Review Article

Journal of
Environmental
Nanotechnology

Review of Nanotechnology-assisted E Waste Valorisation for Circular Economy Applications: Precious Metal Recovery and E-Plastic Upcycling

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Received: 31.03.2026 Accepted: 15.05.2026 Published: xx.xx.xxxx
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ABSTRACT

The escalating production of electronic waste is a major environmental and resource management problem globally. However, electronic waste is also a source of precious metals and polymeric materials, which can be recovered through circular economy approaches. In this review, recent progress in nanotechnology enabled approaches for electronic waste valorisation, including precious metal recovery and e plastic upcycling, is discussed. The use of magnetic nanoparticles, graphene nanomaterials, metal organic frameworks and nanocatalysts for selective metal extraction is presented, as well as novel methods for transforming e plastics into pyrolytic oils, carbon nanotubes and other high value added materials. It underlines the potential of these technologies to improve resource efficiency, mitigate environmental impacts and contribute to the development of sustainable urban mining. Major challenges such as scalability, economic viability and environmental safety will be discussed, as well as interesting avenues for the future potential integration of green nanotechnology and circular economy principles in sustainable electronic waste management.

Keywords: Electronic waste recovery; Nano technology; Circular economy; Valuable metal recovery; E plastic upgrading; Urban mining; Green recycling.

1. INTRODUCTION

The rapid development of digital technologies and ever-increasing consumer demand for electronic gadgets have contributed to a massive surge in the generation of electronic waste globally. Currently, electronic waste is considered one of the largest waste streams that contain both hazardous material as well as secondary valuable resources, such as precious metals, rare earth elements and high performing polymers. It is estimated that more than 60 million tons of electronic waste is generated around the globe annually and this figure is anticipated to increase over the next decades, posing severe environmental, economic and resource management issues (Forti *et al.* 2020; Nithya *et al.* 2021). The disposal and recycling of this toxic waste in an unregulated manner causes the release of lead, mercury, cadmium, brominated flame retardants and other hazardous materials into the environment with dire consequences for human and ecosystem health. (Nithya *et al.* 2021; Mohamed *et al.* 2025).

The management of electronic waste has been traditionally based on linear economic thinking, which involves obtaining raw materials, manufacturing the goods, using and disposing of them. Traditional recovery methods such as high-temperature smelting and hydrometallurgical leaching allow marginal recovery of precious metals, but these techniques are energy-intensive and are associated with high consumption of chemicals and generation of secondary pollutants (Nagarajan and Panchatcharam, 2023; Nithya *et al.* 2021). Consequently, the demand for shifting from a linear economy model towards a Circular Economy (CE) model, which focuses on the efficiency of resources, reduction of wastes and the recirculation of materials in the production cycle, is increasingly high. In this regard, electronic waste is nowadays regarded as an "urban mine," as it contains concentrations of precious metals that can be greater than those of natural ores (Forti *et al.* 2020; Mohamed *et al.* 2025).

The outstanding physicochemical properties of nanomaterials, such as large surface area, high surface to volume ratios, modifiable surface functionality, enhanced catalytic activity and selective adsorption, have made them potential candidates in the circular economy of electronic waste valorisation.

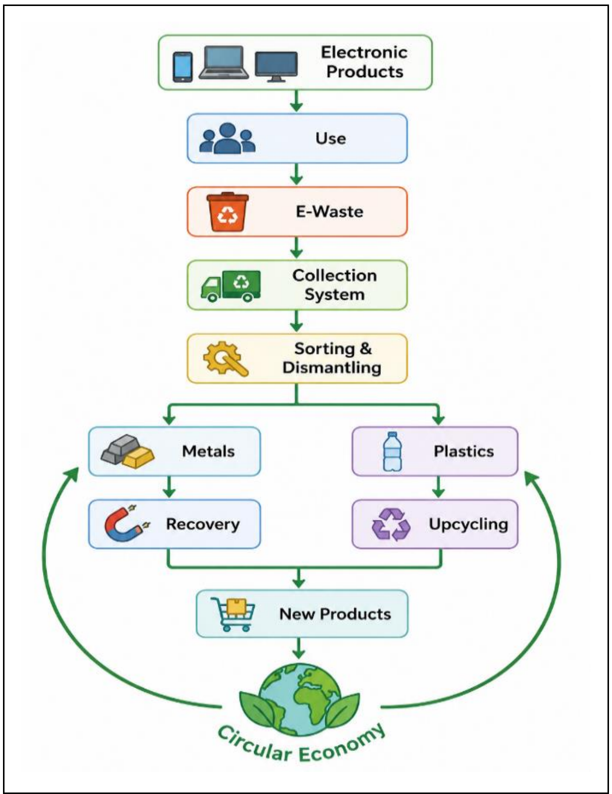

Fig. 1: E-waste circular economy flowchart

These features have enabled the development of intelligent nanomaterials that can enhance the efficiency and selectivity of metal recovery with minimised environmental impact. A few recent reports have revealed the applicability of magnetic nanoparticles, graphene derived adsorbents, metal organic frameworks (MOFs) and other nanomaterials for selective separation of precious metals like gold (Au), silver (Ag) and palladium (Pd) from complicated electronic waste environments (Hernández-Saravia *et al.* 2023; Nagarajan and Panchatcharam, 2023). In addition, green synthetic methodologies utilizing natural resources have become intriguing for the synthesis of nanomaterials for recycling and other applications (Osman *et al.* 2024).

