Journal of Materials Chemistry A

ROYAL SOCIETY OF CHEMISTRY

PERSPECTIVE

View Article Online
View Journal | View Issue

Cite this: J. Mater. Chem. A, 2026, 14, 13318

Can recycled e-waste polymers power the future of sensors?

Berly Robert, †[a] Suvitha S. Kumar, †[a] Tiju Thomas *[ab] and Sreeram K. Kalpathy *[ab]

Industries in both developed and developing countries are under growing pressure to align with sustainable development goals (SDGs) while simultaneously contributing to economic development. Several SDGs inevitably require maintenance of air, water, and soil quality. Industrial effluents typically pollute these natural resources, which in turn need effective monitoring through sensors. Conventionally, sensors have relied largely on semiconductor materials; however, their high cost, manufacturing bottlenecks, availability, and environmental footprint limit their suitability in many low- and middle-income countries. In contrast, polymeric sensors, particularly if derived from recycled plastics, could offer a scalable, customizable, and cost-effective platform. Their inherent flexibility, light weight, and easy fabrication enable seamless integration into Internet of Things (IoT) devices, which would help industries move closer toward decentralized monitoring. Electronic waste (e-waste) could serve as a suitable and valuable source of polymers for sensor materials, given their high diversity and that much of recycled e-waste polymers are incinerated or landfilled. This article unearths new opportunities in the field of urban mining in the form of combining recycled e-waste plastics and IoT-integrated polymer science to advance sustainable and customizable sensor development. It is hoped that these ideas would tremendously strengthen circular economy initiatives, particularly in resource-constrained economies.

Received 6th November 2025
Accepted 5th February 2026

DOI: 10.1039/d5ta09015f

rsc.li/materials-a

1 Introduction

Economically critical sectors such as agriculture, pharmaceuticals, and textiles constitute the backbone of many national economies by supporting employment, infrastructure development, and technological advancement. At the same time, governments mandate strict environmental monitoring for the management of wastewater generated from these industries and their processing units.[1] However, these sectors operate with thin profit margins, particularly in developing countries, battling the rising inflation as well as increasing regulatory pressures from Industry 4.0 and the emerging mandates of Industry 5.0 sustainability frameworks.[2,3] In response to the latter, government policies are evolving to enforce sustainable manufacturing, thereby keeping a check on industrial effluents and emissions. To address this scenario, industries require affordable, scalable, and IoT integratable sensor solutions that enable real-time monitoring without adding financial strain.[4,5] These sensors are essential for detecting a wide spectrum of contaminants, in air, water, and soil, such as heavy metals over broad concentration ranges, pH fluctuations, residual disinfectants such as chlorine, and dissolved gases like oxygen and nitrogen. Beyond performance, such sensor technologies must also meet regulatory standards, remain economically viable, and support broader societal goals such as employment generation and sustainable living (SDGs 8 and 11: Decent Work and Economic Growth and Sustainable Cities and Communities, respectively).[6]

Urban mining is increasingly recognized not only as a strategy for resource recovery but also as a pathway to achieve circularity.[7,8] While it has traditionally been associated with the extraction of critical metals, a closer examination reveals that large amounts of non-metallic materials such as plastics, polymeric resins, ceramics, and glasses can also be recovered. In this context, recycled polymers from electronic waste (e-waste) may serve as a promising input for developing low-cost, repurposed polymeric thin-film sensors. Their inherent flexibility, light weight, and diverse richness in engineering chemistry make them particularly suitable for functional applications like sensors. The United Nations reports that, in 2021, globally, an average individual was responsible for generating 7.6 kg of e-waste, amounting to about 57.4 million tons worldwide. Of this, only 17.4% was officially recorded as appropriately collected, treated, and recycled.[9] The amount of e-waste generated globally had nearly doubled from 34 million tonnes (Mt) in

[a]Department of Metallurgical and Materials Engineering, Indian Institute of Technology Madras, Chennai - 600036, India. E-mail: tijuthomas@smail.iitm.ac.in; sreeram@iitm.ac.in

[b]Centre for Resource Efficiency, Recyclability, and Circularity in Energy Transition, School of Sustainability, Indian Institute of Technology Madras, Chennai - 600036, India

† These authors contributed equally to this work.

2010 to a record 62 Mt in 2022. It is further projected to reach 75–85 Mt by 2030, growing five times faster than documented recycling efforts.[10,11] Despite the massive volume, only 22.3% (13.8 Mt) of e-waste was formally collected and recycled in 2022, leaving an estimated USD 62 billion worth of recoverable natural resources unaccounted for and exacerbating environmental and health risks.[12] Polymers constitute up to 30% of e-waste by weight, which is a diverse mix of engineering plastics, fibers, and resins. This compositional diversity presents a wide-range of possibilities of combinatorics for sensing (selectivity and sensitivity) by blending and tailoring electrical, optical, and mechanical properties. In this context, reusing recycled polymers in sensors would promote circularity, reduce environmental impact, and align with SDG 12 (Responsible Consumption and Production). It would also help to reduce landfill waste and reinforce the circular economy model.

Printed circuit boards (PCBs) are considered to be the most valuable portion of e-waste due to their richness in high purity precious metals such as gold, silver, palladium, nickel, aluminium, and copper.[13,14] However, once these metals are extracted, what remains is a substantial non-metallic fraction ($\approx$70% by weight of PCBs), composed mainly of glass fibers and thermoset resins such as epoxy, derived from the substrate and dielectric layers.[15–17] Lacking direct economic value, this polymer-rich residue is typically discarded or landfilled, overlooking its potential as feedstock for sustainable technologies. Despite the introduction of e-waste management rules in different countries, which include extended producer responsibility (EPR) frameworks mandating producers to manage end-of-life electronics, the actual implementation remains weak.[18,19] Previous studies have illustrated methods for reuse of e-waste components, such as depleted battery casings and electrodes, in electrochemical energy-generation systems.[11,20] Recent literature further suggests that polymers recovered from waste electrical and electronic equipment (WEEE) plastics and non-metallic PCB fractions can be valorized through reintegration into polymer composites, construction materials, and additive manufacturing.[21–23] Therefore, non-metallic fractions of e-waste can be viewed as valuable, valorizable materials.

Mazher Mohammed *et al.* demonstrated the recovery and recycling of acrylonitrile butadiene styrene (ABS) polymers from e-waste into 3D-printing filaments, followed by reuse in additively manufactured products with only modest loss in mechanical performance.[21] Gaikwad *et al.* transformed polycarbonate-rich plastics from end-of-life printers into filaments for 3D printing, showing that the printed parts retained up to about 80% of the tensile strength of virgin ABS while lowering CO_2 emissions by roughly 28% compared with virgin polymer filaments.[22] Mtibe *et al.* comprehensively reviewed sustainable pathways for recycling e-waste plastics, covering mechanical, chemical, and thermal recycling routes and highlighted their conversion into value-added products such as composites, construction materials, and 3D-printing filaments within a circular economy framework.[23] Thus, various possibilities exist by which non-metallic waste can be utilized, in the form of building materials or other low-value use cases, but their vast majority remain underutilized due to limited awareness and lack of market incentives to support their recovery.[24,25] Re-purposing this fraction could provide a valuable source of flexible, processable polymers ideally suited for sensor fabrication.

