



Circular Economy in the Reuse of Electronic Components Recovered from Printed Circuit Board Waste: A Systematic Literature Review

Economía circular en la reutilización de componentes electrónicos de placas de circuito impreso de desecho: una revisión sistemática de la literatura

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ABSTRACT

Introduction: The growing generation of waste electrical and electronic equipment (WEEE) and the potential value of printed circuit boards (PCBs) reinforce the need for recovery strategies aligned with the circular economy. **Methodology:** A Systematic Literature Review was conducted according to PRISMA 2020. The search was performed in Google Scholar between 1 and 8 August 2026, considering publications from 2012 to 2025 in Portuguese, Spanish, and English. Fifty records were identified and, after screening, eligibility assessment, and relevance analysis, 25 studies were included and qualitatively synthesized. **Results:** Thematic analysis showed a predominance of studies on circular economy, urban mining, and the transition to circular models (32%), followed by reverse logistics and WEEE management (20%), PCB material recycling and recovery (16%), and reuse, remanufacturing, and recovery (16%). The remaining studies addressed environmental impacts, management and operational support (12%) and public policy/PNRS (4%). **Conclusions:** The reviewed literature confirms the potential of WEEE and PCBs as secondary sources of materials and components. The main gap identified was the limited integration of disassembly, characterization, functional testing, classification, and direct component reuse. The development and validation of standardized procedures is therefore recommended.

Keywords: Circular economy; Electronic waste; Printed circuit boards; Component reuse; Reverse logistics.

RESUMEN

Introducción: El crecimiento de residuos de equipos eléctricos y electrónicos (WEEE) y el valor potencial de las placas de circuito impreso (PCB) refuerzan la necesidad de estrategias de recuperación alineadas con la economía circular. **Metodología:** Se realizó una revisión sistemática de la literatura según PRISMA 2020. La búsqueda se realizó en Google Scholar entre el 1 y el 8 de agosto de 2026, considerando publicaciones entre 2012 y 2025, en portugués, español e inglés. Se identificaron 50 registros y, tras el cribado, evaluación de elegibilidad y análisis de relevancia, se incluyeron y sintetizaron cualitativamente 25 estudios. **Resultados:** El análisis temático mostró una predominancia de estudios sobre economía circular, minería urbana y transición a modelos circulares (32%), seguidos de logística inversa y gestión de WEEE (20%), reciclaje y recuperación de materiales PCB (16%) y reutilización, remanufactura y reutilización (16%). Los estudios restantes correspondieron a impactos medioambientales, apoyo a la gestión y operativo (12%) y a políticas públicas/PNRS (4%). **Conclusiones:** La literatura analizada confirma el potencial de los WEEE y los PCBs como fuentes secundarias de materiales y componentes. La principal brecha identificada fue la integración limitada entre desmontaje, caracterización, pruebas funcionales, clasificación y reutilización directa de componentes. Se recomienda el desarrollo y validación de procedimientos estandarizados para apoyar esta jerarquía de valoración.

Palabras clave: Economía circular; Residuos eléctricos y electrónicos; Placas de circuito impreso; Reutilización de componentes; Logística inversa.

INTRODUCTION

The rapid growth in the production and consumption of electrical and electronic equipment (EEE) has contributed to the increase in waste electrical and electronic equipment (WEEE), intensifying the environmental, economic, and social challenges associated with its management. Printed circuit boards (PCBs) are particularly important because they concentrate components and materials of economic and technological value, including metallic fractions that can be recovered [1,2].

PCB management has often focused on the recovery of materials and metals; however, the literature also highlights opportunities for component reuse, remanufacturing, and recovery before recycling [3,4,5]. Identifying components that remain functional can preserve embedded value, extend life cycles, and reduce the need for virgin raw materials.

In this context, the circular economy seeks to replace the linear logic of extract, produce, consume, and discard with strategies that keep products, components, and materials in circulation for as long as possible. Reuse, remanufacturing, recycling, and urban mining are complementary mechanisms for WEEE recovery [6,7,8]. Reverse logistics, in turn, provides the supporting conditions for collection, sorting, and reintegration of materials into production chains [9,10].

The diversity of techniques and perspectives found in the literature makes it difficult to identify an integrated sequence that prioritizes the reuse of functional components before material recycling. This issue justifies a systematic review capable of organizing the evidence on recovery, characterization, functional classification, reuse, and recovery of PCB waste.