In addition to metal recovery, electronic waste contains a large amount of polymeric materials that are either landfilled or recycled in low-value processes. With the recent progress in nano catalysts, e plastics can be converted into value added products such as pyrolytic oils, carbon nanotubes (CNTs), carbon nanofibers and other superior carbon materials (Balu *et al.* 2022; Li *et al.* 2020; Liu *et al.* 2021). Catalytic pyrolysis and thermochemical conversion processes show great promise for the production of energy carriers and functional nanomaterials from plastic rich electronic waste fractions, which allows for a convergence of waste abatement and resource recovery (Li *et al.* 2020; Liu *et al.* 2021). These strategies are very much in line with circular economy thinking since they prolong material lifecycles and extract further economic value from waste streams.

The combination of nanotechnology with circular economy principles provides remarkable potential for enhancing resource efficiency, mitigating greenhouse gas emissions and promoting sustainable industrial development. It has been reported that systems for distillation enhanced by nanotechnology can reach better recovery efficiencies at reduced energy demands and environmental loads than traditional distillation techniques (Nithya *et al.* 2021). In addition, new trends based on artificial intelligence (AI) and the Internet of Things (IoT) and smart recycling infrastructure are also expected to further improve the scalability and efficiency of nano mediated electronic waste treatment systems (Mohamed *et al.* 2025).

In consequence, this work will briefly review the recent progress of nanotechnology enabled circular economy for electronic waste valorisation. Especially, the precious metal recovery techniques and e plastic upcycling methods are focused on presenting their mechanisms, advantages, challenges and future perspectives. This review will, therefore, critically assess recent trends in order to establish a knowledge baseline for sustainable urban mining to support the shift towards a resource efficient circular economy.

Several reviews have addressed e-waste recycling and resource recovery (Nithya *et al.* 2021; Van Yken *et al.* 2021; Hsu *et al.* 2019), nanotechnology applications in waste valorisation (Hernández-Saravia *et al.* 2023; Osman *et al.* 2024) and circular economy strategies for sustainable e-waste management (Pan *et al.* 2022; Srivastav *et al.* 2023). However, few studies have comprehensively integrated precious metal recovery and e plastic upcycling within a unified nano enabled circular economy framework. Hence, the present review is an attempt to fill this void by reviewing advancements in technologies and prospects for the future.

2. REVIEW METHODOLOGY

This review aims at a critical overview of how nanotechnology can contribute to enhancing circular economy approaches for electronic waste valorisation, particularly in precious metal recovery and e plastic upcycling processes. A systematic review of the literature is given to analyse recent advancements in e-waste recycling and urban mining, nanotechnology based resource recovery, catalytic plastic conversion and green waste management. It particularly concerned studies from 2017 to 2025, the period during which breakthroughs were indicated (Forti *et al.* 2020; Nithya *et al.* 2021) in nanotechnology enabled recycling technologies and the application of circular economy strategies.

The relevant literature was sourced from scientific journal articles, review articles, conference proceedings and technical reports by employing keywords pertinent to e-waste recycling, circular economy, urban mining, nanotechnology enabled resource recovery, magnetic nanoparticles, graphene based adsorbents, metal organic frameworks, precious metal extraction, e plastic upcycling, catalytic pyrolysis and carbon nanotube synthesis. Special consideration was given to literature on the recovery of the gold (Au), silver (Ag) and palladium (Pd) and other precious metals from electronic waste with nanostructured materials as well as studies dealing with the transformation of plastic rich electronic waste fractions into value-added products and energy resources (Nagarajan and Panchatcharam, 2023; Hernández-Saravia *et al.* 2023; Li *et al.* 2020; Liu *et al.* 2021).

The selected articles were screened against the objectives of this review. Studies on traditional recycling methods were included mainly to discuss the comparative merits and demerits of nano enabled techniques. Research papers showing recovery efficiency, selectivity and sustainability of the processes (reduced impacts on the environment and/or integrated with circular economy concepts (Nithya *et al.* 2021; Mohamed *et al.* 2025) were given priority. In addition, literature concerning green nanoparticle synthesis, life cycle assessment, environmental sustainability and industrial scalability was reviewed to capture a comprehensive view of the possibilities as well as constraints for electronic waste valorisation based on nanotechnology (Osman *et al.* 2024; Nithya *et al.* 2021; Mohamed *et al.* 2025).