Conventional e-waste recycling methods, such as burning and pyrolysis, are highly energy-intensive and thus unsustainable. Besides, they cause the release of hazardous and toxic emissions due to the presence of brominated flame retardants (FR) in e-waste.[26–29] Furthermore, the complex nature of resins, polymer blends, and fibers contained in e-waste[30] make valorization processes difficult, thus letting high-quality materials end up in riverbeds or landfills. In contrast, advanced separation techniques such as solvothermal depolymerization[31] offer a more precise and less energy-demanding approach by selectively breaking down polymers under controlled conditions. Solvothermal depolymerization enables the recovery of well-defined chemical components that can then be tailored and functionalized for use in sustainable sensor technologies. This chemical strategy not only reduces the environmental burden but also unlocks new possibilities for upcycling e-waste polymers into high-performance materials with desirable properties for advanced applications such as thin-film sensors. Recent research on e-waste derived sensors has demonstrated the use of graphite, metal nanocomposites, metal–organic frameworks (MOFs), and related materials for sensing applications.[32–34] Accordingly, polymers recovered from e-waste can provide a sustainable supply chain for developing sensors for environmental monitoring.

Beyond addressing environmental burdens, recycled and detoxified polymers gain their strongest relevance in the rapidly expanding IoT,[5] a domain projected to deploy billions of interconnected sensors across industrial, environmental, healthcare, and consumer sectors.[35] While the material demand per sensor may be relatively small, the cumulative scale of IoT deployment amplifies both the need and the opportunity for circular material utilization. In this context, recycled polymers offer a dual advantage: they ensure sustainable access to the vast material volumes required for large-scale fabrication, and they integrate seamlessly with flexible electronics, energy-efficient components, and wireless communication modules such as Bluetooth, enabling direct connectivity with smartphones for real-time monitoring.[36] These ideas are succinctly captured in Fig. 1.

Given the large, under-utilized polymeric fraction in e-waste, this perspective article inquires into its potential as a sustainable material platform for sensor technologies aimed at environmental monitoring. The discussion opens with a comparison between conventional semiconductor-based sensing technologies for environmental monitoring with polymer-based alternatives, highlighting differences in performance, scalability, and sustainability. We then elaborate on the various classes of polymers in e-waste and how we can gainfully utilize them as a viable and environmentally friendly feedstock for sensor development, followed by a discussion of design considerations and fabrication strategies for polymer thin films. In particular, we elaborate on the application of materials informatics and the relevance of e-waste polymeric sensors in

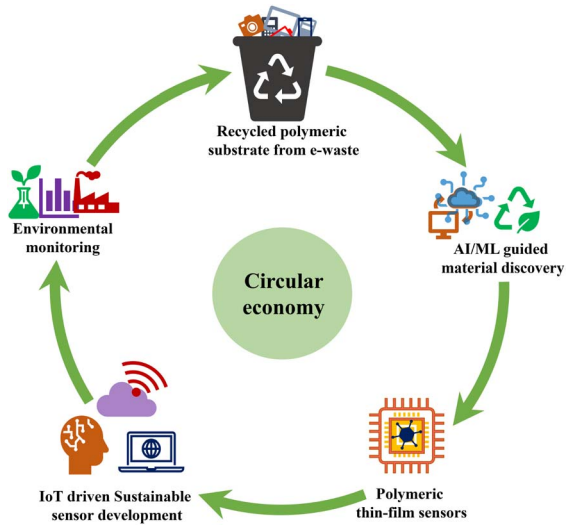

Fig. 1 A capsule of the envisioned idea: advancing circular economy by using e-waste polymers for sensor development.

the context of IoT boom. The article concludes by outlining future research avenues and the broader role of such ideas in advancing a circular economy.

2 Conventional semiconductor sensors *vs.* polymeric sensors

Sensors, being subsets of electronics, have traditionally been associated with conventional semiconductors such as silicon. In terms of performance, conventional semiconductors are indeed excellent, characterized by high sensitivity, accuracy, stability, and fast response times.[37] The success of these sensors has been based on their characteristic ability to convert physical or environmental parameters (like temperature, light, or pressure) into electrical signals that can be processed by an electronic device. However, for feedback based on certain responses (*e.g.* colorimetric, chemical, *etc.*) polymeric sensors could be more apt choices. There is enormous potential to tailor the structural, functional and chemical properties of polymers across a diverse spectrum.[38] Hence, polymers are being increasingly recognized as highly promising materials for the development of next-generation sensor devices.[39,40]

Table 1 provides a comparative examination of conventional semiconductor sensors and polymer-based sensors for the purpose of environmental monitoring. Although semiconductor sensors are reliable and accurate, their manufacturing processes are intricate, necessitating cleanroom facilities and high-vacuum systems, restricting their economic viability for developing countries.[41,42] On the other hand, polymer sensors offer simplified processing, customization potential, and align with cost-effective manufacturing settings. Upon extraction and purification, these polymers are amenable to engineering into versatile nanocomposites through chimie douce (soft chemistry) methodologies,[43] which function under mild and energy-efficient conditions. Their intrinsic flexibility, low glass transition temperatures, and adjustable surface characteristics render them particularly suitable for the development of scalable, printable, and conformable sensor platforms.[44,45] Therefore, in recent years, sensors based on polymers have gained substantial recognition in the field of environmental monitoring.[46–48]

An ideal sensor platform relies on materials that integrate several properties, such as electrical conductivity, dielectric permittivity, mechanical compliance (flexibility/stretchability), surface wettability, optical characteristics (*e.g.* refractive index, absorbance, fluorescence quantum yield, *etc.*), and chemical functionality, to enable high sensitivity, selectivity, stability and fast response/recovery times.[49–51] These properties govern charge mobility, analyte-to-signal conversion efficiency, light–matter interaction, and interface interactions, which are critical for applications in resistive, capacitive, piezoelectric, electrochemical, and optical sensors (*e.g.* colorimetric, fluorescent, or plasmonic platforms). In this context, the degree of tunability

Table 1 Comparative analysis of conventional semiconductor sensors and polymeric sensors for environmental monitoring

Features	Semiconductor sensors	Polymeric sensors
Fabrication processes	Epitaxy, photolithography, and chemical vapor deposition	Soft lithography, injection molding, and inkjet printing
Equipment requirement	Cleanroom and vacuum systems	Solution-based processes (drop-cast, spin-coating, *etc.*)
Fabrication cost	High due to process complexities	Low due to simpler, low-end capital equipment
Processing temperature	Typically >400 °C	Typically <150 °C
Tunability	Limited and involves compositional engineering, doping, applying fields, *etc.*	High and chemically modifiable through molecular design
Environmental impact	High, as semiconductor manufacturing processes release high amounts of greenhouse gases	Low to moderate, especially if recycled
Scalability	Limited, as deposition processes are sophisticated	Highly scalable, as solution-based large area coating processes can be used
Substrate versatility	Narrow (often rigid)	Broad (including flexible or stretchable)
Suitability for IoT	Moderate (rigid and energy-intensive)	High (flexible, scalable, and low-power)
Recyclability	Current methods are minimal, expensive, and environmentally unfriendly	Easier, as polymers have much lower melting and glass transition temperatures

offered by polymers is far greater, due to their diverse molecular structures and the presence of reactive functional groups along their backbones, enabling various sensing responses such as adsorption, chemical reaction, charge transport, *etc.* The tunability in conventional semiconductor materials is limited to use of methods like addition of dopants, which pose significant engineering hurdles for integrating materials with different growth conditions and inherent defect structures.[52]

