Literature Review on the Feasibility of Recycling Electrical and Electronic Waste (WEEE)

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The growing amount of waste electrical and electronic equipment (WEEE) is a global problem, with generation increasing five times faster than documented recycling. In 2022, 62 million tons of e-waste were produced, but less than 22.3% was collected and recycled properly. The aim of the work was to analyze the main polymers in WEEE, discuss the challenges of recycling and characterizing them, and explore the feasibility of applying them in the production of filaments for 3D printing. The methodology consisted of a qualitative analysis of 8 scientific articles selected from the Scopus and Web of Science databases. The research was limited to publications in English between 2003 and 2025. The results highlight the importance of characterization for recycling. Techniques such as FTIR, TGA and DSC are essential for understanding the chemical, thermal and mechanical properties of polymers. FTIR identifies compounds such as hydrocarbons and aromatic rings and is useful for unknown polymers. TGA measures the loss or gain of mass with temperature, indicating thermal degradation. DSC identifies changes in physical state, such as melting temperature (Tm), glass transition temperature (Tg) and crystallization temperature (Tc). Two recycling techniques are promising: chemical and mechanical. Chemical recycling, via pyrolysis, can convert plastics into useful monomers or fractions. However, plastics with brominated flame retardants (BFRs) can generate toxic substances. Pre-treatment methods, such as the CreaSolv® process, have proven effective in removing BFRs. Mechanical recycling faces challenges such as property degradation and material heterogeneity. Additive manufacturing (AM), especially FDM/FFF technology, is an alternative for reusing WEEE plastics and adding value. However, the variability of equipment shapes and sizes makes process automation complex.

Keywords: Recycling. WEEE. Polymers. Characterizations.

Abbreviations: (WEEE), Waste electrical and electronic equipment. (PS), Polystyrene. (ABS), Acrylonitrile Butadiene Styrene. (PC/ABS), Polycarbonate/Acrylonitrile Butadiene Styrene. (HIPS), High Impact Polystyrene. (PP), Polypropylene. (PLA), Polylactic acid. (FTIR), Fourier Transform Infrared Spectroscopy. Thermogravimetric Analysis, (TGA).(NIR), Near Infrared Spectroscopy. (DSC), Differential Scanning Calorimetry. Additive Manufacturing, (AM). (FDM), Fused Filament Deposition.(FFF), Fused Filament Fabrication. (PABS), (Poly (Acrylonitrile Butadiene Styrene)). (LDPE), Low Density Polyethylene. (TBBPA), Tetrabromobisphenol A. (TBPE), Decabromodiphenyl ethane (DecaBDE), Decabromodiphenyl ether. (PBDEs), Polybrominated diphenyl ethers. (BRFs), Flame retardants.

The amount of plastic waste grows every year. Since 1950, 8.3 billion metric tons have been produced, with only 9% recycled [1]. In waste electrical and electronic equipment (WEEE), plastic accounts for 21% by weight [2]. The management of this waste is necessary to mitigate improper disposal and promote the circular economy. According to the Global E-waste Monitor 2024 [3], global e-waste generation is growing five times faster than its documented recycling. In 2022, 62 million tons of electronic waste were produced, an increase of 82% since 2010, but only 22.3% was collected and recycled properly, highlighting the urgency of effective management.

WEEE recycling faces the challenge of plastic diversity, with more than 15 types of engineering polymers [4]. It is essential to characterize these materials to define the best ways to recycle and

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Received on 22 February 2026; revised 17 April 2026.

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J Bioeng. Tech. Health 2026;9(5):480-486

reuse them. Ma and colleagues (2016) [5] indicate that Polystyrene (PS), Acrylonitrile Butadiene Styrene (ABS), PC/ABS, High Impact Polystyrene (HIPS), and Polypropylene (PP) represent 55% of plastics in WEEE. Among the recycling techniques, mechanical and chemical recycling stand out. Chemical recycling, especially pyrolysis, breaks down polymers into monomers or useful fractions, and is promising for mixed or degraded plastics [6]. Mechanical recycling involves shredding, washing, and reprocessing, but it is sensitive to contaminants and degradation.

As an alternative for recovery and circular economy, Additive Manufacturing (AM), especially Fused Filament Fabrication (FDM/FFF), emerges as a viable way to reuse waste, expanding recycling with cleaner and more efficient processes [7].

To optimize reuse and recycling, material characterization is essential, with Fourier Transform Infrared Spectroscopy (FTIR), Thermogravimetric Analysis (TGA), and Differential Scanning Calorimetry (DSC) standing out [4].

Thus, it is essential to understand the characteristics of plastics in WEEE and assess the potential of chemical, mechanical, and additive manufacturing recycling. This work analyzes the main polymers in WEEE, the challenges of recycling and characterization, and explores their application in the production of recycled filaments for 3D printing.

Materials and Methods

This study adopts a qualitative approach, combining an analysis based on scientific articles in databases with a careful analysis of the works produced, with the aim of deepening knowledge on the subject and understanding the various methodologies and applications of the materials in question.

For data collection, the Scopus and Web of Science databases were selected due to their wide reach and reliability in the academic community and their rigorous indexing of scientific journals.

The search strings were constructed with the terms “waste electric and electronic equipment,” “recycling,” and “polymer,” applied in the title, abstract, and keyword fields (Scopus) and in “Topics” (Web of Science). The search was limited to English-language publications of the “article” type, covering the period from 2003 to 2025.

After the search, the data were exported in Bibtex format and RStudios was used to exclude possible duplicate works, where a single RIS file was generated and imported by a software extension, Bibliometrix, so that a spreadsheet could be created. The file resulted in 32 articles. These were submitted to a two-step selection process: first, the titles were read to exclude works that did not align with the scope of the research. Next, the abstracts of the remaining articles were analyzed, with the criterion of selecting those most relevant to the objectives of this study. This refinement process resulted in a final portfolio of eight articles, which formed the basis for the subsequent analysis.

Results and Discussion

As the last resort for waste that cannot be reduced or reused, recycling consists of transforming the material from a discarded product into raw material for the manufacture of new items, a fundamental process for sustainability, in which the importance lies in the ability to address problems in an integrated manner and generate profits from environmental benefits, such as the conservation of natural resources and reduction in pollution, to economic benefits in the form of job creation and reduced production costs, as well as social benefits in the development of environmental awareness and improved quality of life.

How to Characterize Samples

To this end, it is crucial to separate and characterize materials that have been discarded, especially given the enormous complexity and variety of polymers, where they are the basis that guarantees the success, viability, and purpose of recycling. Without efficient separation and characterization, plastic recycling becomes impractical, generating low-quality products and, in many cases, rendering the entire cycle unfeasible.

Among the characterization techniques, Fourier Transform Infrared Spectroscopy (FTIR) stands out as one of the most widely used for the identification of polymeric materials from WEEE. Through this analysis, a beam of infrared light interacts with the sample, allowing the identification of characteristic functional groups, such as aromatic rings and double or triple bonds. This capability is of great importance for the evaluation of unknown polymers, since each material has a unique infrared absorption spectrum, which acts as a molecular “fingerprint.” Thus, FTIR has established itself as a simple, fast, and accurate identification method [8].

According to research by Achilias and colleagues (2009) [4] on the development of polymer recycling techniques from WEEE, using FTIR made it possible to identify polymers such as PABS (Poly (Acrylonitrile Butadiene Styrene)), where, according to the study, some characteristic functional groups were observed, such as absorption bands from 3000 to 3100, 700, and 755 cm^{-1}, referring to styrene structural units, stretching vibrations of the aromatic ring at 1494 and 1452 cm^{-1}, the band at 1602 cm^{-1} caused by the double bond of aromatic carbon and C=C stretching vibration, as well as the nitrile group (-C≡N) by the acrylonitrile units in ABS at 2238 cm^{-1} and the bands at 911 and 966 cm−1 corresponding to the unsaturated groups of the butadiene phase in ABS.

On the other hand, Charitopoulou and colleagues (2023) [6] used various polymers from WEEE (remote controls, calculators, computers, printers, and televisions) to identify, debrominate, and recycle them through pyrolysis, in order to reduce the volume of this waste through an environmentally friendly approach. By using FTIR on samples from each piece of equipment, the author was able to identify obvious bands in the 2840-2950 cm^{-1} range, which are due to the C–H bond, but also a band of lower intensity at approximately 1550–1600 cm^{-1} due to the C=C double bond. This combination indicates the presence of styrenic polymers, characterized by the presence of benzene rings in their polymer chain, such as ABS and HIPS, polymers commonly used in the manufacture of these products. However, when observing two samples of different products, a band was noted around 1750 cm^{-1}, a vibration value characteristic of polyesters, such as PC, due to the C=O bond, i.e., it indicates that it includes a mixture of PC with HIPS or ABS.

Thermal analysis is another fundamental method for identifying polymeric materials, as their thermal properties are directly linked to their molecular structure. For example, linear and branched polymers generally have higher thermal expansion coefficients due to weak secondary bonds between chains. As the number of cross-links increases, the structure becomes more restricted, resulting in a lower expansion coefficient.

Following this same structural logic, each polymer exhibits a unique thermal profile, with distinct points of degradation, melting (Tm), glass transition (Tg), and crystallization (Tc). Tm is the temperature at which the crystalline structure of the material breaks down and it changes from a solid to a liquid state. Tg, in turn, is a transition characteristic of amorphous polymers, where the material changes from a rigid and brittle state to a flexible or “rubbery” state due to the increased mobility of the chains. After this transition, the amorphous material can release heat and reorganize itself into a crystalline structure, an event that defines its crystallization temperature, Tc.

Differential Scanning Calorimetry (DSC) is a technique used to identify changes in the physical state of a material. It works by measuring the energy that the sample absorbs or releases when subjected to a constant heat flow compared to an inert reference. Based on the energy difference between the two, DSC accurately identifies the temperatures of key events, such as melting and glass transition, which are unique to each polymer. Such reference values are well documented in works such as Textbook of Polymer Science [9] and Introduction to Physical Polymer Science [10].

Other common thermal characterization is Thermogravimetric Analysis (TGA). This technique measures the mass change of a sample as a function of temperature or time while it is subjected to a controlled heating program. Additionally, TGA results can be expressed as the first derivative of the mass loss curve, which allows for clearer identification of the temperatures at which the main stages of material degradation occur.

In a study that sought to examine the thermal behavior and products obtained after the pyrolysis of polymer blends, it was shown that, after the TGA test, ABS and HIPS have very similar thermal degradation, since their degradation begins and ends at very similar temperatures. Specifically, ABS completes its degradation at 515 °C and HIPS at 509 °C, but they had different residual mass percentages, 2.3% and 1.1%, respectively. This can be explained by the presence of aromatic rings in their structure, which makes it difficult to break bonds at low temperatures. On the other hand, the same study observed that the degradation and decomposition of PC occur at high temperatures, 664 °C, and has a residual mass of 23%, showing that it is more heat resistant than the other polymers evaluated. Its high residual mass can be attributed to carbon, which is formed from the aromatic parts [11]. The use of polymers with high flame retardancy in Electrical and Electronic Equipment (EEE) is a safety requirement due to contact with components capable of generating heat or sparks. In contrast, common polymers such as Low Density Polyethylene (LDPE), composed solely of carbon and hydrogen, are highly flammable; when heated, they melt, drip, and burn similarly to candle wax. To meet this safety requirement, the electronics industry uses additives, notably brominated flame retardants. Among them, tetrabromobisphenol A (TBBPA) is the most widely used in plastics for this sector [11-13].

Although it is possible to “get to know” the polymer using a single technique, the complete characterization of an unknown material requires a set of tests to create its “performance profile.” By combining the results, it becomes possible to compare them with data from known materials and thus arrive at an accurate classification. In this context, mechanical tests are fundamental methodologies for drawing up this profile.

Polymers are, in many ways, different from metals and ceramics, as they exhibit three different types of stress-strain behavior. Some, such as thermosets, exhibit rigid and brittle behavior, fracturing with little deformation. Others, such as elastomers (rubbers), exhibit fully elastic deformation, with large elongations under low stresses. Thermoplastics, in turn, are the most widely used in the EEE industry and exhibit behavior similar to that of metals: their initial deformation is elastic and reversible, followed by a creep that initiates plastic deformation, which is permanent [14]. From these behaviors, it is possible to obtain important information about the mechanical performance of each polymer, since, like thermal characteristics, each material has a performance “signature.”

The tensile test, for example, evaluates the performance of a material when subjected to a tensile force. Among the various data obtained, the Modulus of Elasticity (or Young's Modulus) is fundamental, as it determines the stiffness of the material. Defined as the ratio between stress and strain in the elastic region, a high modulus value indicates that the material is stiff. In contrast, a low value characterizes a flexible material [15].

The impact resistance test evaluates the toughness of a material, that is, its ability to resist deformation at high speed. This analysis was used by Pelto and colleagues (2023) [16] in a study on the mechanical properties of PC and ABS polymer blends. In the test, the samples were subjected to the Charpy notch test under standard conditions (23 °C and 50% humidity). It was observed that the blend composed only of recycled polymers, without additives, had very low impact resistance, confirming it as a fragile material. However, when a compatibilizer was added to the recycled mixture to overcome this problem, the improvement in performance was dramatic. The toughness of the material increased significantly, reaching levels comparable to or even higher than those of a similar blend made with virgin polymers.

Even though it was not an application to determine information about an unknown polymer, the test served to verify whether, after some type of change in the structure of the material, it would retain, lose, or increase its properties.

Recycling Techniques

Some of the main polymers commonly found in EEE are HIPS, PC, PP, and ABS, as well as PC/ABS blends, representing about 20-30% of the total weight [4-6]. The recycling of these materials is of great importance due to the amount of waste currently produced. Thus, there are several recycling methods that can be used, including:

Pyrolysis

Pyrolysis is a thermochemical method that allows the recovery of monomers and the formation of valuable secondary materials. The process occurs in an inert atmosphere, at medium to high temperatures (300 °C–900 °C), with or without the presence of catalysts. During pyrolysis, plastic waste is converted into liquids, gases, and solid waste. This method enables the recovery of material and energy from waste polymers. The quality and distribution of pyrolysis products are influenced by several parameters, such as temperature, residence time, and heating rate, in addition to the presence of catalysts. These materials can be used as fuels or raw materials for the production of new products [6-12].

Despite this, the pyrolysis of plastics containing brominated flame retardants can generate toxic substances, which compromises the reuse of the products obtained. This obstacle can be overcome by applying catalytic pyrolysis, in which the selectivity of the derived products is increased due to the presence of catalysts and the formation of undesirable substances can be inhibited [17]. To circumvent this problem, many pretreatment methods have been investigated. The study by Charitopoulou and colleagues (2023) [6] demonstrated that the CreaSolv® process was able to remove BFRs, such as TBBPA, Decabromodiphenyl ethane(TBPE), and Decabromodiphenyl ether (DecaBDE), reducing the bromine concentration to less than 500 ppm. Solvent extraction, such as the CreaSolv® process, has proven to be effective in decontaminating WEEE plastics by removing halogens and flame retardants. Another pretreatment technique, Soxhlet extraction with solvents such as butanol and isopropanol, has also been shown to be efficient in reducing the bromine content in WEEE plastics while maintaining the polymer structure for subsequent pyrolysis [16].

Mechanical Recycling

Mechanical recycling can also be a viable route, but the degradation of properties, especially notched impact strength, is a challenge. In addition, heterogeneity is another challenge posed by WEEE recycling. The study by Chancerel and Rotter (2009) [18] suggests that proper classification of equipment according to type would reduce the heterogeneity of the plastic fraction resulting from a treatment process. The thorough characterization of WEEE plastics, using techniques such as FTIR, XRF, and DSC, is essential to identify the composition and guide recycling strategies, ensuring that the final products meet the desired quality standards.

Thus, depending on the materials identified and their mechanical and chemical characteristics, such as styrene-based polymers, ABS, and high-impact polystyrene (HIPS), which represent more than 50% by weight of WEEE plastics, can be used as filaments for additive manufacturing (AM) through fused deposition modeling technology. In fact, ABS with polylactic acid (PLA) is the most widely used material, in general, as polymers that can be melted at a suitable temperature without degradation and are generally useful candidates for material extrusion systems [19].

Possible Challenges

The recycling of WEEE poses a major challenge, mainly due to the complex nature of this equipment. Approximately 20% of the total weight of EEE is composed of polymeric material, covering up to 15 different types of engineering polymers. Improper disposal causes environmental impacts and health risks. Efficient management faces relevant issues, among which high cost stands out [4].

Among the challenges of treating WEEE are: the diversity of polymers, which makes sorting and recycling difficult; the presence of brominated aromatic compounds (BRFs); and the fact that the thermal treatment of these substances can generate halogenated dibenzodioxins and dibenzofurans, which are toxic compounds [4]. Perrin and colleagues (2016) [20] point to plastic waste as a significant source of pollution and argue that, considering the desired properties of recycled plastics, it would be possible to reduce waste. However, the number of studies is limited. There is potential for recycled plastics to meet more stringent specifications, but classification—especially by Near Infrared Spectroscopy (NIR)—still presents technical difficulties or practical unfeasibility.

Regarding BRFs, Altarawneh and colleagues (2019) [6] highlight environmental and health concerns, emphasizing the global discontinuation of mixtures such as polybrominated diphenyl ethers (PBDEs). Studies indicate that prolonged exposure to certain chemicals causes adverse effects on the endocrine, reproductive, and nervous systems [21].

Cafieiro and colleagues (2021) [18] point out that the variability in shapes and sizes of EEE—from refrigerators to smartphones—affects the efficiency of the recycling process, making the automation of the stages complex and compromising its viability.

Conclusion

Given the scenario in which the volume of electronic waste (WEEE) grows every year and there is a low rate of document management, it is urgent to create strategies to mitigate impacts and reuse polymeric materials. This study showed that plastics represent a significant portion of WEEE, composed of a variety of engineering polymers, whose identification and characterization are essential for efficient and sustainable recycling.

Characterization techniques—FTIR, TGA, and DSC—proved indispensable for understanding the chemical, thermal, and mechanical properties of polymers, enabling their identification, performance evaluation, and reuse potential. Chemical recycling, especially by pyrolysis, and mechanical recycling have proven to be promising avenues, especially when combined with pretreatments that minimize toxic contaminants.

Additive manufacturing emerges as an innovative and sustainable alternative, capable of adding value to recycled materials and expanding applications. However, technical, economic, and environmental challenges require investment in research, more accurate sorting technologies, and public policies that encourage the circular economy.

This work reinforces the importance of integrating characterization, recycling techniques, and emerging technologies, such as 3D printing, for more efficient management of WEEE. Advancing in this field is not only an environmental necessity but also an opportunity for economic and social transformation.

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