The retrieved studies were divided into four major groups: (i) electronic waste generation and resource potential, (ii) precious metal recovery techniques enabled by nanotechnology, (iii) nano-catalytic e-plastic upcycling and generation of value-added products and (iv) sustainability, environmental impacts and future visions of circular economy application. Outcomes of these works were critically reviewed and integrated to recognise the technological trends and gaps in research and potential future directions for advancement in the sustainable and resource efficient management of electronic waste (Forti *et al.* 2020; Srivastav *et al.* 2023).

3. E-WASTE COMPOSITION AND RESOURCE POTENTIAL

The increasing use and availability of electrical and electronic equipment results in the generation of more and more waste of this type (electronic waste), leading to environmental hazards, but also to possibilities for recovery of resources. Instead of being simple municipal waste, electronic waste is a heterogeneous mix of materials with different value embedded in complex product matrices. These are precious and base metals, rare earth elements, engineering plastics, glass and ceramics. The reclamation of these resources is getting more and more essential in light of the increasing demand for critical raw materials and the exhaustion of natural mineral reserves. As a result, waste is considered a potent secondary resource stream to enable circular economy goals through material recovery and reuse (Forti *et al.* 2020; Mohamed *et al.* 2025).

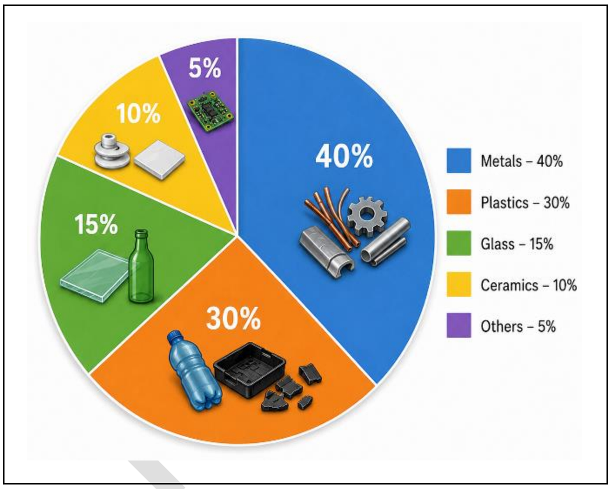

Fig. 2: Composition of E-waste

3.1 Metallic Components of E-Waste

Metals are among the most valuable materials recovered from electronic waste. Components such as printed wiring boards (PWBs), integrated circuits (ICs), connectors, processors and communication devices contain significant amounts of copper, gold, silver, palladium and other strategically important metals. In many cases, the concentration of these precious metals in discarded electronic products is much higher than that found in natural ores, making e-waste a highly attractive resource for urban mining and metal recovery efforts (Nithya *et al.* 2021; Nagarajan and Panchatcharam, 2023).

Table 1. Typical concentrations of valuable metals present in electronic waste

Material	Typical Concentration (g/t)
Gold	200–350
Silver	1000–3000
Palladium	50–100
Copper	100000–250000

Copper is the most easily recoverable metal in electronic waste and is essential for the electrical conductivity industry. The high conductivity and corrosion resistance of precious metals, such as gold and silver, are utilized in connectors and circuit traces. Palladium is used in capacitors and multilayer ceramic capacitor (MLCC) electrodes due to its high catalytic and electrical activity. The reclamation of these metals creates economic value but also reduces the dependence on traditional mining that has a high environmental burden (Nagarajan and Panchatcharam, 2023).

Electronic waste also contains critical raw materials such as rare earth elements, which are essential for the production of modern electronic devices, solar panels, wind turbines and advanced communication systems. With the growing demand for these materials worldwide, there is now a growing interest in developing efficient recovery methodologies to retrieve them from end of life electronics products.

3.2 Non-metallic Components and E-Plastics

The non-metallic portion of electronic waste is mostly plastics, glass fibres, ceramics and composites. Within these, plastics are a sizeable part and found in device casings, cable insulation, keyboards, monitors and other electronic items. Typical polymer types are acrylonitrile butadiene styrene (ABS), high impact polystyrene (HIPS), polypropylene (PP), polyethylene (PE) and polycarbonate (PC) (Balu *et al.* 2022).

While plastics provide strength and functionality to electronic products, they are difficult to manage at the end of product life. Numerous e plastics have additives such as flame retardants, stabilisers and pigments that hinder standard recycling methods. Consequently, substantial amounts of plastic laden electronic waste are being discarded in landfills or burned, thus wasting resources and polluting the environment.

Following recent technological advances, focus has been turned from the mere disposal to the valorisation of e plastic fractions. High end thermochemical processes such as catalytic pyrolysis and gasification facilitate the transformation of waste plastics into fuels, chemicals and value-added carbon materials. These processes allow for an additional stream of reclaimable value from electronic waste and at the same time potentially alleviate the environmental harm of plastic disposal (Li *et al.* 2020; Liu *et al.* 2021).