Kalpathy *et al.*[53,54] have reported that polymers such as poly(3,4-ethylene dioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) and polyaniline can selectively adsorb heavy metal ions from aqueous solutions upon dip-coating, based on the ligation of metal ions with functional groups within the polymer matrix. Employing a straightforward drop-cast fabrication technique, these polymer-based sensors facilitate highly sensitive detection across a broad concentration range, thereby offering a facile, scalable, and economically viable solution for water quality monitoring. Similarly, Gualandi *et al.*[55] demonstrated that conducting polymers can combine polymer flexibility with semiconductor-like conductivity, enabling real-time, noninvasive chemical sensing. Their biocompatibility and efficient signal transduction make them promising materials for wearable sensors, particularly in sweat analysis.[55] Additionally, recent advances in polymer nanocomposites, such as graphene–polymer hybrids, improve sensor multifunctionality and performances in various contexts.[56,57]

As highlighted by Cichosz *et al.*, polymers can reversibly or irreversibly respond to diverse external stimuli, including pH, temperature, ions, light, and mechanical stress, making them highly adaptable for sensing applications.[58] Their ability to form various morphologies such as films, gels, and nanoparticles enhances functional flexibility, allowing polymers to serve as ideal matrices for embedding functional dyes, conductive fillers, or ion-selective elements. This versatility underpins the broad applicability of polymer-based sensors, which have been extensively investigated over the past decade for use as gas sensors, ion-selective sensors, pH sensors, temperature sensors, humidity sensors, and biosensors.[55,56,58–61] The market for smart polymers is experiencing significant expansion owing to their applications in healthcare, environmental monitoring, wearable technology, and sustainable materials. Going forward, the focus of polymeric sensor research ought to be on recycled and/or biodegradable polymers to reduce environmental footprint. Expanding on this concept, Gao *et al.* have demonstrated that biomass-derived biodegradable polymers and biomass-based carbon materials can be used for electronic and energy-storage applications with performance comparable to that of conventional systems while simultaneously enhancing resource efficiency and end-of-life recyclability. These findings underscore the potential of such green materials to serve as viable substitutes for synthetic, petrochemical-based polymers in the development of next-generation sustainable devices.[62]

Notwithstanding their limitations, conventional semiconductor-based electronics cannot be replaced abruptly, as technologies based on silicon-like materials have matured over several years. However, such technologies are not viable for all countries, as only a few countries are manufacturing the relevant components while several others import them. Hence, for a sustainable future, it is necessary to have locally produced sensors in most countries. Given the global drive to process electronics at low temperatures and/or in a recyclable manner, polymers would serve as an apt choice for next-generation sensor materials. Life cycle assessment (LCA) studies have consistently indicated that replacing virgin petrochemical polymers with recycled or bio-based analogues can substantially reduce embodied energy and associated greenhouse-gas emissions while preserving acceptable functional performance.[63,64] In light of the global imperative to manufacture and process electronic devices at reduced temperatures and/or in formats that are recyclable, polymeric materials, particularly those that are recycled or readily recyclable, emerge as highly suitable candidates for next-generation sensor platforms.

3 E-waste derived polymers: a sustainable solution for sensing applications

E-waste contains a substantial reservoir of valuable polymeric materials, as components such as PCBs, device casings, keyboards, capacitors, and display panels consist of various plastics and polymers. These polymers make up a significant proportion (25–30%) of e-waste by mass.[65] Polymers recovered from these sources, unlike virgin polymers, exhibit highly tunable electrical, mechanical, chemical, and optical properties. This tunability enables researchers to design polymer-based sensors with tailored sensitivity, selectivity, flexibility, and stability to detect a wide range of environmental targets.[66,67] Experimental demonstrations in the broader recyclable-sensor literature indicate that polymer matrices derived from recycled or recyclable feedstocks can provide the mechanical and dielectric reliability required for sensing, provided they are integrated into appropriate device architectures. Polymer-assisted flexible sensors based on commodity or recyclable polymers (*e.g.*, polyesters, PVA, *etc.*) maintain stable strain, pressure or temperature sensitivity over repeated deformation and even multiple recycling/reconstruction cycles, confirming that robust sensing does not require virgin polymer substrates. In parallel, studies on polymer and hydrogel-based flexible sensors show that long-term electrical and mechanical stability under humidity, mechanical cycling and environmental exposure is primarily governed by encapsulation and multilayer device design, with fully encapsulated devices retaining stable resistance and signal response over extended storage and operation. Aradoaei *et al.* demonstrated that thermoplastic carcass plastics recovered from WEEE can be compounded with talc, fly ash and elastomers to give composites with tailored dielectric properties (permittivity >5 and loss factor >0.04) that meet electromagnetic shielding requirements for electrical/electronic components in electric vehicles.[68]

There are about 15 different types of plastics in WEEE, such as polycarbonate (PC), ABS, polystyrene (PS), and so on.[69] The list of polymers in WEEE and their sources are given in Table 2. A significant fraction of the recovered polymers consists of

Table 2 Common polymers found in waste electrical and electronic equipment (WEEE)

Polymer type	WEEE source components	Ref.
Acrylonitrile Butadiene Styrene (ABS)	Computer/printer housings, TV casings, electrical casings, *etc.*	94 and 95
High-impact polystyrene (HIPS)	TV/monitor backs, refrigerator liners, audio equipment, *etc.*	95
Polycarbonate (PC)	Optical media (CD/DVD), electrical housings, LEDs, screens, *etc.*	96 and 97
Polypropylene (PP)	Cable insulation, capacitors, some appliance parts, *etc.*	67
Polyethylene (PE: HDPE and LDPE)	Cable insulation, appliance components, connectors, *etc.*	67 and 95
Polyvinyl chloride (PVC)	Cable sheathing, hoses, flexible insulation, *etc.*	95
Polyethylene terephthalate (PET)	Transparent display panels, some housings/insulation, *etc.*	67 and 94
Polymethyl methacrylate (PMMA)	Display screens, indicator lights, *etc.*	97 and 98
Polytetrafluoroethylene (PTFE)	Wire insulation (high-temp), gaskets in electronics, *etc.*	67 and 97
Polyamides (PA, *e.g.*, nylon)	Connectors, gears, cable ties, durable internal parts, *etc.*	67 and 95
Polyoxymethylene (POM)	Gears, precision printer parts, camera components, *etc.*	67
Polyphenylene oxide (PPO)	Electronic enclosures, electrical components, *etc.*	97
Polyurethane (PU)	Foams, adhesives/potting compounds in electronics, *etc.*	67 and 97
Thermosetting resins (epoxy)	PCBs, encapsulation, potting materials in electronic devices, *etc.*	99 and 100

thermoplastics, which can be readily melted again and reformed, allowing them to be utilized in molding, coating, and printing applications.[70] This reprocessability makes them excellent candidates for a wide range of sensing platforms, including electrical, optical, mechanical, infrared, and colorimetric systems. From a chemical interaction perspective, the diverse functional groups present in e-waste-derived polymers offer significant advantages. Applying the Hard–Soft Acid–Base (HSAB) theory, these polymers can engage in selective interactions, such as complexation, chelation, and surface affinity, with target analytes based on their chemical hardness, thereby enhancing selectivity across different sensing mechanisms.[71] Such chemical versatility also supports the design of multiplexed "strip-type" test beds, where multiple polymer-based sensing elements can be integrated for simultaneous, multi-analyte detection.[53,54]

