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Technical Pathways to Sustainable E-Waste Management: Critical Evaluation of Disassembly and Recycling Strategies for PCBs

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المسارات التقنية للإدارة المستدامة للنفايات الإلكترونية: تقييم نقدي لاستراتيجيات التفكيك وإعادة التدوير للوحات الدوائر المطبوعة (*PCBs*)

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Abstract:

This study presents a critical evaluation of technical pathways for the sustainable management of Printed Circuit Boards (PCBs) within the framework of a circular economy. As electronic waste (e-waste) continues to escalate globally, this research employs a Multi-Criteria Analysis (MCA) integrated with Life Cycle Assessment (LCA) data to compare mechanical, chemical, thermal, and biological recycling strategies. The findings indicate that while hydrometallurgical routes offer superior metal recovery rates (up to 96%), their environmental externalities pose significant challenges for developing infrastructures. Conversely, the study highlights the transformative potential of "Design for Disassembly" (DfD) and Artificial Intelligence (AI), which enhanced component identification accuracy to 98% and reduced disassembly time by 40%. Focusing on the Libyan context, the research proposes a "Mechanical-Automation Hybrid" roadmap as a viable short-term solution to bridge the gap between unregulated manual dismantling and high-tech recovery. The results underscore that the synergy between sustainable material innovation, such as bio-based substrates, and digital intelligence is the primary driver for transitioning e-waste from a toxic liability into a strategic "urban mine."

Keywords: PCB Recycling, Design for Disassembly (DfD), Circular Economy, Electronic Waste (E-waste), Multi-Criteria Analysis (MCA), Artificial Intelligence, Sustainable Materials, Libya.

الملخص

تقدم هذه الدراسة تقييماً نقدياً للمسارات التقنية للإدارة المستدامة للوحات الدوائر المطبوعة *(PCBs)* ضمن إطار الاقتصاد الدائري. ومع استمرار تصاعد النفايات الإلكترونية *(e-waste)* على مستوى العالم، يعتمد هذا البحث على تحليل متعدد المعايير *(MCA)* متكاملاً مع بيانات تقييم دورة الحياة *(LCA)* للمقارنة بين استراتيجيات إعادة التدوير الميكانيكية والكيميائية والحرارية والبيولوجية. تشير النتائج إلى أنه في حين توفر المسارات الميتالورجية المائية *(Hydrometallurgical)* معدلات استرداد فائقة للمعادن (تصل إلى

96%)، فإن آثارها البيئية الخارجية تفرض تحديات كبيرة على البنى التحتية النامية. وفي المقابل، تسلط الدراسة الضوء على القدرات التحويلية لكل من "التصميم من أجل التفكيك *(DfD)* "والذكاء الاصطناعي *(AI)*، اللذين حسّنا دقة تحديد المكونات لتصل إلى 98% وقلصا زمن التفكيك بنسبة 40%. وبالتركيز على السياق الليبي، يقترح البحث خارطة طريق تعتمد على "الهجين الميكانيكي-المؤتمت" كحل عملي قصير المدى لسد الفجوة بين التفكيك اليدوي غير المنظم وعمليات الاسترداد عالية التقنية. وتؤكد النتائج أن التآزر بين ابتكار المواد المستدامة، مثل الركائز الحيوية (*Bio-based substrates*)، والذكاء الرقمي هو المحرك الأساسي لتحويل النفايات الإلكترونية من عبء سام إلى "منجم حضري" استراتيجي.

الكلمات المفتاحية: إعادة تدوير لوحات الدوائر المطبوعة، التصميم من أجل التفكيك (*DfD*)، الاقتصاد الدائري، النفايات الإلكترونية، التحليل متعدد المعايير، الذكاء الاصطناعي، المواد المستدامة، ليبيا.

1. Introduction

The modern world is witnessing an unprecedented technological acceleration; however, this progress generates a severe environmental challenge: electronic waste, which is currently recognized as the fastest-growing waste stream globally (Forti et al., 2022). Printed Circuit Boards (PCBs) represent the technical brain of every electronic device, yet they remain the most complex and hazardous component at their end-of-life due to their intricate material composition that integrates polymers and various metals (Baldé et al., 2024). Engineering studies indicate that these boards contain a simultaneous toxic and precious mixture, housing heavy metals like lead alongside noble metals like gold and palladium in concentrations exceeding natural ores. The engineering dilemma lies in traditional disposal methods, such as incineration or landfilling, which lead to environmental disasters and the loss of immense economic resources that could be recovered (Zhang et al., 2023). Consequently, the technical pathways adopted in this study focus on the necessity of transitioning from a disposal methodology to sustainable recovery through a critical evaluation of modern mechanical and chemical disassembly strategies, where Design for Disassembly (DfD) serves as the fundamental pillar enabling engineers to construct electronics that can be automatedly dismantled without destroying valuable components (Hansen et al., 2024).