3.3 E-Waste as an Urban Mine

The idea of urban mining has brought about a sustainable solution to conventional resource exploitation. Urban mining is the process of reclaiming raw materials from spent products, buildings and waste from industrial processes. Of all the urban resources, e-waste is one of the richest sources of metals that are recoverable because it contains concentrations of precious and strategic elements (Mohamed *et al.* 2025).

Urban mining has many benefits over traditional mining, such as less land disturbance, energy consumption, greenhouse gas emissions and better resource use (Forti *et al.* 2020; Nithya *et al.* 2021). In addition, material recovery from electronic waste also contributes to risk mitigation in the supply chains of critical raw materials and national and global sustainability objectives. In a circular economy system, urban mining reclaims discarded electronics from waste and turns them into resources that may be re- utilized in industrial processes (Forti *et al.* 2020; Hagelüken and Goldmann, 2022).

3.4 Resource Recovery Potential in a Circular Economy

The circular economy encourages keeping the material value as long as possible through reuse, recycling, remanufacturing and recovery of resources. Electronic waste is a significant secondary resource stream and hydrometallurgical recovery remains one of the most widely investigated approaches for recovering critical and precious metals from end of life electronic products (Sun et al. 2017; Sethurajan et al. 2019). Good reclaiming practice lessens dependence on virgin raw materials and leads to more sustainable manufacturing processes.

Nanotechnology advances have escalated the opportunities for electronic waste valorisation through greater efficiency and selectivity in recovery processes. Nanomaterials possess unique properties that enable the extraction of targeted metals, superior separation performances and catalytic processing of plastic waste into valuable products. These trends are reinforcing the strategic resource nature of electronic waste in emerging circular economy models and the movement towards sustainable materials management (Nagarajan and Panchatcharam, 2023; Balu *et al.* 2022).

Table 2. Major components and resource potential of e-waste

Component Category	Typical Materials	Potential Value Recovery
Precious Metals	Gold, Silver, Palladium	Secondary raw materials for electronics
Base Metals	Copper, Aluminium, Iron, Nickel	Industrial manufacturing and infrastructure
Critical Materials	Rare Earth Elements	Renewable energy and advanced technologies
Plastics	ABS, HIPS, PP, PE, PC	Fuels, chemicals, CNTs, carbon materials
Glass and Ceramics	Display panels, insulation materials	Construction and secondary applications

4. NANOTECHNOLOGY-ENABLED RECOVERY OF PRECIOUS METALS FROM E-WASTE

Recovery of precious metals from electronic waste has attracted research owing to the growing supply risk of critical raw materials and the nonexistence of high-grade natural ores. In electronic waste, the concentration of precious metals is high and these metals, including gold, silver and palladium, are used extensively on printed circuit boards, connectors, integrated circuits and electronic components due to their excellent electrical conductivity and corrosion resistance. Traditional extraction processes, such as thermal metallurgical and hydrometallurgical processes, are generally polluting the environment and consuming a lot of energy and chemicals. In order to address the aforementioned deficiencies, nanotechnology has been considered as a potential strategy for enhancing metal recovery efficiency, selectivity and environmental-friendliness (Gulliani et al. 2023; Nagarajan and Panchatcharam, 2023; Hsu *et al.* 2019).

4.1 Role of Nanotechnology in Metal Recovery

Nanomaterials possess unique physicochemical properties that make them very efficient for metal separation and extraction applications. The high surface-area to volume ratio, tunable surface chemistry and enhanced adsorption capacity facilitate efficient interaction with metal ions present in complex electronic waste leachates. Unlike conventional adsorbents, nanomaterials can be designed for selectivity towards specific metals, thus improving the efficiency of recovery while reducing the use of reagents and the generation of waste (Nagarajan and Panchatcharam, 2023).

Fig. 3: Nanotechnology-based precious metal recovery mechanism

The use of nanotechnology in recycling of electronic waste has seen significant growth in recent years, mainly with the advent of nano adsorbents, magnetic nanoparticles, graphene derived materials and metal organic frameworks. These materials allow selective metal capture, fast separation and effective regeneration and they are promising alternatives to traditional extraction methods (Hernández-Saravia *et al.* 2023).

4.2 Magnetic Nanoparticles for Precious Metal Extraction

Magnetic nanoparticles, particularly magnetite (Fe_3O_4), have attracted significant attention for the recovery of precious metals from electronic waste streams. Due to their magnetic properties, they can be easily separated from liquid solutions using an external magnetic field without the need for energy consuming filtration or centrifugation steps. Furthermore, the surface of magnetite (Fe_3O_4) nanoparticles can be functionalized with functional groups such as thiol (-SH), amino group (-NH_2) and carboxyl (-COOH) ligands, which can enhance their affinity towards target metal ions (Hernández-Saravia *et al.* 2023).