Thermoset polymers, primarily epoxy resins reinforced with glass fibers, account for approximately 60–70% of the non-metallic fraction of PCBs.[72] While their highly cross-linked network confers outstanding thermal stability and mechanical robustness, it simultaneously makes conventional recycling strategies both technically demanding and cost-intensive.[73,74] The complexity of recycling is further compounded by the incorporation of flame retardants, particularly halogenated additives, which exhibit poor compatibility with many established polymer recovery technologies and substantially contribute to the high energy demand associated with most documented e-waste polymer recycling processes. Accordingly, there is a pressing need for energy-efficient and economically viable recycling strategies capable of effectively processing additive-containing thermoset polymers. In this context, recent developments in chemical recycling methodologies, encompassing solvolysis,[75] glycolysis,[76] supercritical fluid processing,[77] as well as catalytic and enzymatic strategies, have enabled the depolymerization of crosslinked epoxy networks into reusable monomeric species. These recovered monomers can subsequently be valorized through incorporation into newly fabricated composite materials or rigid sensing components.[78]

The increasing number of independent studies demonstrating high depolymerization efficiencies, improved reaction selectivity, and compatibility with flame-retardant thermoset matrices indicates that these methodologies are progressing beyond isolated proof-of-concept implementations and are evolving into more robust, scalable, and broadly applicable processing frameworks. Importantly, while conventional thermoset depolymerization routes are often energy- and cost-intensive, newer economical strategies are rapidly emerging. For example, Yang *et al.* reported that anhydride-cured epoxy thermosets can be completely depolymerized in ethylene glycol at temperatures $\leq$140 °C using the commercially available, low-cost transesterification catalyst DBU (1,8-diazabicyclo[5.4.0] undec-7-ene), thereby substantially decreasing both the energy demand and catalyst-related expenses relative to earlier supercritical or high-temperature depolymerization strategies.[79] Continued progress in solvent system optimization, reaction engineering, and process integration is expected to further enhance process scalability and improve tolerance toward halogenated additives. A particularly significant recent development in the treatment of flame-retardant-containing PCBs is the solvothermal depolymerization strategy reported by Kalpathy *et al.*[31] This strategy enables the efficient isolation of brominated species as ionic salts (*e.g.*, KBr) while concurrently promoting the depolymerization of the epoxy matrix into value-added monomeric products, including bisphenol A (BPA) and *p*-isopropenyl phenol.

The recovered species can be valorized across a broad spectrum of high-performance material applications, including their use as constituents in adhesive formulations, protective and functional coating systems, and sensor platforms. In parallel, glass fibers reclaimed from PCB waste, whether employed as standalone reinforcing phases or incorporated within optically transparent resin matrices, demonstrate significant potential as nanocomposite encapsulant materials for photovoltaic thermal management.[80] Moreover, these glass fibers can function as both structural and functional components in foldable and flexible electronic devices.[81–83] Such composite materials can exhibit increased hardness and

enhanced haptic performance, analogous in principle to polymer-based active surface layers currently implemented in commercial foldable electronic devices, including Samsung's foldable smartphones.[44] In addition, techno-economic analyses (TEA)[84] suggest that solvothermal processing pathways with high solvent recovery efficiencies (greater than 90%) can attain cost parity with pyrolysis-based process configurations when accounting for the economic credits associated with polymer and metal recovery.[85,86] Although enzymatic recycling of thermosets is an emerging technology, with proof-of-concept demonstrations reported for polyurethanes and select epoxy systems,[87,88] its development remains at a relatively nascent stage when compared with poly(ethylene terephthalate) (PET) hydrolase-based approaches.

Consequently, this perspective article identifies chemically driven recycling pathways as the most viable near-term strategy for achieving circularity in thermoset polymers derived from electronic waste. As recycling technologies continue to mature, the costs associated with repolymerizing plastic waste for application in sensor fabrication are expected to decrease to a point where this strategy becomes economically viable. Thus, a broader vision of urban mining that extends the concept beyond metals is necessary, to include polymers as critical feedstocks for sensing applications. Looking ahead, the integration of artificial intelligence (AI)-driven material design could further accelerate innovation (for example, by enabling the development of phase-change materials derived from e-waste polymers), thus opening up entirely new pathways for sustainable, next-generation sensor technologies. Together, recycled thermoplastics and epoxy derivatives open sustainable pathways for fabricating composite-based sensing platforms with tailored flexibility and robustness. Consequently, they constitute a noteworthy resource stream that can be converted into high-value sensing materials, thereby simultaneously addressing the growing e-waste crisis.

A legitimate concern for e-waste-derived polymers is the presence of "legacy" additives (*e.g.*, brominated flame retardants, plasticizers, metal stabilizers, *etc.*) that are known to persist in recycled WEEE plastics and, if unmanaged, can migrate or leach under environmental exposure. This risk is well recognized in the literature and is not unique to sensor applications but applies broadly to any reuse of recycled polymers, including construction materials, consumer products, and composites.[89–91] However, mitigation requires material purification, careful additive choice, binding or encapsulation strategies, and rigorous leaching/toxicity testing to ensure environmental and human safety over the device lifetime.[92,93] Recent reports suggest that solvothermal debromination can achieve >95% bromine removal from waste PCBs, nearly eliminating brominated flame retardants prior to polymer recovery.[31] Overall, the safe use of e-waste-derived polymers in sensors and other applications depends not on excluding recycled materials but on appropriate purification, informed material selection, device-level encapsulation, and regulatory compliance. When these factors are integrated into the design process, leaching risks can be effectively minimized, supporting the responsible and sustainable reuse of polymers in the context of circularity.

Although this perspective article primarily envisages the use of e-waste–derived polymers for sensor development as a forward-looking strategy, the broader domain of electronics manufacturing could likewise benefit from the implementation of vitrimer-based epoxy systems.[101] Vitrimers are a new class of covalently crosslinked polymers that incorporate dynamic covalent bonds (such as ester, imine, or disulfide linkages).[102,103] Like conventional thermosets, they maintain the strength and dimensional stability of a crosslinked network, but above a certain activation temperature these dynamic bonds undergo exchange reactions that permit reshaping, welding, and reprocessing. This unique adaptability may ease the end-of-life waste management of thermoset-based e-waste plastics. Importantly, such vitrimers could fundamentally overcome the current limitations of thermosets, paving the way for fully recyclable and repairable electronic components.[104,105] Zhang *et al.*[101] introduced vitrimer-based printed circuit boards (vPCBs) using transesterification networks that enable repair, reuse, and recycling while maintaining industry-standard electrical and mechanical properties. After fabricating and testing the vPCBs, they demonstrated a solvent-swelling recycling process that allowed the materials to be separated and reused, achieving 98% polymer recovery, 100% fiber recovery, and 91% solvent recovery. This closed-loop approach paves the way for sustainable and circular PCB manufacturing.[101] These emerging research-based solutions further empower the vision of sensor technologies based on recycled e-waste polymers.

Recycled polymers do not necessarily need to be universally converted into intrinsically semiconducting materials. Instead, they are most commonly functionalized *via* surface and interfacial engineering to impart sensing capabilities, whereas the actual signal transduction is typically carried out by established inorganic or organic conductive materials. In practical applications, insulating polymer matrices, regardless of whether they are virgin or recycled, are typically endowed with functional activity through surface modification strategies.[106] Common approaches include plasma treatment or chemical grafting, which introduce polar or otherwise chemically reactive functional groups at the polymer–air interface. Such surface functionalization enhances interfacial adhesion, wettability, and analyte affinity, thereby converting an intrinsically inert polymer film into an active sensing interface. In applications where electrical conductivity is required, composite design strategies are generally preferred. In such systems, recycled polymers serve as mechanically robust, easily processable host matrices that support percolating networks of conductive fillers, including carbon black, graphene, carbon nanotubes (CNTs), and metal oxides. These fillers confer piezoresistive, chemiresistive, or capacitive transduction functionalities, while simultaneously tolerating and compensating for the impurity profiles that are intrinsic to recycled polymer feedstocks.[107,108]

While functional fillers and surface modifications enable precise tuning of polymer properties for sensing applications, the long-term operational stability and reliability of sensors fabricated from recycled polymers constitute a fundamental

prerequisite for their successful implementation and continuous performance in real-world field applications. Prior to deployment in practical sensing scenarios, both the polymeric constituent materials and the complete device architectures should be subjected to standardized accelerated ageing protocols[109] conducted under rigorously controlled, extreme environmental conditions (*e.g.*, elevated relative humidity, intensified ultraviolet irradiation, extreme pH values, and exposure to application-relevant chemical fouling agents). The degradation kinetics and associated failure modes identified in these accelerated ageing studies can subsequently be extrapolated to moderate, application-relevant conditions over extended operational timescales by employing established empirical or mechanistic kinetic models. This methodological framework facilitates conservative, quantitatively grounded prediction of sensor lifetime and provides a basis for the rational optimisation of materials selection, encapsulation or packaging strategies, and the overall device architecture.