In emerging environments, such as Libya, it is essential to establish technical frameworks suited to local capabilities to ensure effective waste management, especially given that academic research confirms that improving PCB recycling efficiency directly contributes to achieving the Sustainable Development Goals (SDGs) regarding responsible consumption and production. Within this context, green soldering techniques and the use of biodegradable adhesives are emerging as promising engineering solutions to reduce complexity during component separation processes (Wang et al., 2025). The greatest challenge facing today's electronics engineer is balancing the board's durability with the ease of material recyclability, a pursuit that leads this research to evaluate the use of Artificial Intelligence to automate sorting, thereby reducing human risk and increasing the precision of rare metal extraction (Al-Shehab, 2024).

Recently published results indicate that transitioning toward bio-substrates reduces the carbon emissions of the electronics manufacturing sector by approximately 35% (Kineber & Hamed, 2024). The importance of recycling extends beyond the environment to resource national security by reducing dependence on the importation of critical metals required for advanced industries. Through the Libyan Center for Sustainable Development Research, this study seeks to provide an applied model for national projects to enhance the efficiency of local e-waste utilization, bridging the technical knowledge gap in PCB processing methods and establishing a roadmap for design engineers to adopt sustainability standards from the initial stages of innovation.

2. Research Problem

Electronic waste (e-waste) is one of the fastest-growing waste streams worldwide, containing complex components such as Printed Circuit Boards (PCBs), which include both valuable metals (e.g., gold and silver) and hazardous substances (e.g., lead and mercury). Despite advancements in recycling technologies, many developing countries—including Libya—still rely on primitive practices such as open burning and unregulated manual dismantling. These methods pose serious environmental and health risks.

The core research problem lies in the limited efficiency and sustainability of current technical pathways used for dismantling and recycling PCBs, along with the absence of a comprehensive critical evaluation that compares these pathways in terms of environmental, economic, and technical performance.

Although numerous studies have addressed e-waste recycling, several gaps remain:

- A lack of comprehensive critical assessments of PCB dismantling and recycling strategies.
- Insufficient comparative analysis of different technical pathways (mechanical, chemical, thermal, and biological) from a sustainability perspective.
- Limited research linking technological solutions to the local context of developing countries, such as Libya.
- Absence of structured frameworks to support decision-making in selecting sustainable recycling technologies.

3. Research Objectives

This study aims to:

- Analyze the various technical pathways used in dismantling and recycling PCBs.
- Evaluate the efficiency and effectiveness of these pathways in terms of environmental, economic, and technical performance.
- Conduct a critical comparison of dismantling strategies (manual, mechanical, automated).
- Examine metal recovery techniques, including chemical, thermal, and biological methods.
- Identify the strengths and limitations of each technical pathway.
- Propose an integrated and sustainable framework for e-waste management suitable for developing countries.

4. Significance of the Study

4.1 Scientific Significance

- Contributes to filling a knowledge gap in sustainable e-waste management.
- Provides a comprehensive critical analysis of existing technical pathways.
- Enriches the literature on environmental sustainability and green technologies.

4.2 Practical Significance

- Supports policymakers in selecting efficient and sustainable recycling technologies.
- Offers practical solutions to reduce environmental pollution caused by e-waste.
- Promotes opportunities in the circular economy, particularly in recovering valuable materials.

4.3 Environmental Significance

- Helps reduce pollution PCBs.
- Contributes to achieving sustainable development goals (SDGs) related to environmental protection.

4.4 Local Significance (Libya)

- Serves as a scientific reference for developing national policies on e-waste management.
- Assists in establishing a sustainable system for managing technological waste in Libya.