Table 3. Nanotechnology-based materials for recovery of precious metals from e-waste

Nanomaterial	Primary Function	Target Metals
Fe_3O_4 Magnetic Nanoparticles	Adsorption and magnetic separation	Au, Ag, Pd
Thiol-Functionalized Nanoparticles	Selective adsorption	Au, Pd
Graphene Oxide	Metal ion adsorption	Au, Ag, Pd
Carbon Nanotubes	Adsorption and separation	Precious metals
Metal–Organic Frameworks	Selective metal capture	Au, Ag, Pd

Among these functional groups, thiol-functionalized magnetic nanoparticles showed high selectivity for gold and palladium due to the formation of stable metal sulfur coordination bonds. Recent studies have shown that thiol-functionalized magnetite Fe_3O_4 nanoparticles can achieve gold recovery efficiencies >95% under optimum conditions and proved to be suitable for selective extraction of precious metals from complex electronic waste leachates. Such selective adsorption mechanism enables efficient recovery of precious metals from very complex leachate solutions with multiple competing ions. Following adsorption, the nanoparticles can be magnetically separated, regenerated and reused in the subsequent recovery cycles, contributing to a more sustainable recycling process (Xu *et al.* 2023; Hernández-Saravia *et al.* 2023).

4.3 Graphene-based Nanomaterials and Advanced Adsorbents

Graphene derived materials have proven to be very effective at recovering precious metals. This is due to their large surface area, strong chemical stability and adjustable surface features. Recent studies have also highlighted the recovery and reuse of metallic nanoparticles from electronic waste for advanced biomedical and sustainable applications (Kumar et al. 2025). Graphene oxide and reduced graphene oxide can be chemically changed to create active binding sites that interact specifically with metal ions. These materials have displayed high adsorption capacities for recovering gold, silver and palladium from diluted solutions and electronic waste leachates. (Hernández-Saravia *et al.* 2023; Xu *et al.* 2023).

Graphene derivatives and other carbon-based nanostructures have been studied for use in metal adsorption. Their porous structure and high conductivity make them great options for separation systems, where the transport and adsorption of metal ions need to be efficient. These materials can achieve high recovery rates while also lowering the environmental impact of traditional extraction methods. Graphene-based adsorbents show strong adsorption performance and high selectivity. However, they often face challenges such as high production costs, a complicated functionalization process and low efficiency in regeneration after several adsorption desorption cycles. These issues could hinder their large scale industrial use.

4.4 Metal–organic Frameworks for Selective Recovery

Metal organic frameworks are a new type of porous nanomaterials that have gained significant interest for resource recovery applications. Metal organic frameworks consist of metal ions bonded to organic linkers, creating well organized porous structures with very large surface areas.

These materials can be designed to selectively adsorb specific metal ions by precisely tuning the pore structures and functional groups.

The performance of MOFs in the selective recovery of precious metals from complicated waste matrices such as leachates of electronic waste has been confirmed in recent reports. Their high adsorption capacity and selectivity have some advantages compared to traditional adsorbents, especially in the treatment of low metal concentrations. The real application of MOFs is still limited by the relatively high cost of MOF synthesis, moisture sensitivity and difficulties in large-scale production. In addition, MOFs can be, in many cases, regenerated and reused, hence adhering to circular resource use (Hernández-Saravia *et al.* 2023; Xu *et al.* 2023).

4.5 Green Nanotechnology Approaches

However, despite the positive aspects of nanotechnology for metal recovery, the environmental impact of nanoparticle synthesis has raised concerns and prompted the need for the development of green synthesis routes. Green nanotechnology involves the use of biological materials, including plant extracts, microorganisms and natural polymers as reducing and stabilising agents in the synthesis of nanoparticles. These methodologies minimise hazardous chemical usage and the environmental impact of nanomaterial fabrication (Osman *et al.* 2024).

Utilising green synthesised nanoparticles for electronic waste processing is consistent with the tenets of the circular economy, as it facilitates enhanced resource recovery with reduced environmental harm. Approaches of this kind will help lead to sustainable recycling technologies that can be implemented on a large scale in the future.

Table 4. Recovery efficiency comparison of nanomaterials for precious metal recovery

Nanomaterial	Target Metal	Recovery Efficiency (%)	Reference
Fe_3O_4 Magnetic Nanoparticles	Au	95–99	Hernández-Saravia *et al.* (2023); Xu *et al.* (2023)
Graphene Oxide	Ag	85–95	Hernández-Saravia *et al.* (2023)
MOFs	Pd	90–98	Xu *et al.* (2023)

4.6 Challenges and Future Perspectives

Nanotechnology enabled aqueous metal recovery systems still face several challenges that limit their large-scale industrial application. The mass production of nanomaterials, long term stability of adsorbents, regeneration efficiency and environmental risk caused by the release of nanoparticles are still critical issues to be considered. Moreover, cost effectiveness and process integration are to be addressed if these technologies should be transferred to commercial recycling plants (Srivastav *et al.* 2023; Hagelüken and Goldmann, 2022).