4 Use of materials informatics, soft processing, and applications in IoT systems

In addition to outlining current opportunities for e-waste-derived sensing materials, it is important to consider how key bottlenecks, material heterogeneity, process complexity and product purity can be systematically mitigated. Practical strategies include information-rich sorting of polymer streams (for example, QR-code or digital-watermark identification introduced at the manufacturing stage to enable class-specific separation),[110] upgrading of mixed plastics through controlled depolymerisation to pyrolysis oils or monomers followed by chromatographic or distillation-based purification, and application-oriented chemical modification of recycled backbones to introduce functional groups tailored for sensing and IoT integration. Rumetshofer and Fischer highlight how information-based tracking systems, such as physical markers, digital product passports, and blockchain, can provide the material history and composition data needed to manage heterogeneous plastic streams and enable higher-quality, application-specific recycling loops.[111] Recent industrial deployments also highlight the use of digital watermarking, where invisible barcodes embedded in packaging encode the polymer type and recommended recycling route, enabling optical systems to route items into polymer-specific streams even for complex, multi-layer packaging. In parallel, state-of-the-art sorting lines integrate NIR and visible-light spectroscopy, hyperspectral imaging, and AI-based classification to generate "molecular fingerprints" for common packaging polymers and separate PET, high density polyethylene (HDPE), PP and other resins at throughputs above 3 tons per hour per sorting unit with typical purities exceeding 95% when streams are properly prepared.[112] This 2025 industry report therefore illustrates that heterogeneity in mixed plastic packaging is increasingly a problem of technology deployment and data infrastructure, rather than a fundamental barrier to obtaining application-relevant, polymer-specific fractions for advanced recycling and upcycling.[112]

Combinatorial approaches using materials informatics would also serve as a powerful strategy to address the chemical heterogeneity of recycled e-waste polymers and to accelerate material optimization. Given the various types of polymers present in e-waste, such approaches are crucial alternatives to conventional trial-and-error and/or rational design methodologies for sensor applications. Combinatorial methods involve synthesis of extensive libraries of polymer variants with systematic alterations in the composition, structure, and processing. These methods facilitate high-throughput screening to identify optimal materials with specifically tailored sensitivity, selectivity, stability, and flexibility. This approach effectively reduces the time and cost associated with sensor development, while helping to elucidate the structure–property–performance relationships.[113–119]

Potyrailo *et al.* employed a combinatorial screening methodology for evaluating polymeric sensing materials using battery-free RFID (Radio Frequency Identification) sensors.[120] In their study, a 6 × 8 matrix of polymer-coated RFID tags was employed to systematically explore the combined effects of polymeric plasticizers and annealing temperature on the performance of materials. This RFID-based sensing platform facilitated a rapid and cost-efficient assessment of the dielectric properties of the developed sensing materials, underscoring its efficacy in high-throughput optimization within sensor development. Furthermore, computational combinatorics and materials informatics augment this process by enabling pre-screening of candidates *via* platforms such as PolyInfo, Gaussian, and Matminer, with the aim of predicting critical properties such as adsorption energies, solubility, and dielectric responses.[121–124] The integration of active ML algorithms with real-time experimental feedback accelerates material discovery, reduces experimental workload, and addresses the variability of recycled feedstocks.[123] Taken together, these combinatorial strategies establish a scalable, data-driven framework to efficiently identify and optimize polymers derived from e-waste for advanced environmental sensing applications.[115,118,119]

Following the combinatorial selection of promising polymers from e-waste, the enhancement of these materials through nanofiller incorporation offers new functional possibilities. Although the integration of nanofillers into virgin polymer matrices is well established,[125–127] the deliberate coupling of functional nanomaterials, such as quantum dots (QDs), CNTs, and MOFs, with polymers recycled specifically from e-waste remains largely underexplored. This presents a critical knowledge gap and a promising opportunity: e-waste-derived polymers, which already have diverse chemical characteristics, could benefit significantly from the introduction of nanofillers to enhance the sensor performance. Process complexity in mixed-plastic recycling can be reduced by moving from generic flowsheets to application-oriented chemical upcycling, where the polymer backbone is selectively edited or functionalised so that the recycled material directly matches target performance (*e.g.*, introducing polar, crosslinkable or depolymerisable motifs for sensing and IoT uses).[128,129] Recent reviews on

catalytic and photochemical upcycling emphasise that "polymer editing" strategies, such as metathesis, backbone insertion of cleavable linkages, or tandem depolymerisation–repolymerisation, allow cleverly modified structures to simultaneously simplify process steps and upgrade low-value mixed waste into higher-value, functionally tailored polymers.[130,131]

Drawing parallels from analogous studies, the inclusion of QDs could impart photoluminescence for optical detection,[57,132,133] CNTs could boost the electrical conductivity for resistive sensing,[134–136] and MOFs could confer selective adsorption and high porosity for chemical selectivity.[137–139] As highlighted in the work of Kar *et al.*, carbon dots (CDs) and related QDs have emerged as promising photoluminescent nanomaterials owing to their high photostability, excellent biocompatibility, excitation-dependent multicolor emissions, and ease of surface functionalization.[140] These features enable sensitive and selective detection of chemical and biological analytes. Their tunable fluorescence, coupled with robust chemical stability and water dispersibility, makes them attractive candidates for incorporation into polymeric or hybrid nanocomposites to enhance optical sensing performance.[140] Similarly, Zhang and Wang's benzoxazole-functionalized conjugated mesoporous polymer demonstrated that tailored pore structure and heteroatom-rich recognition sites can deliver rapid, selective fluorescence quenching toward Fe^{2+} and Fe^{3+} ions, achieving low detection limits of 0.56 μM and 0.72 μM, respectively.[141] These studies underscore the value of structural design in achieving high-performance sensing. Studies directly addressing recycled polymer functionalization for sensing applications are scarce. Nevertheless, the aforementioned examples suggest that recycled polymers could also be functionalized or incorporated with CDs, QDs, MOFs, or other nanofillers to significantly enhance their optical, electrochemical, or multi-analyte sensing capabilities.

For highly mixed or contaminated polymer fractions, the dominant route today is bulk conversion to pyrolysis oils, which yields broad, low-selectivity product streams that must compete directly with conventional petrochemical feedstocks.[128,142] Recent analytical work, however, shows that these complex oils can be deconvoluted into well-defined chemical families and boiling-range cuts using high-resolution and two-dimensional gas chromatography (GC), providing a basis for distillation–chromatography cascades or continuous chromatographic separation that isolates high-purity monomer or oligomer fractions.[143,144] In this perspective, purity is therefore treated as an engineering variable: controlled depolymerisation followed by tailored fractionation can deliver reagent-grade streams suitable for re-polymerisation or higher-value chemical applications, rather than a single undifferentiated oil.

