the need for financial and technological incentives for these cooperative companies in order to value the end-of-life product, contributing to the improvement of material circularity, in

addition to economic, environmental and social gains, according to [39], aiming for sustainability [40].

With regard to the practice of Adoption of Strategies to Reduce the Informal Sector of WEEE at the intermediate level of ranking of results, its importance for CE in the WEEE segment, refers to the need of the government, legislative and environmental entities to create stimulus and training strategies of workers and companies for this type of waste. Convergent to the above, the Sectoral Agreement advocates the importance of training, stimulation, incubation and institutional strengthening of cooperatives, which can contribute to a more effective CE in the current Brazilian reality. Although publications by [5, 15] related the need for improvements in WEEE regulations in order to reduce the informal market, they did not show strategies to reduce this market. The findings of this study suggest the need to develop strategies and plans to reduce the informal sector, linked to the WEEE segment, to promote CE. It also contributes to managerial practice by showing that companies and governments should invest in training and incubating cooperatives. From the social point of view, it contributes to the importance of professional training, which can generate more and better jobs.

For practices ranked at the lowest levels, in terms of influence on reverse chain management to promote CE, such as Simulation and Optimization of WEEE Reverse Logistics Transport, Simulations for Implementation and Optimization of WEEE Collection Centers and Simulations for Implementation and Optimization of WEEE Recycling Centers, they stand out as undervalued strategies in the WEEE sector, being only implemented in theory. This finding is in line with the scientific literature, which shows that studies related to simulations aimed at the WEEE segment and CE [2]; [13] are lacking in the operational and management practice of WEEE reverse chain.

6. CONCLUSION

This study makes a significant contribution to the scientific literature by filling a gap in research regarding the evaluation of CE practices and their importance in managing the WEEE reverse chain in Brazil. Prior to this study, no research had specifically assessed these aspects, making the findings crucial for guiding future scientific inquiry and practical applications. The study identifies several key insights for management practices in the EEE sector. It highlights a growing trend among EEE companies in Brazil towards implementing WEEE Legislation and Regulations as the most impactful approach to advancing CE. Furthermore, the study encourages companies to focus on managing outsourced WEEE recycling companies and integrating logistics operators into the reverse WEEE chain, emphasizing the importance of

material reuse and reduction. The practice of WEEE Precious Metal Recovery is underscored for its economic benefits, particularly in processing and reclaiming precious metals from PCBs. The study also sheds light on practices that are currently more theoretical and ranked lower, suggesting that companies can enhance resilience and competitiveness by actively implementing these practices. Effective consumer participation in the reverse chain emerges as pivotal for enhancing the material circularity of WEEE, closing the loop between end-of-life products and recycled raw materials. This underscores the social contribution of the study, emphasizing the need for collaborative efforts between governments and companies to establish cooperatives that promote professional training and job creation.

Overall, this study sets a foundation for further research and practical initiatives aimed at advancing CE practices in the management of WEEE in Brazil, contributing to sustainable development and environmental stewardship in the region.

A limitation acknowledged in the study is the inability to conduct a comprehensive mass balance analysis of recycled raw materials in the reverse WEEE chain. Such an analysis could have provided valuable insights into the economic and environmental benefits associated with the reverse chain in Brazil.

For future research directions, the study proposes independently evaluating and redefining the lowest-ranked practices, such as simulations and optimizations. Understanding how these practices can be effectively implemented and integrated into EEE company cultures and strategies is crucial for enhancing CE in the WEEE segment.

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REFERENCES

- [1] Shittu, O.S.; Williams, I.D.; Shaw, P.J. (2021). Global E-waste management: Can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. *Waste Manag.* 120, 549–563.
- [2] Ottoni, M.; Dias, P.; Xavier, L.H. (2020). A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil. *J. Clean. Prod.*261, 120990.
- [3] Rogers, D., & Tibben-Lembke, R. (1998). *Going Backwards: Reverse Logistics Trends and Practices*. Reverse Logistics Executive Council, Reno, NV: University of Nevada.