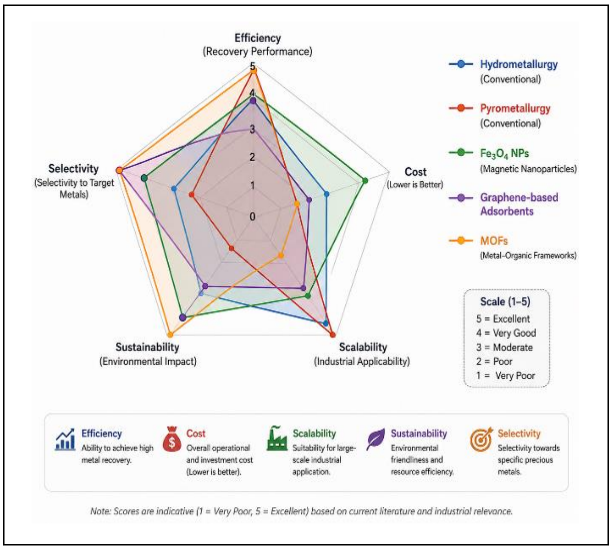

Fig. 4: Comparison of recovery technologies

Upcoming investigations may be oriented towards the design of cunning, cheap and ecofriendly nanomaterials with higher selectivity and multiple uses. The introduction of artificial intelligence, process automation and advanced monitoring systems may further improve the recovery efficiency and enhance industrial implementation.

These advances could turn electronic waste recycling into a high rate urban mining system that contributes to sustainable resource management and the circular economy target (Hagelüken and Goldmann, 2022).

5. NANOTECHNOLOGY-ASSISTED E-PLASTIC UPCYCLING TECHNOLOGIES

E-plastics make up a large space in the electronic waste and are mainly constituted by polymers such as ABS, HIPS, polycarbonate and polypropylene. Landfilling or incineration of these wastes, however, leads to wastage of resources and pollution of the environment. As such, high value upcycling approaches for e-plastics to high-end products in line with circular economy have attracted significant attention (Balu *et al.* 2022; Li *et al.* 2020).

5.1 Nano-catalytic Pyrolysis

Catalytic pyrolysis is an efficient tool to convert e plastics into liquid fuels, flammable gases and solid carbonaceous products. The application of nanocatalysts, especially nano zeolites and metal oxide nanoparticles, can increase the reaction efficiency, the quality of products and decrease by product emissions. The pyrolytic oil thus produced can be exploited as a substitute for industrial fuel (Balu *et al.* 2022; Li *et al.* 2020).

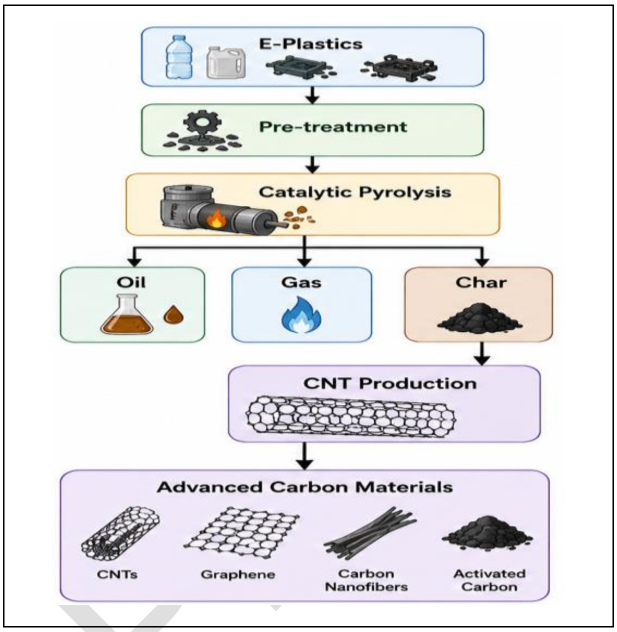

Fig. 5: E-Plastic upcycling pathway

5.2 Carbon Nanotube Production

Waste plastics can act as carbon feedstock for the synthesis of carbon nanotubes (CNTs) through catalytic pyrolysis and chemical vapour deposition (CVD). Carbon nanotubes (CNTs) also have excellent electrical, thermal and mechanical properties and can be used in energy storage, electronics and high-performance composites (Li *et al.* 2020; Liu *et al.* 2021).

5.3 Environmental and Economic Benefits

Upcycling aided by nanotechnology minimises the disposal of plastic waste and recovers precious resources to produce high value products such as fuels and carbon nanomaterials. These advantages contribute to the circular economy objectives by reducing environmental impacts and enhancing the economic feasibility of the recycling of electronic waste (Balu *et al.* 2022).

5.4 Challenges and Future Outlook

Nevertheless, hurdles associated with the catalyst price, process scalability and feedstock variation remain. Future investigations should be directed towards the development of more efficient nanocatalyst, process optimisation and the integration of intelligent technologies that allow scaling up of electronic waste plastic valorisation systems (Mohamed *et al.* 2025).