With regard to processing routes, soft processing techniques such as fabrication of thin-film structures *via* solution casting would be natural choices for developing scalable and flexible polymer-based sensor platforms for environmental monitoring. Thin films not only maximize the surface-to-volume ratio, critical for enhancing analyte interaction and transduction efficiency, but also support scalable, low-temperature processing compatible with flexible substrates and diverse sensing platforms.[145] Other suitable techniques are inkjet printing, screen printing, drop casting, dip coating, and soft lithography.[53,146,147] These methods are particularly advantageous for processing recycled polymers derived from e-waste, as they operate under mild thermal and chemical conditions that help preserve the functional integrity of upcycled materials. Additionally, such soft-processing techniques are energy-efficient and compatible with green chemistry principles, minimizing waste, and the overall environmental impact.

A compelling direction for next-generation sensor technologies is integration with IoT ecosystems.[127,148,149] These systems would require interfacing polymeric films with mobile and cloud-based technologies to support real-time environmental monitoring through communication devices. Polymers would be particularly suitable for these systems, given their compatibility with diverse substrates such as paper, textiles, and flexible electronics. Although each sensor uses only a tiny amount of polymer, the IoT boom (with billions of sensors needed for thousands of applications) would mean that the total amount of polymer required would be very large. Therefore, it is important to consider how these polymers are produced, reused, or recycled in a sustainable way and to ensure that industries take responsibility for their use. If e-waste polymers can be reused in valuable ways, it will not only support the IoT market but also contribute to a circular global economy and the achievement of the United Nations SDGs worldwide.

Roadmap for translating e-waste derived polymers in IoT sensors:

Recycled polymers derived from electronic waste constitute a widely available feedstock for the development of sustainable sensing technologies; however, their deployment in IoT-enabled environmental monitoring applications requires a structured and scalable workflow that connects raw waste streams to operational sensor networks. Fig. 2 depicts this development roadmap, delineating sequential stages starting from polymer recovery to integration within an IoT system. The initial phases involve both manual and automated disassembly of electronic waste components (*e.g.*, printed circuit boards, device casings, *etc.*) to isolate polymer-rich fractions. These fractions are subsequently subjected to washing and mild chemical cleaning, and targeted de-polymerization. Solvothermal or enzymatic depolymerization of crosslinked thermosetting polymers enables the generation of monomeric or oligomeric species, while concomitant metal recovery is achieved through established hydrometallurgical processes.[150] Subsequent pre-processing steps, including pulverization and granulation, enable the fabrication of functional sensing matrices from the recovered e-waste-derived polymers. These matrices are then systematically optimized through combinatorial screening methodologies. To further enhance their performance, the polymers can be tailored through targeted chemical modification, surface functionalization, or incorporation of functional fillers, thereby improving their physicochemical and sensing properties under application-relevant conditions.[151,152]

Once polymers with suitable functionalities are identified, they can be processed into sensing devices using low-

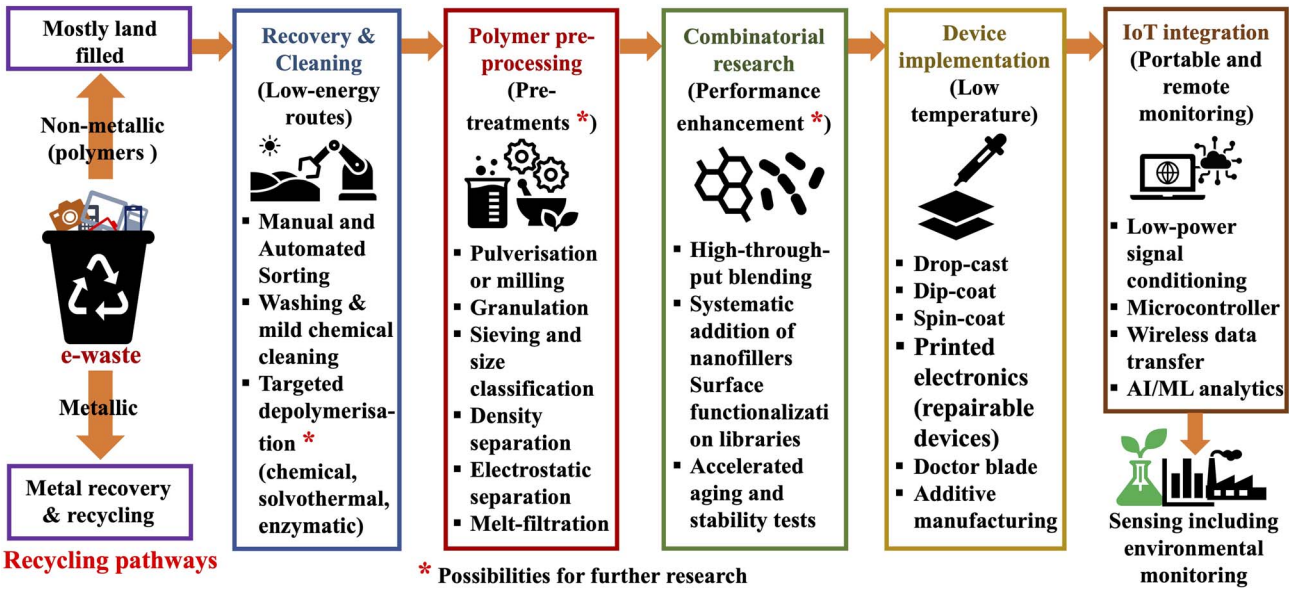

Fig. 2 Schematic roadmap for translating recycled e-waste polymers into IoT-enabled sensing systems for environmental monitoring.

temperature deposition methods such as drop-casting, spin-coating, and dip-coating. These platforms can be engineered to detect a wide spectrum of targets, including inorganic contaminants (*e.g.*, heavy metals), biologically relevant species (*e.g.*, cells, pathogens, biomarkers, *etc.*), and environmental analytes (*e.g.*, nutrients, dissolved gases, organic pollutants, *etc.*), depending on the specific chemical or biorecognition elements incorporated. Owing to their mechanical flexibility, low processing temperatures, and compatibility with printed interconnects, polymer-based sensors can be seamlessly interfaced with low-power microcontrollers *via* standard digital communication buses and lightweight IoT protocols for real-time data streaming to cloud platforms and dashboards.[153] In practice, this makes polymers a far more "IoT-ready" materials platform than conventional rigid semiconductors, enabling compact, flexible, and easily scalable sensor deployments across diverse environments.

4.1 Life cycle perspective for chemically recycled epoxy polymers

In real-world settings, the life-cycle impacts of chemically recycled polymers depend strongly on the particular polymer involved, the regional electricity and heat production, and the exact design of the chemical recycling process. In the context of WEEE, particularly relevant material streams include: (i) FR-4 epoxy/fiberglass laminates derived from PCB substrates, (ii) ABS originating from monitors and household appliance housings, and (iii) polycarbonate/acrylonitrile–butadiene–styrene (PC/ABS) blends recovered from connectors and load-bearing structural components.[154,155] Epoxy–glass laminates constitute approximately 60–70% of the non-metallic fraction of PCBs[15] and are traditionally managed through high-temperature thermal treatment or disposal due to their thermoset nature and additive content. To contextualize the techno-economic feasibility of the approaches discussed in this perspective article, a screening-level LCA analysis is provided in Table S1 of the SI. This assessment uses epoxy resin, commonly employed as a PCB substrate material, as the material system for a representative case study. Comparable LCAs can be conducted on a case-by-case basis for other polymers, including the recycled e-waste derived polymer obtained after the pre-processing steps outlined in Fig. 2. Only those formulations and process windows that comply with predefined thresholds for embodied energy, CO_2 emissions per kilogram of product, or additional indicators of environmental burden (such as water use or resource depletion) are selected for subsequent experimental optimization. In this context, LCA outputs can be integrated as quantitative constraints in Design of Experiments (DoE), thereby restricting the experimental design space to combinations with low environmental impact and, in turn, guiding combinatorial screening toward sensor formulations that are optimized for sustainability.