- [4] Isernia, R.; Passaro, R.; Quinto, I.; Thomas, A. (2019). The reverse chain of the e-waste management processes in a circular economy framework: Evidence from Italy. *Sustainability*, 11, 2430.
- [5] Bressanelli, G.; Saccani, N.; Pigosso, D.C.A.; Perona, M. (2020). Circular Economy in the WEEE industry: A systematic literature review and a research agenda. *Sustain. Prod. Consum.*, 23, 174–188.
- [6] Sengupta, D.; Ilankoon, I.M.S.K.; Kang, K.D.; Chong, M.N. (2022). Circular economy and household e-waste management in India: Integration of formal and informal sectors. *Miner. Eng.*, 184, 107661.
- [7] Anandh, G., PrasannaVenkatesan, S., Goh, M., & Mathiyazhagan, K. (2021). Reuse assessment of WEEE: Systematic review of emerging themes and research directions. *Journal of environmental management*, 287, 112335.
- [8] Matarazzo, A.; Tuccio, G.; Teodoro, G.; Failla, F.; Giuffrida, V.A. (2019). Mass balance as green economic and sustainable management in WEEE sector. *Energy Procedia*, 157, 1377–1384.
- [9] Marconi, M.; Gregori, F.; Germani, M.; Papetti, A.; Favi, C. (2018). An approach to favor industrial symbiosis: The case of waste electrical and electronic equipment. *Procedia Manuf.*, 21, 502–509.
- [10] Brito, J.L.R.; Ruiz, M.S.; Kniess, C.T.; dos Santos, M.R. (2022). Reverse remanufacturing of electrical and electronic equipment and the circular economy. *Rev. Gestão*, 29, 380–394.
- [11] Alves, D.S.; Farina, M.C. (2018). Disposal and reuse of the information technology waste: A case study in a Brazilian university. *Eur. Bus. Rev.*, 30, 720–734.
- [12] Parajuly, K.; Wenzel, H. (2017). Product family approach in e-waste management: A conceptual framework for circular economy. *Sustainability*, 9, 768.
- [13] Shevchenko, T.; Saidani, M.; Danko, Y.; Golysheva, I.; Chovancová, J.; Vavrek, R. (2021). Towards a smart E-waste system utilizing supply chain participants and interactive online maps. *Recycling*, 6, 8.
- [14] Bridgens, B.; Hobson, K.; Lilley, D.; Lee, J.; Scott, J.L.; Wilson, G.T. (2019). Closing the loop on E-waste: A multidisciplinary perspective. *J. Ind. Ecol.*, 23, 169–181.
- [15] Cordova-Pizarro, D.; Aguilar-Barajas, I.; Romero, D.; Rodriguez, C.A. (2019). Circular economy in the electronic products sector: Material flow analysis and economic impact of cellphone e-waste in Mexico. *Sustainability*, 11, 1361.
- [16] Wagner, F.; Peeters, J.R.; De Keyzer, J.; Janssens, K.; Duflou, J.R.; Dewulf, W. (2019a). Towards a more circular economy for WEEE plastics—Part A: Development of innovative recycling strategies. *Waste Manag.* 2019, 100, 269–277.
- [17] Wagner, F.; Peeters, J.R.; De Keyzer, J.; Janssens, K.; Duflou, J.R.; Dewulf, W. (2023). Towards a more circular economy for WEEE plastics—Part B: Assessment of the technical feasibility of recycling strategies. *Waste Manag.* 2019, 96, 206–214. *Sustainability*, 15, 4135 26 of 27
- [18] André, H.; Söderman, M.L.; Nordelöf, A. (2019). Resource and environmental impacts of using second-hand laptop computers: A case study of commercial reuse. *Waste Manag.* 88, 268–279.