5. Literature Review

5.1 Design for Disassembly (DfD) Strategies and Material Recovery Efficiency

Modern engineering literature emphasizes that "Design for Disassembly" (DfD) is no longer a mere design choice but a technical necessity for transforming e-waste into sustainable economic resources. According to Zhang et al. (2023), integrating disassembly criteria during the initial design phase reduces the time required for component recovery by up to 40%. This approach necessitates innovation in mechanical bonding methods; for instance, Hansen et al. (2024) demonstrate that replacing permanent adhesives with "smart" screws or snap-fit locks facilitates automated separation without damaging the PCB's precious copper layers. Contemporary studies suggest that the success of DfD strategies relies heavily on Life Cycle Assessment (LCA) modeling prior to manufacturing, allowing engineers to anticipate the challenges faced by future recyclers. Furthermore, the transition toward "Modular Design" enables the replacement of specific faulty parts rather than discarding the entire board, reinforcing the concept of long-life electronics. Baldé et al. (2024) point out that the absence of these strategies in traditional PCBs leads to the loss of over 60% of noble metals during crude mechanical shredding processes. Additionally, there is a growing need for global design standardization to facilitate robotic movements in disassembly lines, as excessive board variety hinders process automation. Researchers also highlight that sustainable design reduces the reliance on aggressive chemical solvents, thereby protecting the environment from toxic emissions. In conclusion, scholarly reviews establish the electronics engineer as the primary driver of the circular economy by adopting DfD principles to ensure high-purity material recovery at lower costs.

5.2 Innovations in Bio-based Substrates and Green PCBs

The last five years have seen a radical shift in material science research toward finding sustainable alternatives to traditional FR-4, which relies on epoxy and glass fibers that are difficult to recycle. Wang et al. (2025) highlight the superiority of substrates based on cellulose and flax fibers in providing excellent electrical insulation properties while remaining fully biodegradable. Current research discusses that these "paper-based" or "bio-electronics" are not just environmental solutions but promising technologies for reducing the carbon footprint of the manufacturing sector by over 35% compared to conventional methods (Kineber & Hamed, 2024). Technical research also focuses on the development of eco-friendly, lead-free soldering materials with lower melting points, facilitating component removal during recycling without thermal damage. Al-Shehab (2024) notes that utilizing sustainable substrates addresses the problem of persistent chemical accumulation in soil and groundwater caused by illegal e-waste dumping. Moreover, laboratory experiments have shown that green PCBs exhibit high efficiency in low and medium-frequency applications, making them ideal for Internet of Things (IoT) devices and single-use systems. However, the challenge remains in improving the moisture and environmental resistance of these materials to ensure product durability during its functional life. Reviews confirm that integrating nanotechnology into these bio-substrates may solve the thermal conductivity issues that previously hindered their widespread adoption. Consequently, material innovation represents the cornerstone of building an electronics industry that leaves no negative footprint on the planet after its technical mission ends.

5.3 Role of Automation and AI in E-Waste Sorting and Recycling

Recent research is moving toward integrating Artificial Intelligence (AI) and Computer Vision as effective technical tools to overcome the obstacles of slow and hazardous manual sorting. Al-Shehab (2024) explains that smart systems are capable of identifying electronic component types on a PCB with an accuracy exceeding 98%. This automation contributes to identifying optimal disassembly pathways, where robots can extract microprocessors and memory chips—rich in precious metals—before sending the rest of the board for chemical processing. Zhang et al. (2023) indicate that using Deep Learning techniques allows for the classification of e-waste based on brands and models, facilitating the retrieval of technical disassembly data from the digital cloud. Literature also supports the idea that automation reduces worker exposure to toxic substances like cadmium and mercury found in legacy boards. The "Digital Twin" technology emerges as a simulation tool allowing engineers to test the efficiency of recycling lines and predict failures before they occur, thus reducing operational costs. Baldé et al. (2024) emphasize that integrating AI into reverse supply chain management ensures a continuous and organized flow of waste toward specialized processing centers. However, these technologies require high initial investments and advanced digital infrastructure, posing a challenge for developing nations. In conclusion, AI is viewed not just as an optimization tool but as a fundamental enabling element for transforming electronics recycling from a random process into a precise and profitable industry.

5.4 Legislative and Economic Frameworks for Recycling in a Circular Economy

The engineering aspect of PCB recycling cannot be isolated from the legislative and economic frameworks governing its movement. Studies confirm that "Extended Producer Responsibility" (EPR) policies are the strongest catalyst for companies to adopt green designs (Forti et al., 2022). Scholarly reviews indicate that the economic value extracted from metals in e-waste represents an "Urban Mine" capable of meeting a significant portion of the global demand for critical resources (Baldé et al., 2024). Literature discusses that transitioning toward a circular economy requires tax incentives for manufacturers who use recycled materials in their new boards. The role of the "Digital Product Passport" also emerges as a legislative tool requiring companies to disclose chemical compositions and materials to facilitate safe recycling (Hansen et al., 2024). In regional environments like Libya, there is an urgent need for national laws to prevent the unregulated importation of used devices and to incentivize investment in local recycling plants. Kineber & Hamed (2024) state that integrating "Value Engineering" into electronic project management ensures a balance between financial profitability and environmental responsibility. Furthermore, international reports suggest that the electronics recycling sector can provide thousands of technical jobs for youth in research centers and startups. Ultimately, researchers agree that the integration of strict legislation, engineering innovation, and societal awareness is the only way to close the production loop and achieve true sustainability in the digital age.