Table 5. Nanotechnology-assisted E-plastic upcycling technologies

Technology	Nanomaterial/Catalyst	Feedstock	Main Products	Key Advantages	Reference
Catalytic Pyrolysis	Nano-zeolites	E-plastics (ABS, HIPS, PC)	Pyrolytic oil, syngas	Higher conversion efficiency and fuel yield	Balu *et al.* (2022); Li *et al.* (2020)
Chemical Vapour Deposition (CVD)	Fe-, Ni- and Co-based Nano catalysts	Plastic-derived carbon	Carbon Nanotubes (CNTs)	Production of high-value nanomaterials	Li *et al.* (2020)
Catalytic Pyrolysis–CVD	Bimetallic Nano catalysts	Waste polyethylene and e-plastics	CNTs and carbon nanofibers	Simultaneous waste reduction and material recovery	Li *et al.* (2020); Liu *et al.* (2021)
Carbonization Processes	Metal oxide nanoparticles	Plastic residues and char	Carbon-rich materials	Resource recovery from waste streams	Balu *et al.* (2022); Liu *et al.* (2021)
Waste-to-Energy Conversion	Nano-catalysts	Mixed e-plastic fractions	Fuel oil and combustible gases	Reduced landfill disposal and energy generation	Balu *et al.* (2022)

6. CIRCULAR ECONOMY INTEGRATION AND SUSTAINABILITY ASSESSMENT

In electronic waste management, circular economy principles convert discarded electronic products into secondary resources by material recovery, recycling and upscaling. Nanotechnology reinforces this strategy through enhanced efficiency and selectivity in precious metal recovery and electronic waste plastics valorisation processes (Forti *et al.* 2020; Mohamed *et al.* 2025).

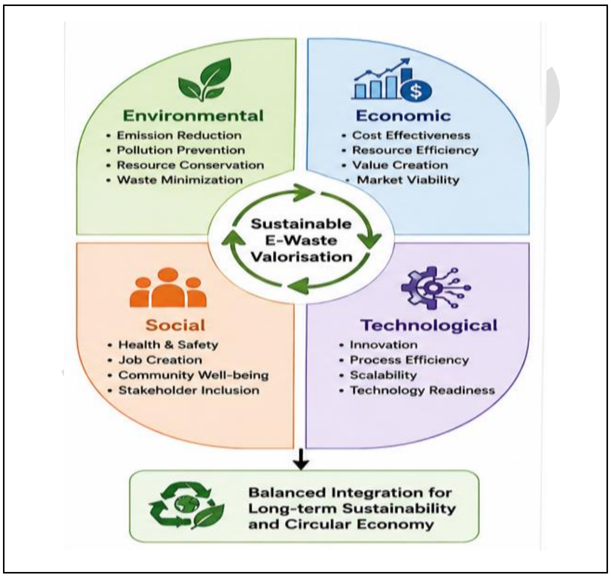

Fig. 6: Sustainability assessment framework

Recycling systems enabled by nanotechnology promote sustainability and environmental conservation, by reducing the reliance on virgin raw materials for production, decreasing the level of energy required and by curbing (or eliminating) environmental pollution brought about by traditional mining and waste disposal methods. Extracting gold, silver, palladium and other precious metals from electronic waste also reinforces the idea of urban mining and turning e-plastics into fuels and high value carbon materials adds to resource circularity (Nagarajan and Panchatcharam, 2023; Balu *et al.* 2022).

Life cycle analysis showed that nanotechnology based recycling processes could potentially offer a reduction in greenhouse gas emissions and better overall resource efficiency when compared to conventional recycling processes. Nonetheless, production, retrieval and environmental security of nanoparticles must be considered in detail in order to guarantee a sustainable long-term status (Nithya *et al.* 2021). Moreover, viability remains a key challenge with infrastructural needs ranging from demonstrating process scale-up to secure large scale application and appropriate policy frameworks to supporting these (Hagelüken and Goldmann, 2022).

In conclusion, the application of nanotechnology to circular economy approaches seems a viable way for sustainable electronic waste valorisation, enabling high resource recovery, low environmental burdens and contributing to the evolution towards a more resource efficient economy.

Table 6. Contribution of nanotechnology to circular economy objectives in E-waste management

Circular Economy Objective	Nanotechnology Contribution	Sustainability Benefit	Reference
Resource Recovery	Selective extraction of precious metals	Reduced demand for virgin materials	Nagarajan and Panchatcharam, (2023)
Urban Mining	Recovery of valuable metals from e-waste	Conservation of natural resources	Forti *et al.* (2020); Nithya *et al.* (2021)
Waste Reduction	Upcycling of e-plastics into fuels and carbon materials	Reduced landfill disposal	Balu *et al.* (2022)

Energy Efficiency	Improved separation and catalytic processes	Lower energy consumption	Li *et al.* (2020); Liu *et al.* (2021)
Environmental Protection	Reduced emissions and chemical waste	Improved environmental performance	Nithya *et al.* (2021)
Sustainable Industrial Development	Circular utilisation of recovered resources	Enhanced economic and environmental sustainability	Srivastav *et al.* (2023); Hagelüken and Goldmann, (2022)

7. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Although great strides have been made in nanotechnology based electronic waste valorisation, several technical, environmental and economic issues remain that hinder large scale application. One of the main issue is the high cost of the synthesis and functionalization of nanomaterials, which might influence the commercial feasibility of recovery procedures. Besides, continuing the long term stability, selectivity and reusability of nano-adsorbent and nano catalyst is a challenging issue for industrial use (Srivastav *et al.* 2023; Hagelüken and Goldmann, 2022).