- [19] Tong, X., Wang, T., Chen, Y., & Wang, Y. (2018b). Towards an inclusive circular economy: quantifying the spatial flows of e-waste through the informal sector in China. *Resources, Conservation and Recycling*, 135, 163-171. <http://dx.doi.org/10.1016/j.resconrec.2017.10.039>.
- [20] Levanen, J.; Lyytinen, T.; Gatica, S. (2018). Modelling the interplay between institutions and circular economy business models: A case study of battery recycling in Finland and Chile. *Ecol. Econ.* 154, 373–382.
- [21] Hagelüken C., Lee-Shin J., Carpentier A. and Heron C. (2016). The EU circular economy and its relevance to metal recycling. *Recycling*, 1, 242-253.
- [22] Sabtu, M.I.; Saibani, N.; Ramli, R.; Rahman, M.N.A. (2015). Multi-criteria decision making for reverse logistic contractor selection in e-waste recycling industry using polytomous rasch model. *J. Teknol*, 77.
- [23] Kumar, A.; Dixit, G. (2019). A novel hybrid MCDM framework for WEEE recycling partner evaluation on the basis of green competencies. *J. Clean. Prod*, 241, 118017.
- [24] Blomsma, F., Pieroni, M., Kravchenko, M., Pigosso, D. C., Hildenbrand, J., Kristinsdottir, A. R., ... & McAloone, T. C. (2019). Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. *Journal of cleaner production*, 241, 118271.
- [25] Forza, C. (2002) Survey research in operation management: A process-based perspective. *Int. J. Oper. Prod. Manag*, 22, 152–194.
- [26] Kumar, R. (2018). *Research Methodology: A Step-by-Step Guide for Beginners*; Sage: Newcastle upon Tyne, UK.
- [27] Yin, R.K. (2009). *Case Study Research: Design and Methods*; Sage: Newcastle upon Tyne, UK, Volume 5.
- [28] Martins, G.A.; Theóphilo, C.R. (2009). *Scientific Research Methodology for Applied Social Sciences*; Atlas: Tokyo, Japan.
- [29] Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA Statement. *Ann. Intern. Med*, 151, 264–269.
- [30] de Oliveira Neto, G.C., da Conceição Silva, A., Filho, M.G. 2023. How can Industry 4.0 technologies and circular economy help companies and researchers collaborate and accelerate the transition to strong sustainability? A bibliometric review and a systematic literature review. *International Journal of Environmental Science and Technology*, 20(3), 3483–3520.
- [31] Cassia, A.R. , 29, I., da Silva, V.H.C., de Oliveira Neto, G.C. 2020. Systematic literature review for the development of a conceptual model on the relationship between knowledge sharing, information technology infrastructure and innovative capability. *Technology Analysis and Strategic Management*, 32(7), pp. 801–821.
- [32] Cohen, J. (1988). *Statistical Power Analysis for the Behavioral Sciences*; Psychology Press: New York, NY, USA, Volume 2.
- [33] Triola, M.F. (2013). *Elementary Statistics Using Excel*; Pearson: London, UK.

- [34] Levin, R. I., & Rubin, D. S. (2004). *Estatística para administração y economía*. Pearson educacion.
- [35] BRASIL. Lei nº 12.305, de 2 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos (PNRS); altera a Lei no 9.605, de 12 de fevereiro de 1998; e dá outras providências. Diário Oficial da República Federativa do Brasil, Poder Executivo, Brasília, DF, 03 mar. 2010.
- [36] MMA—Ministério do Meio Ambiente. Acordo Setorial para Implantação de Sistema de Logística Reversa de Produtos Eletroeletrônicos de Uso Doméstico e Seus Componentes de 2019. Available online: <https://www.cetem.gov.br/antigo/images/reminare/documentos/acordo-setorial.pdf> (accessed on 23 February 2023)
- [37] Neto, G.C.d.O.; Correia, A.d.J.C.; Tucci, H.N.P.; Melatto, R.A.P.B.; Amorim, M. Reverse Chain for Electronic Waste to Promote Circular Economy in Brazil: A Survey on Electronics Manufacturers and Importers. *Sustainability* 2023, 15, 4135. <https://doi.org/10.3390/su15054135>
- [38] Neto, G.C.D.O.,Tucci, H.N.P.,Correia, J.M.F.,...da Silva, D.,Amorim, M. 2021. Stakeholders' influences on the adoption of cleaner production practices: A survey of the textile industry. *Sustainable Production and Consumption*, 26,126–145.
- [39] de Paoli, F.M., de Oliveira Neto, G.C., Lucato, W.C. 2013. Economic and environmental gains resulting from the utilization of the design for the environment (DfE) | Vantagens econômicas e ambientais resultantes da aplicação do projeto para o meio ambiente (DfE). *Espacios*, 2013, 34(12), 11.
- [40] Pinto, L.F.R., Venturini, G.F.P., Digiesi, S., Facchini, F., Neto, G.C.O. 2020. Sustainability assessment in manufacturing under a strong sustainability perspective—an ecological neutrality initiative. *Sustainability (Switzerland)*,12(21), 1–40, 9232.

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