From an LCA perspective, the economic break-even point between virgin and chemically recycled epoxy is primarily governed by solvent recovery efficiency and operating temperature. TEA of solvent-based recycling of engineering plastics from e-waste suggest that when solvent recovery exceeds roughly 90%, the savings from avoided virgin resin production and lower net energy demand can outweigh solvent regeneration costs, allowing recycled epoxy streams to approach or in favourable cases undercut the effective cost of conventional petro-epoxy.[63,64] This break-even condition is achieved when chemical recycling is benchmarked against energy- and capital-intensive thermal routes rather than against low-cost mechanical recycling.

Collectively, this screening-level LCA indicates that solvothermal depolymerization of epoxy-rich electronic waste, when integrated with high solvent recovery, materials-

informatics-guided resin reformulation, and low-temperature manufacturing, can enable approximately 40–60% reductions in cumulative energy demand and CO_2 emissions, while maintaining cost parity or conferring an economic advantage to PCB substrates and sensing applications. Enzymatic recycling emerges as a promising longer-term, complementary strategy for further decreasing the energy intensity; however, it is not yet a broadly mature or widely deployable alternative for epoxy-based systems.[84,87,88]

The recovery and reutilization of epoxy resins or other polymeric fractions derived from WEEE should therefore be conceptualized as a value-added resource management strategy rather than as an inherent economic liability. In line with this perspective, Ghasemi *et al.* integrated TEA and LCA for epoxidized sucrose soyate (ESS: a bio-based epoxy thermoset synthesized from sucrose and soybean oil). They demonstrate that, although its minimum selling price ($\approx$6.6–9.6 USD per kg) exceeds that of conventional BPA-based epoxy at smaller production scales, increasing the production capacity to 10 ton/h, representative of industrially relevant throughput, shifts ESS into a cost range that is economically competitive with petroleum-derived epoxy resins, while simultaneously achieving reductions in global warming impacts. This aligns with the perspective that non-conventional epoxy value chains, whether bio-based, like ESS, or built on chemically recycled WEEE-derived polymers, need process-specific TEA/LCA, but can plausibly approach cost parity with conventional epoxy while delivering superior environmental performance when appropriately designed and scaled.[156]

5 Prospects and innovation avenues

The demand for scalable, sustainable, and locally manufacturable sensors is expected to increase as environmental regulations become increasingly stringent on a global scale. As industrialized countries retreat from large-scale manufacturing due to ecological considerations, the responsibility for innovation is increasingly transferred to emerging economies. Electronics based on plastics, particularly those derived from e-waste, present an economically viable, accessible, and environmentally sustainable alternative.

Looking ahead, this approach opens up compelling research avenues. Recycled polymers from e-waste can serve as versatile precursors for designing advanced nanocomposites, which can be functionalized to suit diverse sensing applications. To ensure environmental and operational integrity, sensor design and fabrication must align with well-established sustainability principles, particularly the 'Twelve Principles of Green Chemistry'.[157,158] This includes adopting non-toxic chemicals and solvents, maximizing atom economy, minimizing energy input through efficient processing, and designing pathways that reduce hazardous by-products and downstream waste. Techniques such as chimie douce would not only lower the processing temperature but also minimize energy input, making them ideal for scalable, low-impact fabrication. Where energy is required for steps such as heating, cooling, or drying, tapping into renewable sources, like solar-assisted drying or thermal recovery systems, would further enhance the environmental profile of the process. In addition, implementing zero liquid discharge (ZLD) strategies[159,160] would promote circularity by minimizing liquid effluents.

Together, these approaches meet nearly nine out of the twelve green chemistry principles, underscoring the strong alignment between sensor innovation and ecological responsibility. This holistic framework not only enables the development of application-specific, high-performance polymeric sensors but also opens doors to a new era of circular, intelligent materials design. To realize this vision, policymakers should promote the use of recycled plastics from e-waste in sensor technologies and provide support to start-ups developing environmental IoT solutions using recycled polymers. Furthermore, it is important to facilitate cross-disciplinary research integrating materials science, electronics, materials informatics, IoT and sustainability.

6 Conclusion

This article outlines a strategy for promoting sustainability and circular economy by the use of recycled e-waste polymers for sensor development. As critical industries face mounting regulatory pressures, rising operational costs, and the transition to Industry 5.0, there is a growing need for affordable, sustainable, and scalable sensor platforms to support real-time environmental monitoring. Plastic electronics derived from recycled e-waste present a promising solution, offering low temperature processability, material tunability, and compatibility with IoT systems while minimizing ecological impact. In contrast to traditional semiconductor-based sensors, polymeric sensors are easier to manufacture and scale up, as well as better suited to the infrastructure and economic conditions of developing regions. This perspective article advocates leveraging e-waste-derived polymers to develop next-generation sensors by clever use of combinatorial methods, soft processing techniques, and capitalizing on the IoT boom. These ideas align well with the principles of circular economy and the SDG mandates, particularly SDG 12 (Responsible Consumption and Production) and SDG 8 (Decent Work and Economic Growth). By emphasizing sustainable material choices, energy-efficient processing, and smart design integration, we envision a shift toward environmentally responsible, economically viable, and globally inclusive industrial ecosystems.

Author contributions

Berly Robert: conceptualization, methodology, investigation, visualization, data curation, writing – original draft. Suvitha S. Kumar: conceptualization, methodology, investigation, visualization, data curation, writing – original draft. Tiju Thomas: conceptualization, supervision, resources, funding acquisition, writing – review & editing, project administration. Sreeram K. Kalpathy: conceptualization, supervision, funding acquisition, writing – original draft, writing – review & editing, resources, project administration.

Conflicts of interest

There are no conflicts to declare.

Data availability

Certain additional data related to an unpublished patent are not publicly available at this time. All other data are based on previously published literature cited within the article.

Supplementary information (SI): LCA data and analyses on recycled epoxy polymers. See DOI: https://doi.org/10.1039/d5ta09015f.

Acknowledgements

The authors acknowledge funding from the following sources for research and deliberation on this topic: (1) Ministry of Education, Govt. of India, through the Swachhta Action Plan (SAP) scheme (grant numbers SAP22-IITM-056 and SAP22-IITM-057), (2) Ministry of Mines, Govt. of India, through the S&T program (Grant No. SNTMOM/1300/2024), (3) HSBC India through the Center for Resource Efficiency, Recyclability, and Circularity in Energy Transition, School of Sustainability, IIT Madras (Grant No. CR24251368CHHSBC008836), (4) Department of Science and Technology (DST), Govt. of India (Grant No. SP24251100MMDSTX008673), and (5) IIT Madras (Exploratory Research Project Grant No. RF24250539MMRFER008687 and Grant No. SB24250661MMIITM008673). The authors also gratefully acknowledge support from Anusandhan National Research Foundation (ANRF), formerly Science and Engineering Research Board (SERB), India through (a) National Post Doctoral Fellowship to Berly Robert (File Number: PDF/2023/002437) and (b) Research grant to Dr Tiju Thomas (SP24251713MMSERB008673). Suvitha S. Kumar acknowledges financial support under the JRF scheme (210510065876) from the University Grants Commission (UGC), Government of India as well as the Women in STEM fellowship from Hindustan Unilever Limited (HUL). We note that the images in this article were prepared using built-in tools, icons, and shapes available under a licensed Microsoft PowerPoint (Microsoft 365 Personal) subscription.