Against this background, the general objective of this study was to analyze the scientific and technical literature on the recovery and reuse of components from printed circuit board waste, identifying approaches to recovery, characterization, functional classification, reuse, recycling, and the environmental, economic, technological, and institutional factors associated with the circular economy. To ensure consistency with the sample actually analyzed, the scope was defined broadly, including scientific studies and academic or technical documents relevant to the WEEE recovery chain.

The analysis variables were organized into five dimensions: (i) recovery within the circular economy context; (ii) recovery and characterization of PCBs/components; (iii) reuse, repair, and remanufacturing; (iv) reverse logistics and WEEE management; and (v) impacts, policies, and implementation conditions. The study was conducted as a Systematic Literature Review following PRISMA 2020 [11], with a qualitative synthesis of the selected studies.

The variables considered in this investigation are the circular economy as the explanatory variable and the reuse of electronic components from printed circuit board waste as the analysis variable, complemented by dimensions related to recovery, characterization, functional classification, sustainability, and electronic waste recovery.

To achieve this objective, a Systematic Literature Review (SLR) was conducted following the recommendations of the PRISMA 2020 protocol, making it possible to identify, select, assess, and critically synthesize the available scientific evidence on the topic while ensuring transparency, reproducibility, and methodological rigor.

METHODOLOGY

Study approach

The investigation adopted a qualitative and documentary approach and was designed as a Systematic Literature Review (SLR). The choice of a qualitative synthesis reflected the heterogeneity of the studies and documents identified, which included experimental research, qualitative studies, reviews, case studies, modeling, documentary analyses, and technical materials.

Method

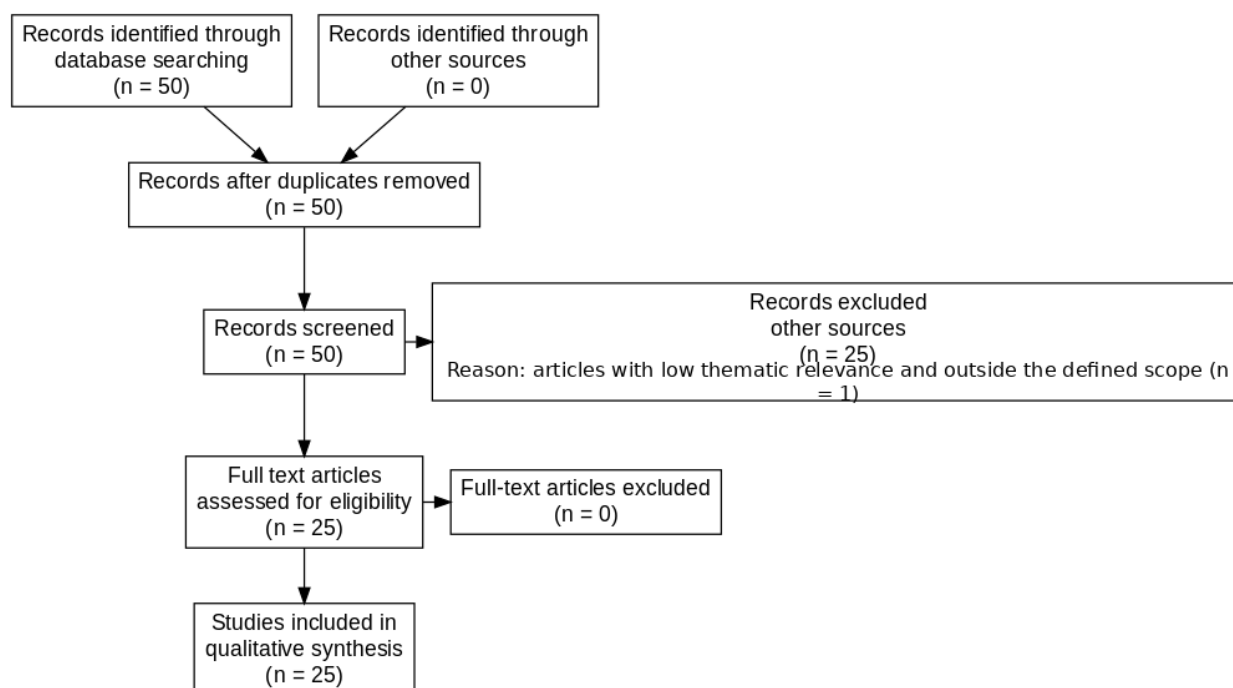
The review was conducted according to PRISMA 2020, which guided the identification, screening, eligibility assessment, extraction, and synthesis of the evidence [11]. The protocol was used as a reporting and process-traceability framework, without performing a meta-analysis.

Study phases

The systematic review was developed in four main phases.

- Phase 1 - Study search: a structured search was conducted in Google Scholar between 1 and 8 August 2026. The base query was: ("circular economy") AND ("printed circuit board" OR PCB) AND (reuse OR recovery OR "electronic components"). Publications in Portuguese, Spanish, and English, published between 2012 and 2025, were considered.
- Phase 2 - Screening and eligibility: 50 records were identified. No duplicates were removed, so all 50 records underwent title and abstract screening. At this stage, 25 records were excluded because they did not show sufficient thematic relevance to the review question, including the absence of an explicit relationship with PCB/WEEE, component reuse or recovery, and the circular economy, according to the inclusion criteria. The remaining 25 records were assessed in full text, and none were excluded at that stage. Thus, 25 studies/documents were included in the qualitative synthesis.
- Phase 3 - Extraction and assessment: for each study, author/year, study type, main topic, relevant finding, and contribution to the circular economy were extracted. Methodological quality was appraised using a structured matrix with five criteria: clarity of the objective, appropriateness of the design/methodology, transparency of the description, consistency between results and conclusions, and relevance to the review question. The appraisal was used to interpret the strength of the evidence and not as a stand-alone exclusion criterion.
- Phase 4 - Evidence synthesis: the results were grouped into thematic categories and compared in terms of trends, contributions, limitations, and gaps. The analysis made it possible to construct the conceptual recovery sequence: discarded PCB -> disassembly -> characterization -> functional testing -> classification -> reuse of functional components -> recycling of non-reusable components.

Figure 1. PRISMA diagram of the study identification, screening, eligibility, and inclusion process



Note. Study screening and selection process according to PRISMA 2020. Authors' own elaboration.

The PRISMA diagram presents 50 records identified in Google Scholar and no records from other sources. No duplicates were removed, leaving 50 records for screening. During title and abstract analysis, 25 records were excluded because of low thematic relevance to the review question and inclusion criteria. The remaining 25 full-text records were assessed for eligibility, with no exclusions at that stage. Thus, 25 studies/documents were included in the qualitative synthesis.

Initially, 50 articles were identified in the database searched and were subsequently subjected to screening and relevance assessment.

After the screening and assessment process, 25 articles were selected, corresponding to 50% of the articles initially analyzed. These studies constitute the documentary basis of the review and

encompass different approaches, including experimental studies, case studies, literature reviews, qualitative studies, techno-economic studies, modeling, and documentary analysis.

The search was conducted exclusively in Google Scholar, selected for its broad coverage and ability to retrieve interdisciplinary literature on WEEE, PCBs, the circular economy, and waste management. This choice constitutes a methodological limitation and was explicitly acknowledged. The publication period of the included studies was 2012-2025; the final search was conducted between 1 and 8 August 2026. Fifty records were identified and 25 studies/documents were included after screening.

Inclusion and exclusion criteria

Studies and academic or technical documents were included if they: (i) had an explicit relationship with WEEE, PCBs, the circular economy, recovery, reuse, remanufacturing, recycling, or reverse logistics; (ii) provided sufficient information to identify the objective, approach, and contribution; (iii) were available in full text; and (iv) were published between 2012 and 2025 in Portuguese, Spanish, or English. To maintain consistency with the sample, the review was not restricted to journal articles and could include proceedings, books/monographs, and technical materials when directly relevant to the WEEE recovery chain.

Duplicates, documents without full text, materials unrelated to the review objective, publications outside the defined period, and documents whose information did not permit assessment of their contribution to the research question were excluded. Theses, books, proceedings, and technical materials were not automatically excluded; when relevant, they were treated as supporting documents and distinguished from journal articles in the synthesis.

General procedure

After the search strategy and eligibility criteria were defined, records were identified, screened, and assessed according to the PRISMA 2020 flow. The extraction matrix was used to organize author/year, study type, topic, results, and contribution to the circular economy. The synthesis was exclusively qualitative because of methodological heterogeneity and the absence of comparable measures that would justify a meta-analysis.

RESULTS

The systematic review analyzed 50 records identified in Google Scholar and included 25 studies/documents in the final synthesis. The publication period of the selected studies was 2012-2025, while the final search was conducted between 1 and 8 August 2026. The analysis was qualitative and descriptive, considering study type, topic, results, and contribution to the circular economy.

The studies were characterized according to year, type of approach, main topic, relevant finding, and contribution to the circular economy. The heterogeneity of the designs prevented statistical aggregation of the results.

The results are presented through documentary synthesis and thematic analysis. The methodological assessment indicated a higher level of detail in experimental and applied studies, while reviews, proceedings, and technical materials showed greater heterogeneity in the description of procedures. This difference was considered when interpreting the findings.

Characterization of the selected studies

Analysis of the 25 included studies/documents identified different methodological and thematic approaches related to the recovery of printed circuit boards and the management of waste electrical and electronic equipment. The selected studies represent different types of research, ranging from experimental studies focused on the characterization, separation, and recovery of materials present in circuit boards to literature reviews and applied studies related to recycling, reverse logistics, reuse, remanufacturing, and the circular economy.

Among the works analyzed, studies specifically focused on the characterization and physical separation of printed circuit boards, recovery of the metallic fraction, and development of PCB recycling and chemical characterization processes stand out [12,13].

Studies addressing reverse logistics as a strategy for WEEE management were also identified. The reviewed literature shows that this approach is related to reducing environmental impacts caused by improper disposal and to the possibility of recovering value from recovered materials [14,15].

Overall, the 25 selected studies/documents show that electronic waste recovery can be approached from different perspectives involving technical, environmental, economic, and management aspects. This diversity made it possible to organize the studies according to the main variables defined in the analysis matrix.

Thematic analysis of the included studies

Analysis of the 25 selected studies/documents identified six main themes related to the recovery of waste electrical and electronic equipment, printed circuit boards (PCB), and the circular economy. The themes were defined from the main focus of each study in order to identify the predominant approaches in the literature.

Table 1. Synthesis of the 25 selected studies/documents

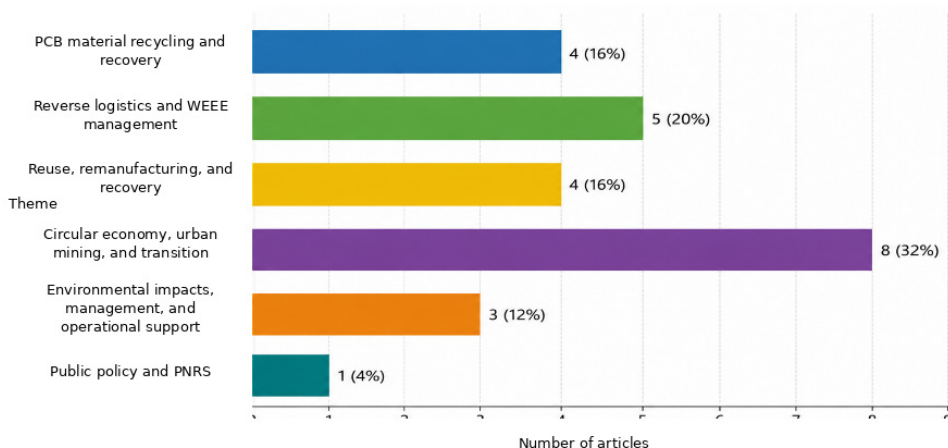
Author/Year	Study type	Main topic	Main findings
Sakurai (2012)	Scientific research	Technical-economic model for PCB recovery	Technical and economic alternatives for PCB recovery
Medeiros (2015)	Bibliographic research	Characterization and physical separation of PCBs from obsolete computers	Characterization of circuit boards and granulometric and magnetic separation techniques.
Medeiros et al. (2015)	Qualitative exploratory research	Recovery of the metallic fraction of printed circuit boards	Recovery of the metallic fraction present in printed circuit boards.
Priya & Hait (2018)	Experimental research	Characterization and valorization of PCBs from end-of-life equipment	Physicochemical characterization of PCBs, identifying metals, precious metals, and rare earth elements with recovery potential.
Bayão & Amorim (2018)	Literature review	Reverse logistics of WEEE: a global view of advances and comparison with the Brazilian situation	Evolution of electronic-waste reverse logistics and comparison of different advances with the Brazilian context.
de Brida (2019)	Qualitative research	Reverse logistics of electrical and electronic equipment: an analysis of the Brazilian system	Structure and operation of the reverse logistics system in Brazil.
Lima & de Lima Maciel (2018)	Qualitative research	Reverse logistics and sustainability: a study of the electrical and electronics sector	Reverse logistics and recycling as sustainable alternatives for electronic components.
Porto et al. (2018)	Documentary research and case study	Management of WEEE disposal with a focus on Green IT	Importance of Green IT, reverse logistics, and electronic-waste management.
Mandarino & de Sinay (2018)	Literature review	Impacts and challenges in electronic-waste management	Identifies environmental and management challenges associated with electronic waste.
Cintra & Cidade (2020)	Review and practical application	Reuse and recycling: jewelry development using components from electronic waste	Study of mobile phones and assessment of components for use in jewelry, highlighting reuse possibilities.
Simonetto et al. (2016)	System dynamics modeling	A system dynamics model for assessing PCB waste recovery in computer remanufacturing	Environmental and financial impacts of extending computer life through reuse and remanufacturing.
de Brito et al. (2019)	Applied study	Reverse remanufacturing of electrical and electronic equipment and the circular economy	Reverse remanufacturing chain for equipment and electronic waste in recycling.
Brejão et al. (2020)	Applied research	Proposal for the circular economy: reuse of microelectronics waste	Reuse of waste generated by microelectronics.
Franz & Silva (2022)	Review	WEEE, the environment, and the circular economy	Analyzes WEEE as a challenge for production chains and the urban environment.
de Sousa Martins et al. (2023)	Integrative review and documentary analysis	Transition from the linear to the circular economy for electrical and electronic equipment	Shift from the "extract-produce-discard" model toward circular models for electrical and electronic equipment.
Xavier & Ottoni (2019)	Technical-conceptual review study	Circular economy and urban mining: waste electrical and electronic equipment	Circular economy and urban mining, with reinsertion of secondary raw materials into production processes.
Contador et al. (2022)	Bibliographic review	Paradoxes of WEEE reverse logistics and urban mining in Brazil	Paradoxes related to reverse logistics and urban mining, with material recovery.

Author/Year	Study type	Main topic	Main findings
Gazzola et al. (2025)	Applied study	Innovation and circular economy of electronic equipment	Analyzes innovation initiatives related to the circularity of electronic equipment.
Souza et al. (2025a)	Case study	Circular economy and planned obsolescence	Obsolescence reduces product life and increases WEEE generation, contrary to circular principles.
Sampaio et al. (2024)	Bibliometrics	Circular economy and waste: a bibliometric analysis of worldwide scientific output	Worldwide scientific production on the circular economy and waste, identifying trends and the evolution of the field.
Souza et al. (2025b)	Qualitative research	Challenges in the transition to the circular economy in Brazil's WEEE sector	Identification of five groups of bottlenecks: logistics, regulation, consumers, markets, and design.
de Oliveira et al. (2017)	Review	Electronic waste: generation, environmental impacts, and management	Risks associated with metals and toxic substances and with improper disposal and recycling processes.
Giese et al. (2021)	Study with a social approach	Cooperatives and WEEE management	Role of cooperatives in the collection, management, and recovery of electronic waste.
de Oliveira et al. (2023)	Technical and educational material	Educational manual on disassembly and disposal of electronic equipment	Procedures for disassembly and disposal of electronic devices as methodological support.
Cosenza et al. (2020)	Qualitative and documentary study	Circular economy as an alternative for sustainable growth in Brazil: analysis of the PNRS	Circular economy as an alternative for sustainable growth under Brazil's National Solid Waste Policy.

Note. Synthesis of the 25 included studies/documents, organized from the analysis matrix. Authors' own elaboration.

Figure 2 presents the six main themes identified in the 25 included studies/documents.

Figure 2. Thematic distribution of the 25 included studies/documents



Note. Percentages calculated from the 25 included studies/documents. Authors' own elaboration.

PCB material recycling and recovery

The first theme comprises 4 articles (16%) focused on the recovery and valorization of materials present in printed circuit boards. The studies address the technical and economic recovery of PCBs, physical characterization and separation, recovery of the metallic fraction, and development of recycling and chemical characterization processes.

This trend shows that material recovery is one of the main pathways identified in the literature for transforming discarded PCBs into resources. Review studies also show that circuit boards contain organic, metallic, and ceramic materials, with the heterogeneity of their constituents representing one of the challenges for recycling.

Thus, recycling is no longer merely a waste-disposal strategy and becomes an opportunity to recover economic value, especially through the recovery of metals and reusable materials.

Reverse logistics and WEEE management

The second theme comprises 5 articles (20%). The studies analyze reverse logistics, WEEE disposal management, and the responsibilities of the different actors involved in the equipment life cycle.

Reverse logistics appears as a fundamental mechanism for enabling equipment and its

components to return to production chains. The reviewed literature also links this practice to reduced environmental impacts and potential cost reductions.

This category is particularly important to the circular economy because it establishes the link between consumption, post-consumption, collection, sorting, recovery, and reintegration of materials.

Reuse, remanufacturing, and recovery

Four articles (16%) directly related to component reuse, remanufacturing, and recovery were identified [16,17].

The studies demonstrate an important shift in perspective: equipment or a component that has reached the end of its original use may still retain functional value. Instead of being sent immediately for recycling, it may be reused, recovered, or remanufactured.

This approach is more directly aligned with circular economy principles because it seeks to extend the useful life of products and components before their transformation into secondary raw materials.

Circular economy, urban mining, and transition

This was the predominant theme, accounting for 8 of the 25 articles (32%).

Studies in this category directly address the circular economy applied to electrical and electronic equipment, urban mining, the transition from linear to circular models, innovation, planned obsolescence, and the challenges of circularity in the sector [18,19,20,21,22].

The literature shows a clear convergence: the traditional extract-produce-consume-discard model needs to be replaced by systems capable of keeping products, components, and materials in circulation for longer periods.

In this context, WEEE is particularly relevant because it contains materials of economic value. The study on planned obsolescence, for example, links life extension, reparability, reuse, remanufacturing, and recycling to circular economy principles.

Urban mining also emerges as a waste-recovery strategy, transforming materials contained in discarded equipment into a type of “secondary reserve” of resources.

Environmental impacts, management, and operational support

Articles 22 to 24 correspond to 3 studies (12%) and present a complementary approach involving environmental impacts, WEEE management, cooperatives, and operational aspects related to disassembly and recovery [23,24,25,26].

The studies show that the electronic waste problem is not exclusively technological. Improper disposal can cause environmental and social impacts, while appropriate collection, sorting, and disassembly are necessary for materials to be recovered.

In the case of PCBs, the literature highlights the need to separate reusable materials from potentially toxic materials, reinforcing the importance of sorting and safe disassembly.

Public policy and PNRS

The final theme is represented by the study by Cosenza, Andrade, and Assunção [8], corresponding to 1 article (4%) of the sample.

Although it is only one study among the 25 selected, it is strategically important because it establishes the relationship between the circular economy, waste management, shared responsibility, and reverse logistics.

The study shows that Brazil's National Solid Waste Policy (PNRS) is an important mechanism for bringing waste management closer to circular economy principles, although barriers to its effective implementation remain.

Synthesis of the thematic analysis

Analysis of the 25 articles shows that the literature does not focus on a single solution. There is a recovery chain for waste electrical and electronic equipment, which can be represented as follows:

Disposal, collection, sorting, reuse, repair and remanufacturing, component recovery, recycling, material recovery, and reintegration into production, as shown in Figure 3.

Figure 3. Recovery chain for waste electrical and electronic equipment



Note. WEEE recovery chain summarized from the 25 selected studies/documents. Authors' own elaboration.

The predominance of studies on the circular economy, urban mining, and transition (32%), followed by reverse logistics and WEEE management (20%) and by recycling/recovery and reuse/remanufacturing (16% each), shows that the literature has evolved from a perspective focused solely on disposal toward an approach oriented to value recovery and keeping resources in circulation.

At the same time, the review reveals an important gap: despite the existence of studies on recycling, reverse logistics, the circular economy, and material recovery, there is room for approaches that integrate recovery, characterization, functional assessment, and direct reuse of electronic components from discarded PCBs.

DISCUSSION

Predominance of the circular economy and urban mining

Analysis of the 25 studies/documents showed that the circular economy, urban mining, and transition to circular models formed the most representative thematic group, at 32%. This result is consistent with literature that interprets WEEE as secondary sources of materials and resources, bringing waste management closer to circularity strategies [1,6,18]. The predominance of this group indicates a shift in focus: waste is no longer viewed only as a disposal problem but also as a potential reserve of value.

The studies show that urban mining can complement conventional extraction through the recovery of secondary raw materials. However, the costs and complexity of reverse logistics may limit the effectiveness of these strategies, reinforcing the need to integrate technological recovery, economic feasibility, and chain organization [18].

Scientific discussion on WEEE therefore progressively moves beyond the logic of collection and disposal and incorporates value recovery, reuse, remanufacturing, and recycling [5,16,7].

PCB material recycling and recovery

Studies on PCB material recycling and recovery accounted for 16%. They show that circuit boards contain material fractions that can be characterized, separated, and recovered. Priya and Hait [2] demonstrated the importance of characterizing PCBs from end-of-life equipment, while Medeiros et al. [3] addressed recovery of the metallic fraction. These results support the need to characterize the board before deciding between reuse, component recovery, or recycling.

Characterization and separation function as decision stages, making it possible to distinguish

materials and components with different destinations. For the present study, this evidence supports a hierarchy in which potentially functional components should be assessed before the board is sent to recycling processes.

In this sense, the results support the adoption of systematic procedures for disassembly, identification, and functional testing. The literature on reuse and remanufacturing reinforces that extending component life can represent a recovery strategy prior to transformation into secondary raw material [4,5].

Reuse, remanufacturing, and recovery

Reuse, remanufacturing, and recovery represented 16% of the sample. These studies are directly aligned with the objective of the review because they show that products and components at end of use may retain functional value and be directed to new applications [4,17,5].

The system dynamics model by Simonetto et al. [5] showed the relevance of assessing the extension of computer life through reuse and remanufacturing. Although it is not specific to a single family of PCB components, the study supports the life-cycle extension logic adopted in this review.

Reuse and recycling studies show, however, that the diversity of equipment and materials makes process standardization difficult [4,17]. Functional assessment is therefore a critical stage for preventing components that are still useful from being prematurely sent for recycling.

These results are important because they show that reusing a functional component can represent a recovery alternative before recycling. Functional assessment of components therefore becomes an important stage in a circular economy strategy.

Reverse logistics and WEEE management

Reverse logistics and WEEE management represented 20% of the studies. The literature shows that circularity depends on mechanisms capable of collecting, transporting, sorting, and directing products and components toward recovery, reuse, or recycling [9,15,10].

Reverse logistics establishes the link between post-consumption and recovery processes. In the PCB context, this means that a reuse system cannot be analyzed only at the workbench: it must consider the origin of the waste, collection, sorting, disassembly, characterization, testing, and final destination.

This finding is especially important for an integrated approach because the availability of components for reuse depends both on the technical condition of the board and on the existence of an organized recovery chain.

Environmental impacts and the need for appropriate management

Studies on environmental impacts, management, and operational support accounted for 12%. They highlight risks associated with improper disposal, the presence of potentially hazardous substances, and handling without safety procedures [24,23].

Appropriate management requires collection, sorting, and safe disassembly, as well as routing compatible with material characteristics. The technical material by Oliveira et al. [26] reinforces the importance of disassembly procedures and responsible disposal.

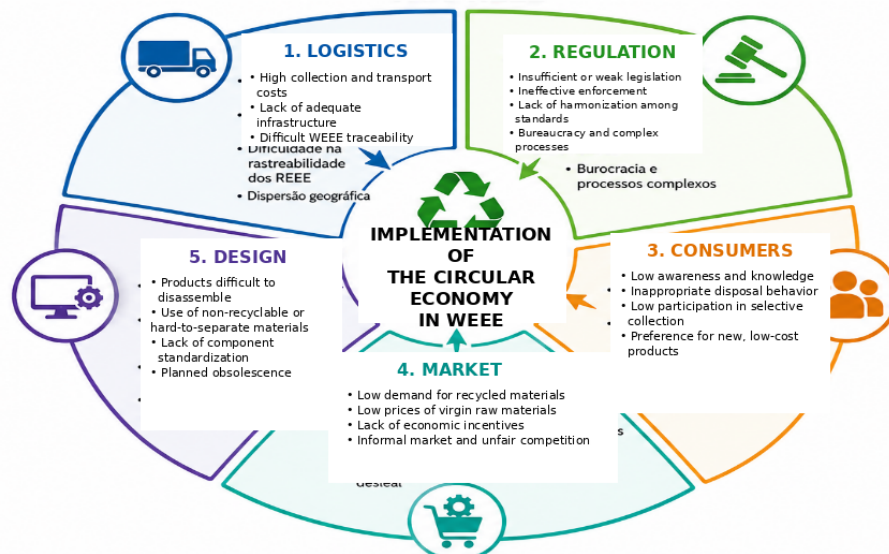
Thus, recovering functional components before recycling is not only an economic strategy but also a measure for preventing impacts and recovering value from waste.

Barriers to implementing the circular economy in WEEE

Despite the benefits, implementing the circular economy in WEEE faces barriers related to logistics, regulation, consumer behavior, markets, and product design. Souza et al. [22] identified these five groups of bottlenecks, showing that the availability of recovery technologies alone does not guarantee circularity.

Consequently, institutional, economic, and technical conditions are required to ensure a second use for recovered components. Circularity requires coordination among technology, markets, regulation, and the behavior of the actors involved.

Figure 4. Barriers to implementing the circular economy in WEEE



Note. Barriers to the circular economy for WEEE. Authors' own elaboration.

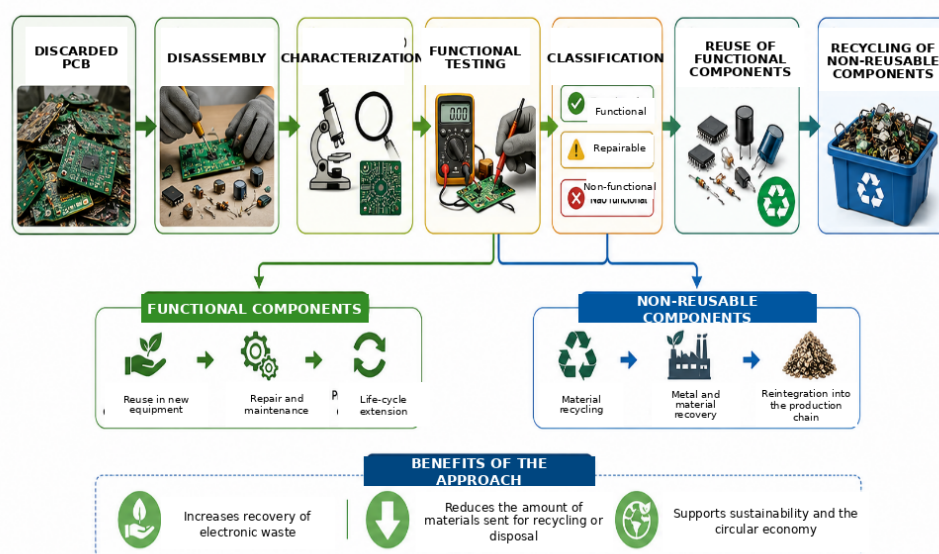
Critical synthesis and identified gap

Overall, the 25 studies/documents analyzed provide convergent evidence on recycling, reverse logistics, reuse, remanufacturing, urban mining, and the circular economy [1,5,7]. However, most of the literature addresses WEEE broadly, and studies integrating disassembly, characterization, functional testing, classification, and direct reuse of PCB components within a single sequence are less frequent.

The main gap identified was therefore the absence of integrated and sufficiently standardized procedures for deciding, on the basis of functional evidence, which components should be reused and which should proceed to recycling. This gap supports the conceptual proposal presented in this study.

The proposal does not replace recycling; it seeks to establish a recovery priority in which functional reuse is assessed before material recovery, preserving a greater share of the value embedded in the component.

Figure 5. Integrated proposal for PCB component recovery in the circular economy context



Note. Treatment sequence for printed circuit boards (PCBs). Authors' own elaboration.

Accordingly, the proposal in this study is organized according to the sequence: discarded PCB -> disassembly -> characterization -> functional testing -> classification -> reuse of functional components -> recycling of non-reusable components.

Discarded PCB, disassembly, characterization, functional testing, classification, reuse of functional components, and recycling of non-reusable components.

This sequence constitutes a conceptual proposal derived from the thematic synthesis of the review and should be experimentally validated in future studies before being treated as a standardized operational procedure.

Limitations

This review has limitations that should be considered when interpreting the results. The search was conducted exclusively in Google Scholar, which may have reduced coverage of specialized databases. The sample also showed methodological heterogeneity and included, in addition to journal articles, proceedings, books/monographs, and relevant technical materials, which limits quantitative comparisons. The documentary period was 2012-2025 and the review did not perform a meta-analysis. Finally, the proposed REC-PCB Framework was not experimentally validated at this stage and should be regarded as a process-organization hypothesis rather than an already validated method.

CONCLUSION

The review identified 50 records and included 25 studies/documents in the final synthesis, with a thematic predominance of the circular economy, urban mining, and transition to circular models (32%), followed by reverse logistics and WEEE management (20%).

The results confirm that PCBs and WEEE can be recovered through characterization, recovery, reuse, remanufacturing, and recycling. Reusing functional components before recycling is a strategy consistent with the circular economy because it seeks to preserve embedded value and extend the life cycle.

Future research should experimentally validate procedures for disassembly, characterization, functional testing, and classification, including indicators of recovery rate, reliability, cost, energy consumption, and environmental benefits. Automated identification and classification systems are also relevant.

The WEEE problem should be broadened beyond the technological dimension by integrating reverse logistics, regulation, markets, consumer behavior, design, occupational safety, and urban mining. Consolidating the circular economy depends on integrating these dimensions.

Prospectively, the sequence discarded PCB -> disassembly -> characterization -> functional testing -> classification -> reuse -> recycling may provide a basis for more efficient recovery systems. The REC-PCB Framework proposed in this study has potential as a conceptual structure, but its effectiveness and generalizability will depend on experimental validation and comparison with conventional recycling routes.

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