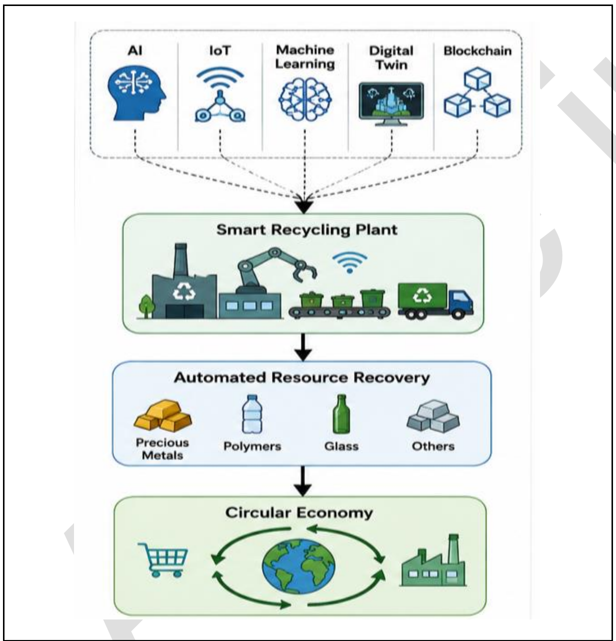

Fig. 7: Future smart recycling ecosystem

Potential environmental and health hazards related to the emission of nanoparticles during recycling processes should also be considered. While the use of nanomaterials increases recovery efficiency, their toxicity and persistence in the environment require that they be handled, recovered and disposed of appropriately. It is thus crucial to conduct full life cycle evaluations to ensure that nano enabled recycling processes provide true environmental gains (Nithya *et al.* 2021).

Another issue is the mixed nature of electronic waste, which can be substantially different from one type of electronic product to another, as well as between manufacturers. Such variation leads to difficulties in standardizing processes and has an impact on the efficiency of both the upcycling of electronic waste plastics and the recovery of metals. In addition, the content of hazardous materials (e.g. brominated flame retardants and heavy metals) necessitates efficient pretreatment and pollution control measures (Nithya *et al.* 2021; Van Yken *et al.* 2021).

Future research efforts should focus on the development of cost-effective and environmentally sustainable nanomaterials through green synthesis approaches. Greater emphasis should also be placed on the recovery and reuse of nanomaterials, improving nanocatalyst lifetime and scaling up laboratory-scale technologies for industrial applications. Furthermore, the integration of artificial intelligence (AI), machine learning (ML) and Internet of Things (IoT) technologies has the potential to enable automated waste sorting, real-time process optimization and intelligent resource recovery systems, thereby enhancing the efficiency, sustainability and economic viability of electronic waste recycling. (Osman *et al.* 2024; Mohamed *et al.* 2025).

Addressing these challenges will be crucial for the translation of lab-scale novelties to market friendly solutions that enable sustainable electronic waste management and circular economy targets.

Table 7. Key challenges and future research opportunities

Challenge	Impact	Future Research Direction
High nanomaterial production cost	Limits industrial adoption	Development of low-cost green synthesis methods
Nanoparticle toxicity concerns	Environmental and health risks	Safe-by-design nanomaterials and recovery systems
Limited scalability	Difficulty in commercial implementation	Pilot-scale and industrial-scale validation
Feedstock variability	Inconsistent recovery performance	Adaptive and intelligent processing technologies
Catalyst deactivation	Reduced process efficiency	Improved catalyst stability and regeneration
Energy and process optimization	Increased operational costs	AI and IoT based process control systems
Regulatory and policy barriers	Slow technology adoption	Development of supportive circular economy policies

8. CONCLUSION

E-waste has become both an environmental concern and a major source of secondary raw material. This review indicates that nanotechnology based methodologies, such as magnetic nanoparticles, graphene-based adsorbents, metal organic frameworks and nano catalytic systems, provide an excellent tool to improve precious metal recovery and electronic waste plastic upcycling. These processes enhance resource production efficiency, minimise waste generation and promote the circular economy by transforming end life electronic products into valuable materials.

However, several challenges such as production cost, scalability, environmental safety and regulatory enforcement remain barriers to large-scale commercialization. In the future, more attention should be paid to design of more cost-effective and green nanomaterials, enhancement of process integration, as well as the use of other advanced technologies such as artificial intelligence and Internet of Things (IoT)-enabled recycling systems.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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