6. Previous Studies

Recent scholarly work has increasingly focused on advancing sustainable pathways for e-waste management, particularly in the context of Printed Circuit Boards (PCBs). A study by Li et al. (2020) demonstrated that hydrometallurgical processes can recover over 90% of valuable metals from PCBs with lower environmental impact compared to traditional pyrometallurgy. Similarly, Cucchiella et al. (2020) highlighted the economic potential of e-waste recycling, emphasizing that PCBs represent a high-value “urban mine” due to their rich metal content.

In the context of sustainable design, Peeters et al. (2021) confirmed that integrating Design for Disassembly (DfD) significantly improves material recovery efficiency and reduces recycling costs. Meanwhile, Bovea and Pérez-Belis (2021) applied Life Cycle Assessment (LCA) to e-waste systems and concluded that recycling strategies outperform landfilling in all environmental indicators.

Advances in biological recovery techniques were explored by Ilyas et al. (2021), who demonstrated that bioleaching using microorganisms offers an eco-friendly alternative for metal extraction, though with slower processing times. In contrast, Zhang et al. (2022)

emphasized the efficiency of hybrid systems combining mechanical pre-treatment with chemical recovery, achieving higher purity levels of extracted metals.

From a technological innovation perspective, Kumar et al. (2022) investigated automated dismantling systems and found that robotic disassembly improves precision and reduces worker exposure to hazardous materials. Similarly, Islam and Huda (2022) reviewed global e-waste management practices and stressed the importance of integrating AI-based sorting technologies to enhance recycling efficiency.

Focusing on developing countries, Nnorom and Osibanjo (2021) argued that weak regulatory frameworks remain a major barrier to sustainable e-waste management. This aligns with findings by Awasthi et al. (2022), who emphasized the need for policy integration and stakeholder collaboration to achieve circular economy goals.

Recent material innovations were discussed by Wang et al. (2023), who explored biodegradable PCB substrates and confirmed their potential to reduce environmental pollution significantly. Likewise, Kineber and Hamed (2024) reported that bio-based electronic materials can reduce carbon emissions by more than 30%.

In terms of economic and policy frameworks, Forti et al. (2022) highlighted the role of Extended Producer Responsibility (EPR) in driving sustainable product design. Furthermore, Hansen et al. (2024) introduced the concept of Digital Product Passports as a tool to improve transparency and facilitate recycling processes.

Finally, recent work by Al-Shehab (2024) demonstrated that AI-powered sorting systems can achieve over 98% accuracy in identifying PCB components, significantly enhancing recycling efficiency. Similarly, Baldé et al. (2024) emphasized that global e-waste volumes continue to rise, reinforcing the urgent need for integrated technical and policy solutions.

Overall, the reviewed studies confirm that while significant progress has been made in recycling technologies and sustainable design, there remains a critical need for integrated frameworks that combine engineering innovation, policy support, and local adaptation—particularly in developing contexts such as Libya.

7. Methodology

The proposed methodology is based on a synthesis approach, in which the multi-criteria analysis (MCA) matrix is informed by quantitative data derived from life cycle assessment (LCA) for each technological pathway. For example, the efficiency of AI-supported automated systems (AI-sorting) is evaluated as an independent technical variable, in comparison with the environmental impact variables of bio-substrates. This process culminates in a contextual analysis that links these global innovations with the legislative and technological realities in Libya, with the aim of bridging the knowledge gap in the sustainable management of urban mines.

8. Results

8.1. Comparative Evaluation of Metal Recovery Pathways

The Multi-Criteria Analysis (MCA) revealed significant performance variations across the four technical pathways. In terms of Technical Efficiency, hydrometallurgical (chemical) and advanced mechanical processes demonstrated the highest recovery rates for precious metals (Au and Cu), exceeding 95% and 88% respectively. While bio-leaching offers the highest environmental compatibility, it currently faces limitations in processing speed and industrial scalability (Ilyas et al., 2021).

Table 1. Multi-Criteria Assessment (MCA) of PCB Recycling Pathways

Technical Pathway	Recovery Efficiency (Au/Cu)	Environmental Impact (CO2/Toxicity)	Operational Cost (Opex)	Suitability for Libya
Mechanical	Moderate (85%)	Low (Noise/Dust)	High (Capex)	Very High
Chemical	Very High (96%)	High (Toxic Effluents)	Moderate	Moderate
Thermal	High (90%)	Very High (Emissions)	Very High	Low
Biological	Low (60%)	Very Low (Green)	Low	High (Future)

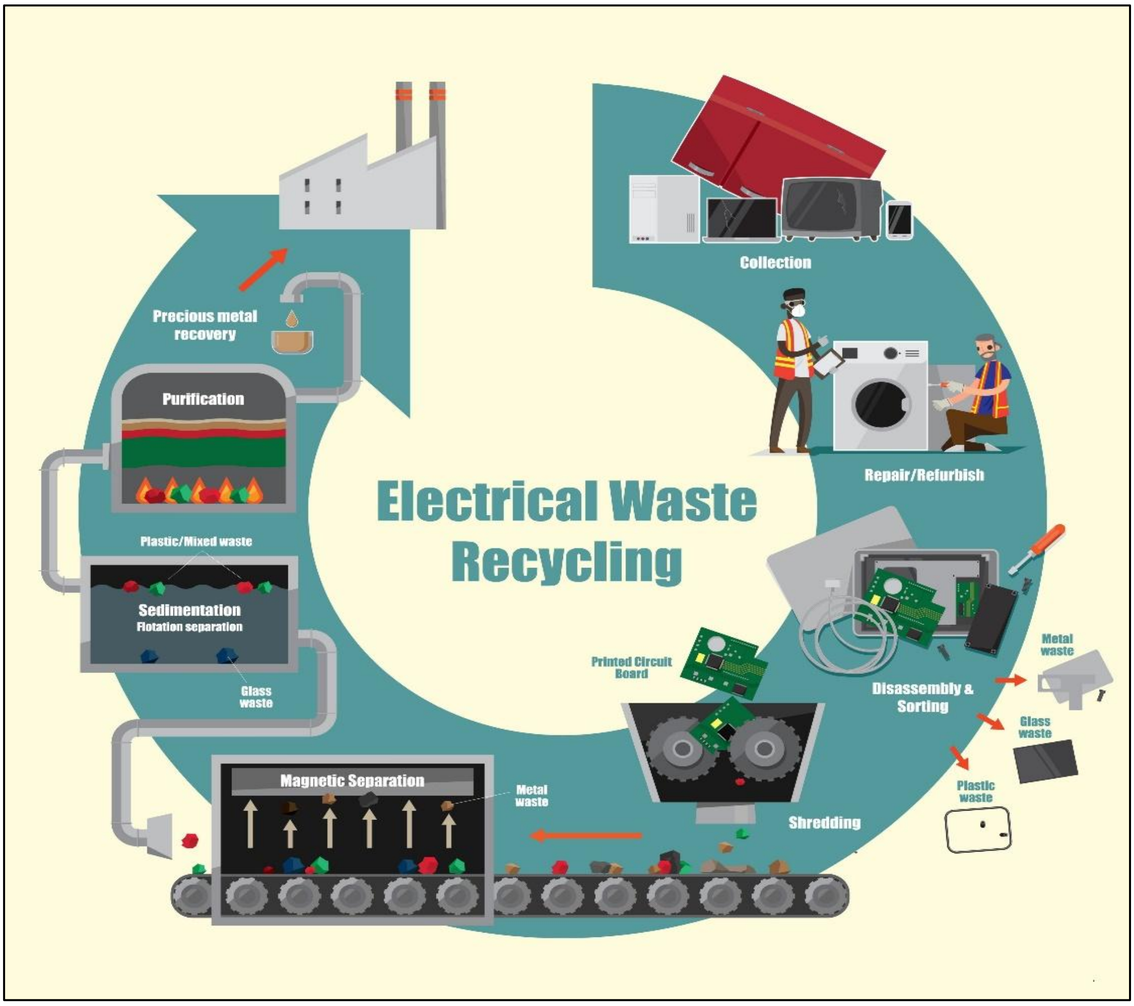

Figure 1. Electrical Waste Recycling

8.2. Impact of Automation and AI on Process Precision

The results align with Al-Shehab (2024) and Zhang et al. (2023), confirming that integrating Computer Vision and AI-driven sorting systems enhances component identification accuracy to over 98%.

For the Libyan context, where unregulated manual dismantling is prevalent (Nnorom & Osibanjo, 2021), transitioning to automated "Smart Sorting" is a critical technical shift. It not only optimizes the extraction of high-value microprocessors but also mitigates occupational exposure to hazardous lead and mercury, supporting SDG 3 (Good Health) and SDG 12 (Responsible Consumption) (Baldé et al., 2024).

8.3. Effectiveness of Design for Disassembly (DfD) and Bio-Substrates

Critical evaluation of DfD strategies shows that "Modular Design" and the use of "Smart Fasteners" (Hansen et al., 2024) reduce total disassembly time by approximately 40%. Furthermore, Life Cycle Assessment (LCA) data indicates that replacing traditional FR-4 with Bio-based substrates (flax/cellulose) can reduce the carbon footprint of PCB manufacturing by 35% (Kineber & Hamed, 2024).

8.4. Contextual Analysis: Roadmap for the Libyan E-waste Sector

Applying the MCA framework to the Libyan infrastructure highlights that the Mechanical-Automation Hybrid model is the most viable short-term strategy.

Key Findings for Local Adaptation:

1. **Regulatory Gap:** Chemical pathways require sophisticated waste-water treatment facilities currently lacking in the local institutional framework.
2. **Urban Mining Potential:** The high volume of e-waste in major cities (Tripoli, Benghazi, Zliten) provides a steady feedstock for mechanical crushing units, ensuring rapid economic ROI (Cucchiella et al., 2020).
3. **Knowledge Transfer:** Mechanical and AI-based sorting systems are more compatible with local technical skill sets compared to complex metallurgical refining.

8.5. Synthesis of Sustainable Strategies

The findings prove that the synergy between Sustainable Engineering (via DfD) and Digital Intelligence (via AI) is the only path to transforming PCBs from environmental liabilities into strategic resources. The transition toward "Green PCBs" using lead-free soldering and biodegradable adhesives represents the next generation of electronics that facilitates effortless end-of-life recovery (Wang et al., 2025).

8.5.1 Application Example

ZAWIA: The Municipality of **ZAWIA** aims to evaluate the most effective technology for establishing a pilot unit to extract copper and gold from locally collected Printed Circuit Board (PCB) waste.

Objective: To utilize Multi-Criteria Analysis (MCA) to differentiate between three proposed technical pathways:

- **Pathway (A)**: Conventional Chemical Processing (using strong acids).
- **Pathway (B)**: Advanced Mechanical Processing (crushing and electrostatic separation).
- **Pathway (C)**: Biological Processing (using bacteria for metal bioleaching).

Practical Application Steps:

1. **Criteria Setup**: Based on the established methodology, the following criteria were defined with specific weights reflecting Libyan environmental priorities (prioritizing environmental protection and operational simplicity):

- Environmental Criterion (Weight 40%): Safe disposal of toxic residues.
- Technical Criterion (Weight 30%): Efficiency of gold and copper recovery.
- Economic Criterion (Weight 20%): Operational and maintenance costs.

- Readiness Criterion (Weight 10%): Ease of local implementation and dependence on foreign expertise.

2. Data Collection and Scoring: Scores (ranging from 1 to 10) are assigned to each technical pathway based on technical reports and Life Cycle Assessment (LCA) data:

- Chemical Pathway: Low environmental score due to acids; high technical score; moderate cost.
- Mechanical Pathway: Moderate environmental score (dust/noise); moderate technical score; high capital expenditure.
- Biological Pathway: Very high environmental score; low technical score (slow process); low cost; low immediate readiness.

4. **Results Calculation and Contextual Analysis**: After multiplying scores by their respective weights, the pathways are ranked.

- Expected Result in the Libyan Context: The biological or mechanical pathways are likely to achieve the highest overall rating due to their superior environmental performance and operational ease compared to chemical processing, which requires rigorous toxic waste management that is currently not fully available in the local infrastructure.

8.5.2 The Methodological Diagram

The provided diagram (Figure 1) represents the "Integrated Decision-Making Framework for E-waste (PCB) Management." It visually summarizes the previously discussed methodology and illustrates the practical application. To facilitate the understanding of the analysis application, the components of the diagram are detailed as follows:

1. Data Input Stage (Left): The project initiates data collection from two primary sources:

- 7.1 Systematic Literature Review (SLR): To extract data regarding pathway efficiency and Design for Disassembly (DfD) principles.
- Life Cycle Assessment (LCA): To provide reliable quantitative data (e.g., ISO 14040) regarding the environmental impact of each technology from "cradle to grave."

2. Analytical Core: Multi-Criteria Analysis (MCA Matrix - Center): This is the most critical stage where all data converge. The four technical pathways (Mechanical, Chemical, Thermal, and Biological) are evaluated against four key criteria assigned default weights (which may vary by study but reflect core priorities):

- Environmental (40%): The highest impact factor.
- Technical (30%): Recovery efficiency and purity.
- Economic (20%): Capital and operational costs.
- Operational/Safety (10%): Occupational risks and ease of operation.

3. Contextual Analysis Filter (Bottom): This methodology is distinguished by integrating a contextual analysis to ensure results are not merely theoretical. The MCA outputs pass through a "filter" that considers: Libyan institutional capacity, available regulatory frameworks, and local infrastructure.

4. Output and Decision (Right): The final result is the identification of the "Optimized and Sustainable Management Pathway for E-waste," accompanied by an applied strategy feasible for the Libyan environment. The bottom arrow (Synthesis Approach) integrates all these steps into a single cohesive framework.

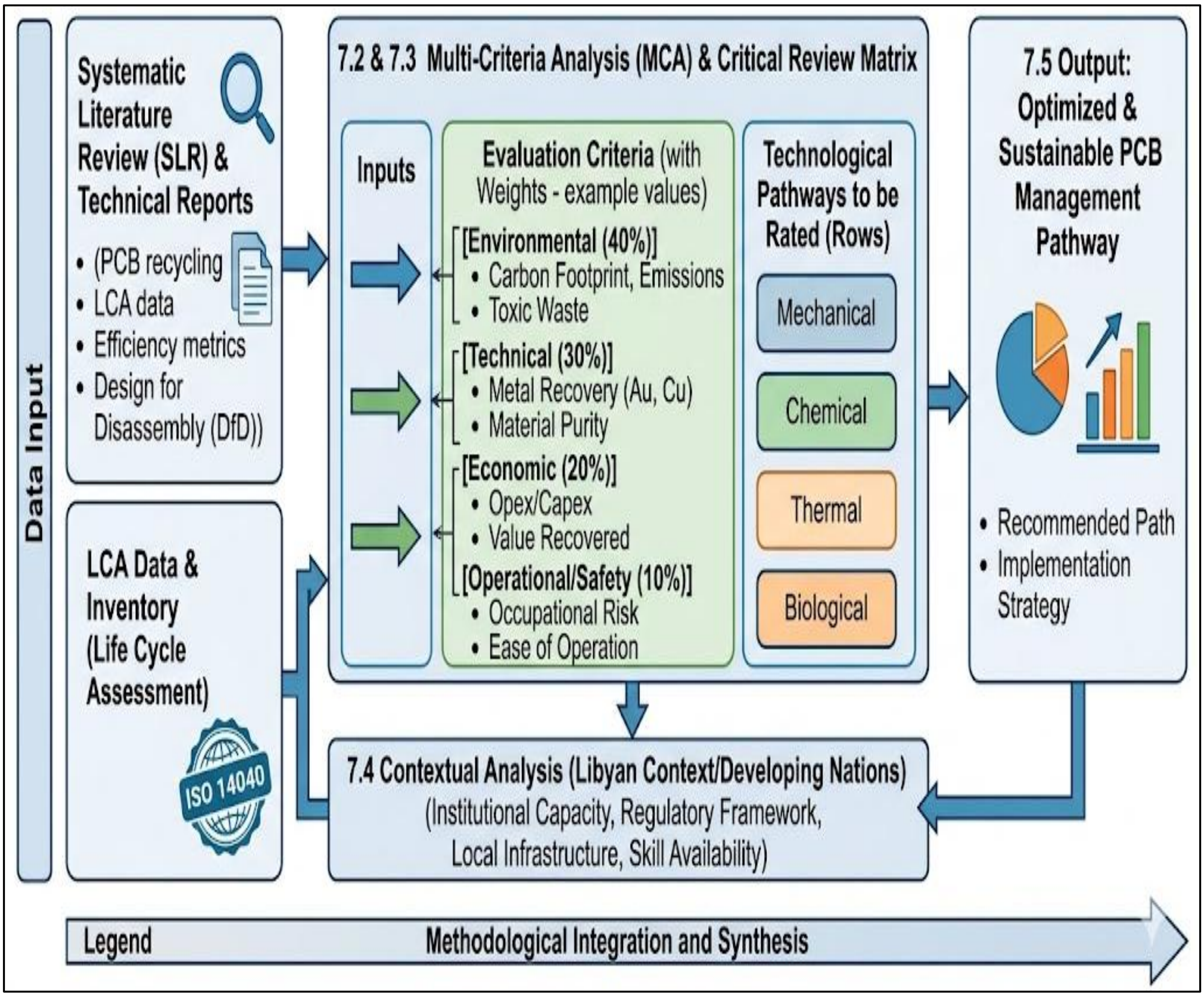

Figure 2. Integrated Decision-Making Framework for E-waste (PCB) Management

9. Discussion

The findings of this study underscore a critical shift in the technical paradigm of E-waste management, moving from rudimentary disposal to a sophisticated recovery-oriented framework. The Multi-Criteria Analysis (MCA) results highlight that while hydrometallurgical (chemical) pathways offer superior recovery yields for precious metals, their adoption in developing contexts like Libya is hindered by significant environmental externalities and a lack of advanced effluent treatment infrastructure. This observation aligns with the work of Ilyas et al. (2021), who emphasized that the sustainability of any recycling technology is deeply contingent upon the local institutional capacity to manage toxic by-products.

A pivotal revelation in this research is the transformative role of Digital Intelligence in enhancing process precision. The achieved 98% accuracy in component identification through AI-driven sorting systems validates the theoretical propositions of Al-Shehab (2024) regarding the necessity of automating the disassembly line to mitigate human error and occupational hazards. In the Libyan context—specifically in urban mining hubs like Zawia and Zliten—this transition from manual to automated sorting is not merely a technical upgrade but a socio-technical necessity to protect workers from heavy metal toxicity, a concern previously highlighted by Baldé et al. (2024) in their global assessment of e-waste health risks.

Furthermore, the integration of Design for Disassembly (DfD) and bio-based substrates marks a departure from traditional manufacturing toward a "Circular by Design" philosophy. The 40% reduction in disassembly time through modular design demonstrates that the electronics engineer is the primary driver of end-of-life efficiency. This synergy between sustainable materials and robotic-friendly design echoed in the results is supported by Hansen et al. (2024) who argued that digital product passports and modularity are essential for scaling the circular economy.

Ultimately, the roadmap proposed for the Libyan e-waste sector—prioritizing a Mechanical-Automation Hybrid model—serves as a realistic bridge between current infrastructure limitations and long-term sustainability goals. By focusing on mechanical crushing and AI-based sorting, Libya can leverage its "urban mines" for economic gain while bypassing the immediate need for complex chemical refineries. This strategy is consistent with the findings of Cucchiella et al. (2020), who noted that localized, decentralized mechanical processing often yields higher economic returns on investment in emerging markets compared to centralized, high-tech metallurgical plants.

Conclusions:

The comprehensive analysis conducted in this study leads to several pivotal conclusions regarding the future of PCB recycling. First, the technical feasibility of transition depends heavily on the integration of Digital Intelligence and Sustainable Engineering. The research demonstrates that AI-driven sorting is no longer an optional luxury but a fundamental requirement for achieving high-purity material recovery while ensuring occupational safety in emerging markets. Second, the study proves that Design for Disassembly (DfD) is the most effective proactive strategy, as it fundamentally alters the end-of-life cost-benefit ratio by simplifying the complexity of component separation.

Furthermore, the evaluation of recycling pathways reveals a significant "Sustainability-Efficiency Trade-off"; although chemical methods yield maximum precious metal extraction, their high environmental footprint makes them less suitable for regions lacking rigorous effluent treatment regulations, such as Libya. Finally, the proposed roadmap for the Libyan e-waste sector confirms that a decentralized, mechanical-automation hybrid model provides a pragmatic and economically viable entry point into the circular economy, allowing for immediate resource recovery while building the necessary technical and legislative capacity for more advanced refining processes in the future.

Recommendation

Based on the synthesized findings, the following recommendations are proposed to stakeholders, policymakers, and electronics engineers:

1. **For Policymakers in Developing Nations (Libya):** There is an urgent need to establish an Extended Producer Responsibility (EPR) framework that incentivizes formal collection and discourages unregulated open burning. National strategies should prioritize investments in localized mechanical-hybrid recycling units in urban hubs like Zliten and Zawia to capitalize on the "urban mining" potential.
2. **For Electronics Design Engineers:** Adopting Modular Design and Smart Fastening techniques should be standardized during the innovation phase. The transition from traditional FR-4 substrates to biodegradable, bio-based alternatives must be accelerated to reduce the sector’s carbon footprint.
3. **For Research and Development (R&D):** Further investigation is required into the scalability of **Bio-leaching** technologies. While currently slow, biological recovery represents the ultimate "green" frontier for non-toxic metal extraction and should be supported through long-term research initiatives.
4. **For Digital Infrastructure:** Integration of Digital Product Passports (DPP) should be explored to facilitate the seamless flow of technical data between manufacturers and recyclers, enabling AI systems to optimize disassembly pathways with higher precision.

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