References

1 S. Tripathy, O. P. Kar and A. Pradhan, *Water, Air, Soil Pollut.*, 2025, **236**, 1–14.
2 M. Golovianko, V. Terziyan, V. Branytskyi and D. Malyk, *Procedia Comput. Sci.*, 2023, **217**, 102–113.
3 S. Luthra and S. K. Mangla, *Process Saf. Environ. Prot.*, 2018, **117**, 168–179.
4 K. C. Rath, A. Khang and D. Roy, *Advanced IoT Technologies and Applications in the Industry 4.0 Digital Economy*, CRC Press, 2024, pp. 1–28.
5 B. Robert and S. K. Kalpathy, *J. Water Process Eng.*, 2025, **75**, 107992.
6 P. K. Mukherjee, B. Das, P. K. Bhardwaj, S. Tampha, H. K. Singh, L. D. Chanu, N. Sharma and S. I. Devi, *Sci. Total Environ.*, 2023, **904**, 166630.
7 L. H. Xavier, M. Ottoni and L. P. P. Abreu, *Resour., Conserv. Recycl.*, 2023, **190**, 106840.
8 Y. Zhang, Q. Wang, N. Yalikun, H. Wang, C. Wang and H. Jiang, *Resour., Conserv. Recycl.*, 2023, **197**, 107087.
9 Geneva Environment Network, The Growing Environmental Risks of E-Waste, 2024, https://www.genevaenvironmentnetwork.org/resources/updates/the-growing-environmental-risks-of-e-waste/, Updated 9 Oct 2024.
10 V. Forti, C. P. Balde, R. Kuehr, G. Bel, N. Peagam and M. Ucci, The Global E-waste Monitor 2024: Rising E-waste, Missed Opportunities, 2024, https://ewastemonitor.info/the-global-e-waste-monitor-2024/, accessed: July 2025.
11 R. R. Pandey, A. Andola, H. Pandey, Y. Kashyap, A. Prakash, H. Nakanishi and R. K. Pandey, *J. Cleaner Prod.*, 2024, **457**, 142430.
12 World Health Organization, *Electronic Waste (E-waste) Fact Sheet*, 2023, https://www.who.int/news-room/fact-sheets/detail/electronic-waste-(e-waste), accessed July 2025.
13 S. Udayakumar, M. I. B. Abd Razak and S. Ismail, *Mater. Today: Proc.*, 2022, **66**, 3062–3070.
14 Y. Dong, J. Zan, H. Lin, *et al.*, *J. Environ. Manage.*, 2023, **348**, 119354.
15 A. K. Moe, J. Chungprempree, J. Preechawong, P. Sapsrithong and M. Nithitanakul, *Polymers*, 2022, **14**, 3531.
16 C. Ma, S. Kumagai, Y. Saito, T. Kameda and T. Yoshioka, *Green Chem.*, 2021, **23**, 6392–6404.
17 L. M. Martelo, M. M. Bastos and H. M. Soares, *Miner. Eng.*, 2024, **206**, 108529.
18 A. Manish and P. Chakraborty, *TerraGreen*, 2019, **12**, 22–28.
19 D. Gupta and S. Dash, *Soc. Responsib. J.*, 2023, **19**, 1595–1612.
20 R. R. Pandey, A. Andola, H. Pandey, Y. Kashyap, A. Prakash and R. K. Pandey, *ACS Sustainable Resour. Manage.*, 2025, **2**(7), 1228–1239.
21 M. Mohammed, D. Wilson, E. Gomez-Kervin, A. Petsiuk, R. Dick and J. M. Pearce, *Addit. Manuf.*, 2022, **50**, 102548.
22 V. Gaikwad, A. Ghose, S. Cholake, A. Rawal, M. Iwato and V. Sahajwalla, *ACS Sustainable Chem. Eng.*, 2018, **6**, 14432–14440.
23 A. Mtibe, T. C. Mokhena and M. J. John, *Curr. Opin. Green Sustainable Chem.*, 2023, **40**, 100762.
24 R. Flores-Campos, R. Deaquino-Lara, M. Rodríguez-Reyes, R. Martínez-Sánchez and R. H. Estrada-Ruiz, *Recycling*, 2024, **9**, 56.
25 P. R. Venkatesan, T. Shanmuga Priya, U. J. Alengaram and A. S. Aswathy, *Sustainable and Cleaner Technologies for Environmental Remediation: Avenues in Nano and Biotechnology*, Springer, 2023, pp. 177–191.
26 H.-G. Ni, S.-Y. Lu, T. Mo and H. Zeng, *Environ. Pollut.*, 2016, **214**, 70–76.

27 T.-Y. Li, J.-L. Ge, J. Pei, L.-J. Bao, C.-C. Wu and E. Y. Zeng, *Environ. Sci. Technol.*, 2019, **53**, 12495–12505.
28 E. Sahle-Demessie, B. Mezgebe, J. Dietrich, Y. Shan, S. Harmon and C. C. Lee, *J. Environ. Chem. Eng.*, 2021, **9**, 104943.
29 P. Kumar, S. Singh, A. Gacem, K. K. Yadav, J. K. Bhutto, M. A. Alreshidi, M. Kumar, A. Kumar, V. K. Yadav, S. Soni, *et al.*, *Toxicology*, 2024, **508**, 153904.
30 J. R. Strien, H. C. Genuino, M. C. van Eijk, P. J. Deuss and H. J. Heeres, *Energy Fuels*, 2024, **39**, 686–698.
31 S. K. Kalpathy, T. Thomas, R. Ravendran, M. M. Bhunia and S. Kumar, Debromination of Waste Printed Circuit Board, 2025, Indian Patent Application 202541002887, filed 13 January 2025.
32 M. Khalid, A. Tariq, M. A. Nauman, K. A. Aljaloud, A. H. Alqahtani, M. T. Alresheedi, M. Zubair, R. Hussain and M. Q. Mehmood, *Mater. Today Commun.*, 2024, **41**, 110751.
33 P. V. Vaishag, S. A. Mohandas, M. Mufeeda, P. Gangadharan and P. A. Rasheed, *ACS Sustain. Chem. Eng.*, 2023, **11**, 12771–12779.
34 M. S. Mondal, A. Paul and M. Rhaman, *Sci. Rep.*, 2023, **13**, 13798.
35 X. Luo, H. Tan and W. Wen, *Bioengineering*, 2024, **11**, 358.
36 Z. Luo, J. Xu, X. Zhou, Z. Wang, Y. Liu, S. Wang, S. Yuan, H. Zhang, B. He, J. Xin, *et al.*, *Adv. Devices Instrum.*, 2024, **7**, 0054.
37 Y. Xu, X. Hu, S. Kundu, A. Nag, N. Afsarimanesh, S. Sapra, S. C. Mukhopadhyay and T. Han, *Sensors*, 2019, **19**, 2908.
38 B. Adhikari and S. Majumdar, *Prog. Polym. Sci.*, 2004, **29**, 699–766.
39 K. A. Pasalwad, N. