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Review

Computational Recycling for Sustainability: A Systematic Review on the Recovery of Valuable Materials and the Reduction of Electronic Waste

Ulises Daniel Barradas Arenas[1], Julia Griselda Cerón Bretón[2]*, Ma del Rosario Vázquez Aragón[1], Rosa María Cerón Bretón[2], José Felipe Cocón Pérez[1], José Alonso Pérez Cruz[1], Youness El Hamzaoui[3]

[1]Facultad de Ciencias de la Información, Universidad Autónoma del Carmen, Calle 31 s/n, Col. Benito Juárez, C.P. 24180, Ciudad del Carmen, Campeche, Mexico
[2]Facultad de Química, Universidad Autónoma del Carmen, Calle 56 Num. 4, Esq. Ave. Concordia, Col. Benito Juárez, C.P. 24180, Ciudad del Carmen, Campeche, Mexico
[3]Facultad de Ingeniería y Arquitectura, Universidad Autónoma del Carmen, Av. Central S/N, Esq. con Fracc. Fátima, Ciudad del Carmen, Campeche, México

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Abstract

The rapid growth of electronic waste, particularly from computer equipment, represents one of today's major environmental challenges. This systematic review aims to analyze recent scientific literature on computational recycling, with an emphasis on the recovery of valuable materials and the effective reduction of electronic waste. The reviewed studies cover a range of topics, including emerging technologies such as automated disassembly, electrostatic separation, circular economy models, and life cycle analysis. Findings reveal that the application of innovative methods – such as electric disintegration, plastic component valorization, and rare metal recovery – enhances recycling efficiency and reduces environmental burden. However, challenges remain regarding regulation, standardization, and informal recycling practices. The review concludes that computational recycling is key to advancing toward sustainable electronic waste management and a more circular economy.

Keywords: computational recycling, electronic waste, clean technologies

Introduction

The rapid growth of the technology industry has led to a constant renewal of electronic devices, which in turn intensifies the generation of electronic waste. These trends pose a global-scale environmental challenge by increasing the volume and complexity of waste management. This complexity arises from the heterogeneous structure of the materials and, most importantly, the presence of hazardous substances [1]. In response to this scenario, computational recycling is understood as the set of computational methods,

*e-mail: jceron@pampano.unacar.mx
Tel.: +52-272-120-3456
0000-0003-1551-7988

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techniques, and models applied to the recycling of electronic waste to optimize the recovery of valuable materials, improve component traceability, and reduce environmental impact. This approach combines tools such as computer modeling, simulation, artificial intelligence, automated disassembly planning, and life cycle assessment (LCA) to design more efficient, sustainable, and scalable recycling processes.

Computational recycling emerges as a strategy framed within a circular economy approach, enabling the recovery of valuable materials [2], including precious metals, rare earth elements, and high-performance polymers. Additionally, it helps reduce the amount of waste that ends up in landfills or in informal recycling sectors, which carry a high risk of environmental harm. It is estimated that by 2030, global e-waste generation could exceed 74 million tons annually, with Asia, the Americas, and Europe being the main contributors [3].

Based on various technological approaches, optimization processes have been proposed for the recycling of computer equipment at the end of its useful life [4]. Techniques such as automated disassembly and the use of environmentally friendly ionic liquids for component separation have been introduced [5, 6]. Additionally, decision support models have been developed to maximize the economic value of recovered materials [7]. Life cycle assessments also demonstrate a high level of efficiency in the recovery of secondary materials, significantly reducing environmental impacts associated with the primary extraction of resources and the production of new devices [8, 9].

Despite technological advances, challenges remain regarding the safety, efficiency, scalability, and profitability of the proposed solutions. Uniform policies with international impact are needed to align practices in countries with weak environmental regulations, where informal recycling exposes communities to toxic substances in hazardous ways [10]. The need to raise consumer awareness, particularly in developing countries, is a critical factor that cannot be overlooked [11]. Furthermore, approaches such as extended producer responsibility and leasing models have shown potential to encourage recycling and the reuse of computer components by closing product life cycles and enabling greater traceability and material recovery [12].

The imminent challenge of electronic waste, often referred to as the "tech-pocalypse", presents a pressing crisis that threatens to inundate us with vast quantities of discarded devices, thereby establishing a toxic legacy for our digital age. While prior analyses have examined e-waste management strategies and computational methodologies independently, this systematic review effectively addresses the existing gap by comprehensively exploring the emerging field of computational recycling. This study transcends a mere summary of current literature; it rigorously assesses the intersection of advanced technologies, optimization models, and sustainable practices. By harnessing the untapped potential of e-waste as a valuable resource stream, we can significantly alleviate its adverse environmental impact and facilitate progress toward a more sustainable future.

In this context, the present systematic review aims to synthesize recent scientific evidence on computational recycling strategies focused on two key outcomes: the recovery of valuable materials and the reduction of electronic waste. The review analyzes studies addressing emerging technologies, optimization models, environmental impacts, and operational barriers, with the goal of identifying trends, knowledge gaps, and opportunities for sustainable development in the management of e-waste.

Unlike previous reviews that primarily describe electronic waste management or recycling technologies separately, this systematic review provides an integrated analysis of computational recycling as an emerging interdisciplinary research field. Specifically, it synthesizes evidence on how computational approaches (artificial intelligence, optimization algorithms, automated disassembly, machine learning, digital traceability systems, and life-cycle assessment) contribute to improving valuable material recovery and reducing electronic waste. This review identifies current research gaps by comparing technological advances, implementation barriers, environmental implications, and policy perspectives, and proposes future directions for the development of intelligent and sustainable recycling systems.

The objective of this systematic review is to evaluate how computational methods contribute to improving electronic waste recycling. Specifically, the review focuses on computational technologies that enhance the recovery of valuable materials while simultaneously reducing electronic waste generation. To achieve this objective, the present review addresses the following two complementary research questions: (i) Which computational technologies have shown the greatest potential for enhancing the recovery of valuable materials from electronic waste? and (ii) In what ways do these technologies support electronic waste reduction within circular economy systems? By focusing specifically on computational recycling, this review brings together the current evidence on how digital technologies can improve electronic waste management while identifying key areas that deserve further investigation and technological advancement.

Materials and Methods

A systematic review was conducted following the PRISMA Statement guidelines [13], with the aim of identifying relevant articles that address the research questions regarding the recovery of valuable materials and the reduction of electronic waste through computational recycling. This study includes a comprehensive search for research works focused on

computational recycling. The research questions that this systematic review aimed to answer were as follows:

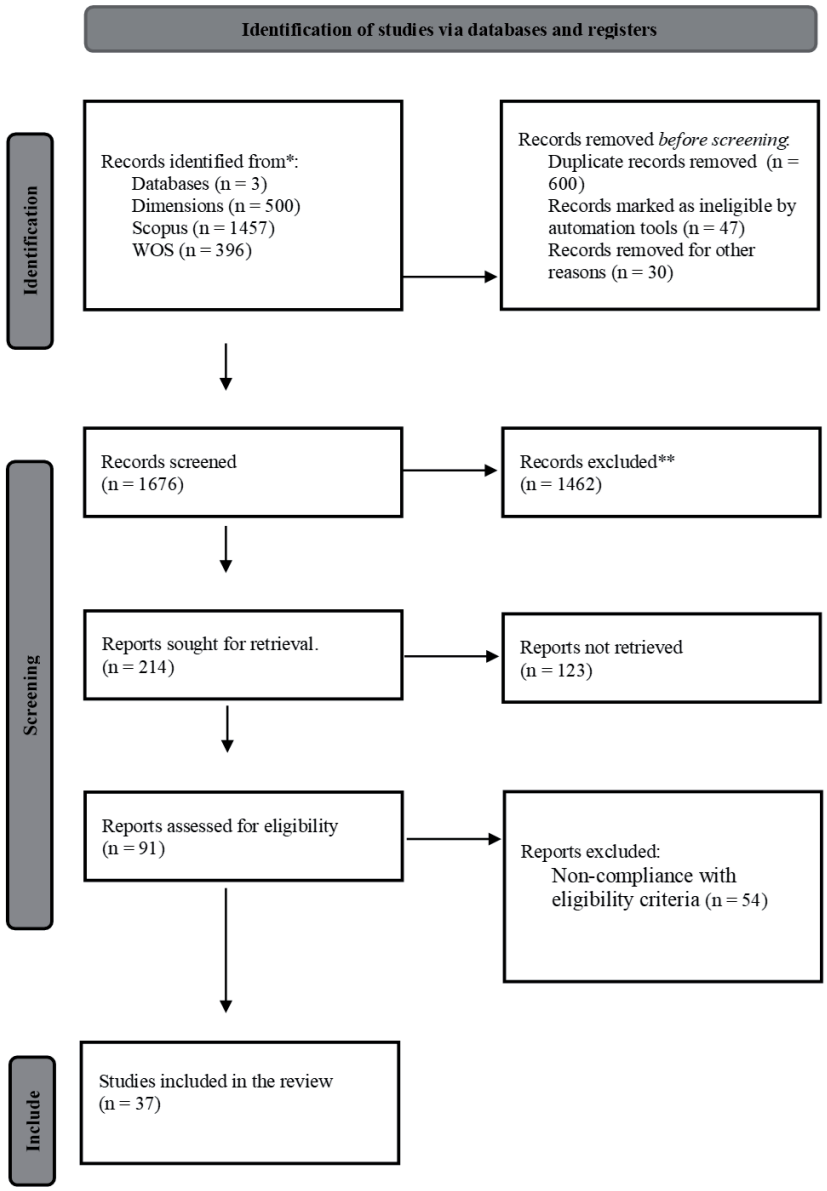
Q1. What methods have proven to be most effective in the recovery of valuable materials from electronic waste?

Q2. What strategies have been most effective in reducing the generation of electronic waste?

A literature search was conducted in the Web of Science, Scopus, and Dimensions databases using the following equation and terms:

("computer recycling" OR "e-waste recycling" OR "electronic waste recycling" OR "IT recycling") AND ("impact" OR "effect" OR "outcome" OR "influence" OR "consequence") AND ("level" OR "degree" OR "extent") AND ("sustainability" OR "environmental impact" OR "green computing" OR "economic impact" OR "cost-benefit" OR "financial impact" OR "health impact" OR "public health" OR "social impact" OR "community impact").

The structuring stages of the review were based on defining key concepts, selecting the databases, designing search strategies, defining inclusion and exclusion criteria, conducting content analysis of the sources, and developing tactics to achieve optimal results while reducing bias. A total of 21 articles with a wide variety of study designs were included in the review. A total of 677 duplicate records were found, 1,462 were excluded due to abstracts lacking sufficient information to answer the research questions, 123 were unavailable in full text, and 70 were excluded for not meeting the inclusion criteria (Fig. 1).



Source: Adapted from Page et al. [13]

Fig. 1. PRISMA flow diagram.

Inclusion and Exclusion Criteria

Empirical research articles were included if at least one of their objectives was to document strategies and methods used in computational recycling. Studies were considered if they reported original data or findings related to the application of computational methods (e.g., modeling, simulation, optimization) to e-waste recycling processes. Articles were required to be available in full-text format in either Spanish or English.

The following exclusion criteria were applied:

• Non-empirical studies: Literature reviews, conceptual papers, and opinion pieces were excluded.

• Studies not focused on computational methods: Articles that discussed e-waste recycling in general but did not explicitly use or evaluate computational techniques were excluded.

• Studies outside the scope of material recovery and waste reduction: Articles focused on other aspects of e-waste management (e.g., policy analysis, risk assessment) without a clear link to material recovery or waste reduction strategies were excluded.

• Systematic reviews and meta-analyses: These types of studies were excluded to avoid duplication of evidence and to focus on primary research findings. While systematic reviews provide valuable overviews of a topic, this review aimed to synthesize the original research findings on computational recycling methods. Moreover, including systematic reviews would have complicated the analysis, as these articles already synthesize the findings of multiple primary studies [14].

• Studies not explicitly including research objectives: Articles lacking clearly defined research objectives were excluded to ensure the included studies had a clear purpose and methodology.

Selection and Evaluation Process

Four researchers [UDBA, JRGB, JCB, and JAPC] carried out the selection process of the included studies. In the first stage, the articles were screened by title and abstract using the Rayyan tool. In the second stage, the full texts were reviewed. Any discrepancies regarding article inclusion were resolved through consensus among the researchers to reach a final decision.

Risk of Bias Assessment of Individual Studies

To assess the risk of bias, the CASP (Critical Appraisal Skills Programme) tools were used for the critical appraisal of quantitative, mixed-method, and observational studies, such as cohort and cross-sectional designs, as well as quasi-experimental intervention studies. The risk of bias assessment was conducted by the researchers [UDBA, JRGB, JCB, and JAPC], and any discrepancies were resolved through consensus among the researchers.

Management of Data and Reporting

A PRISMA-style flow diagram was used to document the article selection process.

The stages included:

1. Identification of records from both search phases;
2. Removal of duplicate entries;
3. Screening of abstracts and titles;
4. Inclusion of the final studies for in-depth review and thematic analysis.

The methodology implemented ensured that all selected articles met the research objectives while also satisfying the inclusion criteria, maintaining academic integrity throughout the data curation process.

Results

Publication Trends

Fig. 2 represents the evolution of the number of publications related to computational recycling, the recovery of valuable materials, and the reduction of electronic waste over time. The horizontal axis displays the publication years from 1972 to 2024, while the vertical axis indicates the number of articles published per year.

In the early decades (1970-1990), the number of studies is minimal, reflecting an emerging field with limited research activity. Beginning in the 1990s, a gradual increase is observed, coinciding with the growing use of electronic devices and the initial environmental concerns regarding technological waste.

Between 2000 and 2015, the scientific output shows a more defined upward trend, with fluctuations but a consistent rise that suggests greater consolidation of the field. This period aligns with the expansion of computational methods and intelligent systems applied to recycling, as well as early international initiatives aimed at sustainable electronic waste management.

From 2016 onward, and particularly between 2020 and 2024, the figure shows a notable increase, reaching peaks of more than 100 publications per year. This accelerated growth reflects:

– The rise of technologies such as machine learning, computer vision, and predictive - modeling applied to recycling.
– The growing global urgency to reduce electronic waste, one of the fastest-growing waste streams worldwide.
– Academic and industrial interest in the efficient recovery of critical materials such as lithium, cobalt, gold, and rare earth elements.

Overall, the figure demonstrates that the field of computational recycling has evolved from an incipient research area to a highly dynamic and relevant domain for global sustainability. The sharp increase in publications in recent years highlights the strategic

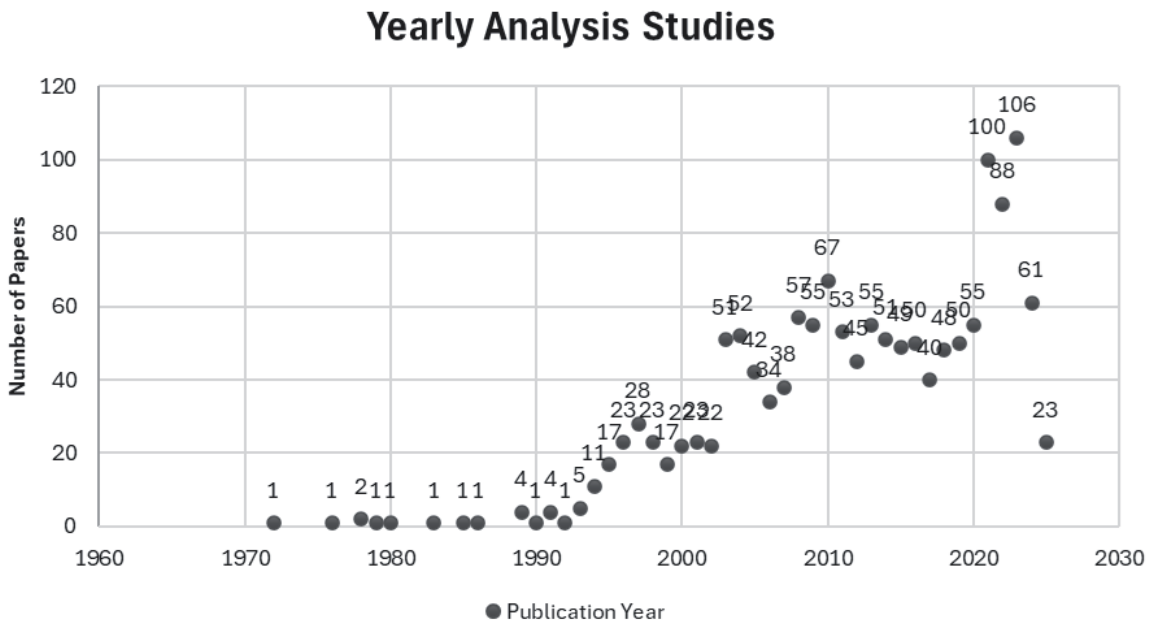


Fig. 2. Yearly analysis of published studies.

importance of the topic and its potential to transform waste management and resource recovery processes.

Keyword Cluster Analysis

Fig. 3 presents a word cloud that synthesizes the most frequent terms identified in the studies analyzed on computational recycling, valuable material recovery, and electronic waste reduction. The size of each word reflects its frequency in the literature, allowing for a visual identification of the dominant concepts in the field.

The most prominent words "recycling", "environmental impact", "computer simulation", "waste management", and "life cycle" highlight the central focus of current research: the application of computational methods to optimize recycling processes and assess their environmental effects.

Additional relevant terms such as "sustainable development", "waste disposal", "electronic waste", "product design", and "optimization" indicate the connection between computational recycling, sustainability, product engineering, and comprehensive electronic waste management. Technical concepts such as "mathematical models", "computer software", "decision making", and "life cycle assessment" also appear, confirming the intensive use of modeling and simulation tools for environmental decision-making.

Overall, the word cloud shows that this research field is characterized by the convergence of computational



Fig. 3. Keyword cluster.

technologies, sustainable material management, and environmental impact assessment, reinforcing the importance of digital approaches for improving recycling efficiency and reducing e-waste generation on a global scale.

Top 10 Journals by Number of Papers

In Table 1, the citation analysis highlights the most influential studies in Computational Recycling for Sustainability, with notable contributions in the areas of the recovery of valuable materials and the reduction of electronic waste.

The most cited paper is by Leung [3], titled "Environmental contamination from electronic waste recycling at Guiyu, southeast China", published in the Journal of Material Cycles and Waste Management, with 331 citations, which discusses higher e-waste generation in developing countries.

Another significant work is that of Hischier [15], which examines Environmental Impact Reduction. This study also stands out for its high citation count (234 citations, published in Environmental Impact Assessment Review) and appears in a journal with an impact factor of 11.2, further reinforcing its scholarly impact.

Synthesis of Computational Approaches for Enhancing Valuable Material Recovery in Electronic Waste Recycling

Table 2 shows a list of references on reduction of electronic waste. For the recovery of valuable and critical materials, Habuer et al. [19] identified metals that are both highly toxic and economically valuable, including silver, lead, and antimony. The study emphasizes the need to incorporate eco-design principles that allow for the recovery of these materials at the end of their life cycle. Using a combined method for recycling LCD screens, Li et al. [26] efficiently recovered indium, a valuable metal found in the indium tin oxide layers of display panels. Peng and Shehabi [38] project that by 2031, up to 2.6 million metric tons of discarded electronic devices containing gold could be generated, from which 48% of the annual gold production could potentially be recovered.

Among the technologies aimed at optimizing disassembly and recovery, Wan and Gonnuru [33] developed a model to maximize the value of reusable components through the implementation of RFID technology. This allowed for the efficient identification of valuable parts, improving decision-making processes during disassembly and maximizing waste reduction. Hischier et al. [40] used life cycle assessment (LCA) to compare the primary production of metals with recycling processes, demonstrating that the reduction of secondary materials has a significant and valuable impact on the recovery of valuable materials. The use of automated disassembly systems, such as robots for dismantling laptops, has been shown to improve the recovery of reusable components and recyclable materials, while also reducing processing time and occupational hazards [41].

Within productive models for estimating recoverable resources, Choubey et al. [24] applied a model to estimate the recovery potential of metals, forecasting that by 2030, electronic waste could contain up to 54% metals by volume, representing a strategic source of secondary resources. Ai-Feng et al. [25] integrated a model that incorporates remanufacturing into closed-loop supply chains using technologies such as RFID, which not only reduces recycling costs but also improves traceability and efficiency in recovering valuable products before they become non-reusable waste.

Specifically, it is indicated that mobile devices incorporate precious metals such as gold, silver, and platinum, along with copper, which justifies their recovery potential. However, these devices also contain potentially toxic metals if they are not properly managed [39]. The evidence indicates that the way e-waste is processed determines both recovery efficiency and the associated impacts. In the informal sector, practices are described that aim to extract valuable metals through the disassembly and crushing of equipment to recover "precious metals", generally without adherence to environmental safety measures [40].

To facilitate comparison among the computational approaches identified in the reviewed literature, Table 3 summarizes the principal technologies according to their primary application within the recycling chain, technological maturity, main advantages, current limitations, and reported performance indicators. The comparison also identifies technological gaps and emerging opportunities that are further discussed in the following sections.

Synthesis of Computational Strategies for Reducing Electronic Waste within Circular Economy Frameworks

Among the articles reviewed, it was identified that by incorporating eco-design and recyclability criteria from the production phase, environmental considerations were successfully integrated into laptop design. This resulted in more durable materials, zero environmental contamination, and component reuse, based on a Green Quality Function Deployment (GQFD) methodology [27]. This suggests that integrating such aspects into product design can extend the lifespan of devices and reduce the volume of e-waste generated.

In addition, considering trends in obsolescence and predictions for early intervention, Yu et al. [35] indicate that by 2030, developing countries will surpass developed ones, generating between 400 and 700 million discarded units. Therefore, the urgent implementation of policies to control the uncontrolled growth of e-waste is necessary. Using a model based on the prediction of secondary resources, it has been observed that from

Table 1. Top 10 most cited papers.

Reference	Type of Study / Approach	Analyzed Product	Methodology / Model	Evaluated Criteria	Main Findings
[16]	Development of a DSS Model with Benchmark-Based Optimization	General EOL (End-of-Life) Electronics	Multicriteria Method with Chebyshev Norm	EOL Value, EWRQ, Processing Time	The recovery of valuable materials must be planned sustainably and efficiently.
[17]	Automated Disassembly Cell Prototype	Desktop PCs	Robotic System with Machine Vision and Sequence Planning	Recognition, Localization, Disassembly Path Planning	Improvement of the Non-Destructive Component Recovery Process
[18]	Evaluation of National Recycling Policy	Notebooks	LCA (Life Cycle Assessment) + Cost-Benefit Analysis	Economic Efficiency, Consumer Participation	Economic Benefit and Environmental Impact Minimization
[19]	Substance Analysis by Impact and Value	PCs and TVs	MFA (Material Flow Analysis) + Multicriteria Categorization (ReCiPe)	Toxic Risks, Metal Recovery Potential	Precious Metals Have High Recovery Priority
[20]	Techno-Economic Case Study	CRT Monitors	Cost and Material Analysis	Recycling Costs, Lead Content, Flame Retardants	Limited Reuse, Need for Redesign
[21]	Industrial-Scale Experiment	PCB	Automated Line with Electrostatic Separation	Copper (95%)	Effective Metal Recovery, Affordable Cost
[22]	Model with Fuzzy Logic and Intuitionism	E-waste Recycling Programs	Fuzzy Multicriteria Decision-Making	Not Applicable (Program Evaluation)	Best Options to Maximize the Recovery of Valuable Resources
[23]	Comprehensive Material Evaluation	CPU	Physicochemical Characterization and Mass Balance	Aluminum (Al), Copper (Cu), Zinc (Zn), Rare Earth Elements (REEs), Plastics	Recycling Potential: 96.66%; Contains Valuable Critical Metals
[24]	Experimental (Laboratory)	PCB	Electrolysis	Copper (98%)	High Recovery Efficiency with Controlled Processes
[25]	Combined Process (Manual + Chemical)	LCD Screens	Disassembly + Chemical Separation	Indium, Glass, Polarizing Film	Recovery Using Mixed Acid with Effective Separation without Pyrolysis
[26]	RFID in Reverse Logistics	Various Electronics	Closed-Loop Supply Chain (CLSC) with RFID	Indirect (Value Chain Optimization)	Reduction of Recycling Costs through Traceability
[25]	Reuse as Thin Clients	Laptops	Motherboard, CPU, RAM Analysis	Diagnosis, Disassembly, Benchmarking	9% Reusable after Evaluation
[27]	Empirical environmental assessment	General e-waste	Field sampling (air, water, soil), surveys, multiple linear regression	Pollution levels, health risks, processing efficiency	Informal recycling recovers valuable materials using crude methods
[28]	Simulation / Agent-Based Modeling (ABM)	Household e-waste	ABM + Theory of Planned Behaviour	Recycling rate, device retention time	Increase the volume of valuable materials sent to formal recycling
[29]	Occupational health evaluation; biomarker analysis	Heavy-metal-containing components	ICP-MS	Exposure to metals, immune response, trace-element imbalance	Dismantling processes in which recovery is carried out without proper control
[30]	Environmental contamination assessment	Heavy-metal-rich e-waste components	Sampling environmental matrices: air PM, soil, groundwater, drinking water	Metal concentration, Pollution Load Index (PLI), ecological risk	Massive release of valuable metals

Table 2. Reduction of electronic waste.

Reference	Type of Study	Intervention	Results	Waste Reduction
[31]	Eco-Design	Application of Green Design in Laptops	Recycling from Product Design	High
[32]	Disassembly Planning Model	Disassembly with RFID	Recovery of Useful Components	High
[33]	Life Cycle Analysis	Recycling System Evaluation	Environmental Impact Reduction	High
[3]	Environmental Pollution	Informal Recycling Analysis	Health Risk Due to Contaminants	Low
[34]	Case Study	Local Management Diagnosis	Lack of Proper Recycling, Ecological Risks	Moderate
[35]	Predictive Analysis of Material Flows	Forecast of Obsolete PC Generation	Higher E-Waste Generation in Developing Countries	High
[36]	Metal Impact Assessment	Impact of Heavy Metals in E-Waste	Pb, Hg, Ni, and Zn are prioritized due to their toxic and ecotoxic impacts.	Moderate
[37]	Technological Innovation Study	Implementation of RFID for Efficient Recycling	RFID can enhance reuse and traceability in recycling.	High
[38]	Material Flow Analysis	Recycling Potential Analysis	Strategic collection can reduce impacts and maximize economic value.	High
[39]	Quantitative, Cross-Sectional	Community Engagement Strategies	47.3% of participants reported recycling e-waste and 63% sold old devices	High
[40]	Quantitative, Cross-Cultural Behavioral	Behavioral Intervention Model Integrating	Regulation drivers showed the strongest positive effect	High

2020 to the present, the annual growth of electronic waste has remained stable. This allows governments to plan for more efficient recycling infrastructure in the medium and long term [37].

Based on sustainable management policies and infrastructure, Peng and Shehabi [38] note that certain regions in the United States have infrastructure that enables the integration of virgin mining with electronics recycling, thereby boosting the circular economy. Projections indicate that by 2031, more than two million tons of small and medium-sized devices will be discarded. Williams et al. [39] emphasize that informal recycling programs in developing countries, while partially reducing waste, generate severe environmental and social impacts, highlighting the urgent need for formal and regulated waste management policies.

In the area of public awareness and collective action, Mamgain et al. [34] report in their study that 78% of respondents are aware of the e-waste problem and the concept of recycling, yet fewer than 30% recycle properly. Therefore, they recommend the implementation of campaigns aimed at raising awareness and promoting regulations that encourage waste reduction, starting from the point of consumption.

By reducing the volume of devices and components that end up in landfills and sanitary dumps through the strengthening of formal collection and recycling practices, proper e-waste treatment directly contributes to decreasing final disposal in landfills and reducing the environmental impact associated with these wastes. At the community level, there is a perception that recycling electronic waste helps mitigate negative environmental effects, which supports the promotion of recycling programs as an effective way to reduce e-waste [42, 43].

The use of technology to improve traceability and disassembly is highlighted by Wan and Gonnuru [33], who propose the use of RFID tags. This enhances the planning of product disassembly at the end of their life cycle, enabling the identification of reusable components and facilitating the recycling process. As a result, there is a potential reduction in final waste output.

The evidence gathered in this review suggests that the effectiveness of computational recycling in reducing electronic waste relies on the combined application of eco-design, predictive modeling, digital traceability, and intelligent decision-support technologies, which together improve resource management across the recycling chain.

Discussion

This review synthesizes current evidence to identify common technological trends, methodological advances, and remaining knowledge gaps in computational recycling.

This review reveals that computational recycling is rapidly evolving from conventional recycling practices toward intelligent and digitally supported systems that integrate automation, artificial intelligence (AI), life-cycle thinking, and circular economy principles. The growing relevance of these technologies is closely

Table 3. Comparative synthesis of computational recycling technologies.

Computational Technology	Main Application	Technological Maturity	Advantages	Limitations	Reported Performance
Artificial Intelligence	Material identification, automated sorting, predictive optimization	Emerging	High classification accuracy, adaptive learning, automation	Requires large datasets, limited industrial validation	Improved classification accuracy and operational efficiency
Machine Learning	Waste prediction, resource forecasting	Emerging	Supports infrastructure planning and decision-making	Dependent on data quality	Accurate prediction of e-waste generation trends
Automated Disassembly	Component separation	High	Faster processing, safer operation, reusable component recovery	High initial investment	Reduced processing time; improved component recovery
Electrostatic Separation	Metal recovery from PCBs	High	High recovery efficiency, scalable	Material pretreatment required	Copper recovery ≈95%
Electrochemical Recovery	Recovery of Cu, Au, Ag	High	Very high recovery efficiency	Chemical consumption	Recovery efficiencies up to 98%
RFID	Traceability and reverse logistics	High	Improved product tracking, optimized logistics	Requires tagging infrastructure	Lower recycling costs and improved reuse
Life Cycle Assessment (LCA)	Environmental evaluation	High	Quantifies environmental impacts	Does not directly recover materials	Demonstrated environmental benefits over primary production
Decision Support Systems	Process optimization	Moderate –High	Supports strategic planning	Model assumptions influence outputs	Improved recovery planning
Digital Twins	Virtual simulation of recycling systems	Emerging	Real-time optimization, scenario analysis	Limited industrial applications	Mainly pilot studies
Blockchain	Material traceability	Emerging	Transparency, secure information sharing	Scalability and implementation cost	Improved supply-chain traceability

linked to the increasing generation of electronic waste worldwide. According to the Global E-waste Monitor 2024, approximately 62 million tonnes of e-waste were generated globally in 2022, and this amount is projected to increase to 82 million tonnes by 2030, while formal recycling systems continue to lag behind e-waste generation rates [44].

Comparative Synthesis of Computational Methods

The evidence gathered in this review indicates that computational recycling technologies vary considerably in terms of both their level of technological development and their role within the recycling process. Technologies directly involved in material recovery – such as automated disassembly, electrochemical recovery, electrostatic separation, and optimization-based disassembly planning – consistently show the strongest quantitative evidence for improving recovery performance. In particular, electrochemical and electrostatic separation techniques have reported recovery efficiencies ranging from 95% to 98%, while automated disassembly has proven effective in reducing processing time, preserving reusable components, and improving worker safety. By comparison, technologies such as RFID, digital traceability systems, decision-support tools, and life-cycle assessment contribute less to the extraction process itself but play a critical role in optimizing logistics, enhancing material traceability, supporting end-of-life management, and improving environmental decision-making. Overall, the reviewed studies suggest that the greatest improvements are achieved not through the application of a single computational technology, but through the integration of physical recovery processes with digital optimization and intelligent decision-support systems across the entire recycling chain.

Technological Maturity

The studies analyzed in this review indicate that computational recycling technologies are currently at different levels of technological maturity. Automated disassembly, electrostatic separation, hydrometallurgical optimization, life-cycle assessment, and RFID-assisted reverse logistics appear to be the most developed,

as their performance has already been evaluated under pilot-scale or industrial conditions. These technologies have consistently demonstrated measurable environmental and economic advantages, reflected in indicators such as higher recovery efficiencies, shorter processing times, lower operating costs, and reduced environmental impacts. The available evidence suggests that these approaches are sufficiently mature to support their implementation in formal recycling facilities, particularly when integrated into existing waste management and recycling infrastructures.

Emerging Computational Technologies

In contrast, technologies such as artificial intelligence, deep learning, digital twins, blockchain-based traceability, and autonomous robotic systems are still at relatively early stages of development for electronic waste recycling. Although recent research has reported encouraging advances in areas such as component recognition, waste classification, predictive maintenance, and process optimization, most of these findings are based on laboratory experiments, simulation studies, or pilot-scale applications rather than on full-scale industrial implementation. As a result, important aspects such as long-term operational performance, economic feasibility, scalability, and the ability to manage the complexity of heterogeneous electronic waste streams have not yet been fully demonstrated. Therefore, while these technologies show considerable promise for transforming future recycling systems, they should currently be regarded as emerging enabling technologies rather than mature solutions ready for widespread industrial adoption.

Industrial Applicability

The findings of this review suggest that the industrial adoption of computational recycling technologies should prioritize solutions that combine high material recovery efficiency with operational reliability and economic viability. Among the different approaches evaluated, automated disassembly systems supported by machine vision, electrostatic separation, hydrometallurgical recovery techniques, and RFID-enabled reverse logistics have demonstrated the most consistent performance and a higher level of technological maturity. In contrast, fully autonomous recycling systems based solely on artificial intelligence are still at an early stage of development. Their implementation is constrained by the need for standardized product designs, large volumes of high-quality training data, and considerable investment in infrastructure. The available evidence indicates that the near-term advancement of computational recycling is more likely to rely on hybrid solutions that integrate well-established mechanical recovery technologies with increasingly sophisticated digital decision-support and optimization tools, rather than on fully autonomous systems.

From a technical perspective, the reviewed research demonstrates the viability of various computational recycling methods for recovering valuable resources. Studies such as that by Choubey et al. [24] report impressive recovery rates for metals like copper, gold, silver, and indium (up to 98%) using techniques like ultrasound-assisted chemical extraction, hydrometallurgy, and electrolysis, with reported efficiency rates of around 90%. Previous investigations reported high recovery efficiencies for metals such as copper, gold, silver, indium, and rare earth elements through electrolysis, hydrometallurgical processes, automated disassembly systems, and RFID-assisted reverse logistics [24-26, 28]. These findings are consistent with the concept of “urban mining”, as highlighted by Williams et al. [39], where metal concentrations in e-waste can surpass those found in primary ores (they found concentrations of up to 2.6 grams of silver and 0.67 grams of gold per desktop unit with a CRT monitor). Habuer et al. [19] further support this, confirming that automated disassembly systems significantly improve the efficiency of separating and processing high-value components. This is further supported by lifecycle assessment and cost-benefit analyses as used by Lu et al. [18], which show a direct economic effect and environmental impact through the recycling of e-waste.

The integration of technologies like RFID in reverse supply chains also offers promise for cost reduction and improved traceability, as shown by Wan and Gonnuru [33]. The study shows how strategies can facilitate the reuse of components and optimization of logistics through recycling tracking. Furthermore, hybrid approaches combining reuse and refurbishment can extend product lifespans, thereby reducing waste streams, as demonstrated by Coughlan et al. [27] in their thin-client evaluations. Li et al. [26] have shown the effectiveness of separating complex materials to recover indium from LCD monitors through a combination of physical and chemical processes (thermal shock, ultrasonic cleaning, and controlled acid dissolution). Artificial intelligence, machine learning, and computer vision technologies are increasingly being applied to automate material identification, waste sorting, disassembly planning, and resource recovery processes. AI-powered systems have demonstrated significant improvements in classification accuracy, operational efficiency, and recovery rates, reducing both labor requirements and processing costs while increasing the value of recovered materials [45, 46]. Furthermore, deep-learning approaches have recently been proposed for component-level recycling of printed circuit boards, enabling the identification and selective recovery of reusable components before destructive treatment processes are applied [47].

Although recent technological developments have significantly enhanced the efficiency of material recovery processes, their successful adoption depends on how well computational technologies are integrated

with economic, regulatory, and social frameworks. From an economic standpoint, optimization models and decision-support tools help identify recycling strategies that are both technically effective and economically feasible by increasing the recovery of critical raw materials while reducing operational costs. Likewise, digital traceability technologies – such as RFID, blockchain, and digital product passports – improve the management of reverse supply chains by enabling accurate tracking of electronic products throughout their entire life cycle. This enhanced traceability facilitates inventory management, reduces material losses, and supports more efficient resource recovery. Recent studies indicate that machine-learning algorithms combined with computer vision can substantially improve material recovery by automating the recognition and classification of electronic components and recyclable materials [46, 48]. These findings complement earlier observations by Habuer et al. [19] and Wan and Gonnuru [33], who highlighted the importance of automation and intelligent decision-support systems for maximizing resource recovery.

From a social perspective, computational technologies have the potential to improve occupational safety by reducing workers' exposure to hazardous dismantling activities through automated disassembly and robotic sorting systems. These approaches can replace labor-intensive practices that are still common in informal recycling sectors, where workers are often exposed to significant environmental and health risks. Nevertheless, the benefits of these technologies cannot be fully achieved without supportive regulatory frameworks, adequate investment in recycling infrastructure, and public policies that promote the transition toward formal recycling systems. As a consequence, computational recycling should be understood not only as a technological advancement but also as a key component of the digital infrastructure needed to support more efficient, transparent, and sustainable governance of electronic waste.

Computational Recycling and the Circular Economy

An important trend identified in recent literature is the increasing integration of computational recycling within circular economy frameworks. Traditional linear production systems based on extraction, consumption, and disposal are gradually being replaced by circular models that prioritize reuse, refurbishment, remanufacturing, and resource recovery. Artificial intelligence has emerged as a key enabling technology for circular economy implementation because it improves waste forecasting, reverse logistics, traceability, and resource optimization [49, 50].

Digital technologies such as blockchain, Internet of Things (IoT) platforms, digital twins, and digital product passports are increasingly being proposed to support circular supply chains and improve material traceability throughout product life cycles. These technologies facilitate the identification of reusable components, optimize end-of-life decision making, and support extended producer responsibility programs, ultimately reducing waste generation and increasing material recovery rates [51].

The growing emphasis on circularity is particularly important for critical raw materials. Current estimates indicate that only a small fraction of global rare-earth element demand is currently supplied through recycling despite the substantial quantities present in discarded electronic products [47].

The evidence synthesized in this review shows that computational recycling contributes to the implementation of circular economy principles through the following interconnected pathways: improving the efficiency of material recovery, extending product lifespans by supporting reuse and remanufacturing strategies, enhancing the traceability of valuable materials throughout their life cycle, and optimizing resource allocation across reverse supply chains. Unlike conventional recycling, which focuses on the physical recovery of materials, computational recycling integrates digital technologies that improve decision-making and enable a more efficient, transparent, and resource-oriented management of the entire recycling process.

One of the main advantages of computational recycling lies in its potential to reduce reliance on informal recycling practices, which remain widespread in many developing countries due to the low investment required for manual dismantling, open burning, and uncontrolled chemical extraction. Although these activities provide a source of income for many communities, they are also associated with serious environmental pollution and significant risks to workers' health. The studies reviewed indicate that computational technologies offer practical alternatives by incorporating automated disassembly, intelligent material identification, and digital traceability systems that facilitate the transfer of end-of-life electronic products into formal recycling streams. Particularly, the combination of machine learning and computer vision enables the rapid recognition of reusable components, while RFID-based tracking and blockchain technologies improve product traceability and help prevent the diversion of electronic waste into informal recycling channels. Consequently, computational recycling not only enhances material recovery but also strengthens environmental governance by promoting transparent, traceable, and more sustainable recycling systems.

Challenges and Barriers to Implementation

Despite these technological advancements, significant challenges remain in scaling up and implementing computational recycling strategies effectively. One key barrier is the complexity of e-waste streams and the need for efficient separation techniques. As Kohl and Gomes

[23] found in their analysis of personal computers, up to 96% of a computer's weight can be recovered using appropriate separation processes, especially components with high metal content (motherboards and heat sinks). However, the effectiveness of these processes depends on device design, efficient pretreatment, and access to clean technologies in recycling centers. This is emphasized by Coughlan et al. [27], who observed that hardware design affects component recovery, suggesting that eco-design principles should be incorporated into the manufacturing of electronic devices. One of the most persistent challenges is the prevalence of informal recycling practices, particularly in developing countries. Informal recovery processes frequently involve crude dismantling, open burning, and uncontrolled chemical treatments that release hazardous substances into the environment and expose workers to toxic compounds [3, 36].

Another critical challenge is the prevalence of informal recycling practices, particularly in developing countries. Williams et al. [39] highlight the ethical and environmental issues associated with unregulated practices, including the shipment of e-waste to developing nations for material recovery. This reinforces the need for stronger governance and effective traceability in reverse supply chains, as well as public policies promoting responsible and sustainable secondary markets. Leung [1] notes that prolonged exposure to heavy metals resulting from poor recycling management can contaminate soil and water, causing severe harm to human and animal health. This is consistent with the findings of Woo et al. [36], who highlight the toxicity present in electronic devices and advocate for eco-design criteria. The integration of virgin mining with electronics recycling through strategic collection can be used to promote a greater circular economy, further suggesting that with planning, there is a great reduction in overall impact [35].

Another challenge involves the need for reliable forecasting and decision-support systems capable of managing increasing e-waste volumes. Recent studies demonstrate that machine-learning models can improve predictions of waste generation patterns, optimize collection systems, and support strategic investments in recycling infrastructure [47, 50, 52]. Such approaches may become increasingly important as global e-waste generation continues to accelerate.

Policy Implications and Recommendations

Overall, the findings of this review indicate that effective electronic waste management depends on the close integration of regulatory frameworks and computational technologies, rather than treating them as separate components. Regulatory instruments such as Extended Producer Responsibility (EPR) can be implemented more efficiently when supported by digital systems that enable product monitoring throughout the entire life cycle. Technologies such as RFID, blockchain, Internet of Things (IoT) platforms, and digital product passports provide the digital infrastructure needed to improve product traceability, facilitate compliance with EPR requirements, enhance the accuracy of reporting systems, and reduce the illegal movement of electronic waste across borders. Ko and Lo [32] advocate a Design for the Environment approach supported by methodologies such as Green Quality Function Deployment, which can transform design attributes to facilitate disassembly, reuse, and recycling.

Public participation plays a fundamental role in the success of computational recycling, as the effectiveness of digital technologies ultimately depends on electronic products being returned through formal collection and recycling systems. Although approximately 78% of surveyed individuals are aware of the environmental importance of recycling electronic waste, fewer than 30% consistently dispose of their obsolete devices through authorized collection channels. These differences suggest that technological advances alone are unlikely to significantly increase recovery rates unless they are complemented by digital solutions that actively encourage consumer involvement. From this perspective, emerging technologies such as mobile applications, digital platforms, QR-based product identification, and artificial intelligence-assisted collection systems can facilitate access to information on nearby recycling facilities, estimate the residual value of discarded devices, and simplify participation in take-back programs. As a result, computational technologies should be viewed not only as tools for improving material recovery but also as effective mechanisms for promoting responsible consumer behavior and strengthening public participation in circular economy initiatives. Furthermore, the need for more active campaigns in the area of public awareness and collective action is highlighted by Mamgain et al. [34], who recommend the implementation of campaigns and regulations that encourage waste reduction starting from the point of consumption.

Computational optimization also provides valuable support for policymakers by helping optimize the location of collection facilities, forecasting regional electronic waste generation, and planning recycling infrastructure more effectively. Incorporating these technologies into regulatory frameworks would facilitate the implementation of evidence-based policies and help translate environmental goals into tangible and measurable outcomes. The study by Hischier and Böni [40] supports these policies and indicates that a structured recycling system has a lower environmental impact compared to scenarios involving incineration or primary material production. New regulatory practices and the implementation of modern technologies are needed in areas such as China, and should align with the proposal by Ko and Lo [32], who advocate for design features that assist in the re-use and safe recycling of the product.

Addressing the global challenge of electronic waste requires strong international collaboration, particularly

through the harmonization of regulatory frameworks, traceability systems, and enforcement mechanisms that can reduce inconsistencies among national regulations and reduce the illegal cross-border movement of electronic waste [10]. In this context, computational technologies such as digital product passports, blockchain-based traceability platforms, and cloud-based information systems provide the digital infrastructure needed to monitor products throughout their entire life cycle, from manufacturing and ownership to repair history and end-of-life management. By facilitating the availability and sharing of reliable information, these technologies facilitate regulatory compliance, strengthen customs control, increase transparency across global reverse supply chains, and support the implementation of internationally coordinated circular economy strategies. As a result, computational recycling has the potential to become a fundamental component of global environmental governance by promoting more transparent, standardized, and data-driven approaches to electronic waste management, while simultaneously supporting environmental protection, resource efficiency, and long-term economic sustainability.

The findings of this review suggest that technological innovation alone will not be sufficient to address the growing e-waste crisis. Strong regulatory frameworks, effective enforcement mechanisms, and international cooperation are essential for promoting sustainable recycling practices and reducing environmental impacts. Extended Producer Responsibility (EPR) schemes, eco-design strategies, and mandatory traceability systems have been widely recognized as effective policy instruments for improving collection and recycling performance [31, 52]. Recent literature further emphasizes the need for harmonized international regulations that facilitate traceability across global supply chains while discouraging illegal transboundary movements of electronic waste [47].

Looking ahead, artificial intelligence is expected to become one of the most influential technologies in computational recycling. Recent systematic reviews suggest that AI-driven optimization systems, intelligent robotics, digital twins, and automated classification platforms will play a central role in the next generation of circular economy strategies and sustainable waste management systems [45, 48, 51]. The integration of these technologies with life-cycle assessment, eco-design, and circular business models may significantly improve recycling efficiency while contributing to global sustainability objectives.

Risk of Bias Assessment

The risk of bias was assessed using the Critical Appraisal Skills Programme (CASP) tools for quantitative, observational, and quasi-experimental studies. Among the 21 included studies, 15 were found to have a low risk of bias, demonstrating strong methodological clarity, internal validity, and relevance of results. Five studies exhibited a moderate risk of bias, mainly due to limitations in sampling descriptions or incomplete reporting of findings. Only one study showed a high risk of bias, primarily due to a lack of transparency in data collection and the absence of appropriate controls. These assessments were taken into account when interpreting the overall findings and in weighing the strength of the conclusions.

By 2030, electronic waste production in developing countries is expected to surpass that of developed nations in terms of obsolete device generation, which is a concerning trend. This unpredictability challenges the implementation of sustainability policies that prioritize the strategic recovery of waste. In the U.S. context, Chugh et al. [41] project that by 2031, up to 2.6 million metric tons of electronic devices will be discarded annually. This scenario presents an opportunity to promote a circular economy through the adoption of efficient computational recycling techniques.

Conclusions

The findings of this systematic review show that computational recycling has emerged as a rapidly developing research field with significant potential to improve the sustainability of electronic waste management. The evidence gathered from the analyzed studies confirms that computational technologies can substantially enhance resource recovery. Particularly, automated separation and electrochemical recovery techniques have reported recovery efficiencies ranging from 95% to 98% for valuable metals, while material characterization studies estimated a recycling potential of 96.66% for computer components containing strategic resources such as copper, aluminum, rare earth elements, and engineering plastics. In addition, predictive models suggest that, by 2030, electronic waste could contain nearly 54% metals by volume, and projections suggest that electronic devices reaching the end of their useful life by 2031 may hold recoverable gold equivalent to almost 48% of current annual global production. Bibliometric analysis revealed a notable increase in research activity, with more than 100 publications per year in recent years, reflecting the growing scientific interest in computational recycling as an essential component of circular resource management. Overall, the evidence suggests that computational approaches offer tangible environmental, technological, and economic advantages by increasing recovery efficiency, reducing reliance on virgin raw materials, and supporting the transition toward more circular and sustainable resource management systems.

In addition to improving the recovery of valuable materials, this review shows that computational recycling also plays a key role in reducing electronic waste by supporting eco-design strategies, predictive modeling, reverse logistics optimization, digital

traceability, and intelligent decision-support systems. However, the available evidence makes it clear that technological advances alone cannot fully address the growing global e-waste challenge. Despite increasing public awareness of electronic waste recycling in many regions, participation in formal collection and recycling programs remains relatively low, suggesting that the successful implementation of computational recycling also depends on supportive public policies, adequate recycling infrastructure, effective regulatory enforcement, and active stakeholder engagement. In addition, weak institutional frameworks, limited recycling capacity, and the continued prevalence of informal recycling practices still expose vulnerable populations to hazardous pollutants and limit the large-scale implementation of advanced computational recycling technologies. Overall, the evidence indicates that future advances will depend not only on continued technological innovation but also on its integration with robust governance, internationally coordinated regulatory frameworks, and sustained investment in formal recycling systems.

Taken together, the studies reviewed here show that computational recycling goes beyond the application of individual technologies and should instead be considered an integrated approach to managing electronic waste. Computational recycling brings together computational intelligence, optimization techniques, digital traceability, and environmental assessment into an integrated framework that improves material recovery, enhances industrial processes, and supports the transition toward a circular economy. This integrated perspective highlights the interdisciplinary nature of computational recycling and its potential to transform electronic waste management into a more efficient, transparent, and sustainable system.

Although the available evidence highlights the significant potential of computational recycling, several limitations should be considered when interpreting these findings. First, computational recycling is still an emerging field, and the number of studies that met the inclusion criteria remains relatively small. In addition, the reviewed studies differed substantially in their methodological approaches, computational techniques, performance indicators, and geographical settings, making direct comparisons difficult and preventing the development of a quantitative meta-analysis. Another limitation is that much of the evidence for emerging technologies comes from laboratory experiments, simulation studies, or pilot-scale applications. As a result, there is still limited evidence regarding their long-term performance, scalability, and economic feasibility under real industrial conditions. Taken together, these limitations indicate that the findings of this review should be interpreted in the context of the current stage of development of computational recycling, which remains an emerging and rapidly evolving field rather than providing definitive evidence of the superiority of any particular technology.

Future research should focus on expanding the current evidence by encouraging the adoption of standardized methodologies and improving the comparability of studies evaluating computational recycling technologies. Establishing standardized indicators for assessing the environmental, economic, and operational performance of computational recycling technologies should be a priority. At the same time, broader life-cycle and techno-economic evaluations are needed to provide a more robust comparison of different recycling strategies. In addition, emerging computational technologies should be tested under real industrial conditions to better understand their long-term feasibility, scalability, and practical performance. Further investigation is also needed to address the social, ethical, and regulatory dimensions of computational recycling, especially those related to informal recycling activities, occupational health and safety, and the development of effective international governance frameworks. As digital technologies continue to advance, combining artificial intelligence, machine learning, digital twins, blockchain, and advanced decision-support systems into integrated recycling platforms offers a promising opportunity to improve the efficiency, transparency, and coordination of recycling processes. Progress in these research areas will be essential to support the continued development of computational recycling and facilitate its broader adoption as a reliable and sustainable approach to electronic waste management.

Conflict of Interest

The authors declare no conflicts of interest.

Artificial Intelligence Use Statement

The authors used Rayyan to support literature screening and automatic identification of duplicate references during the review process. ChatPDF was used to facilitate retrieval of methodological and outcome-related information from previously selected scientific articles. ChatGPT (OpenAI) was used exclusively for language editing, translation from Spanish into English, and improvement of manuscript readability. All information retrieved through these tools was independently verified by the authors. No artificial intelligence system was used to generate data, perform statistical analyses, interpret results, draw conclusions, or make scientific decisions. The authors assume full responsibility for the content of this manuscript.

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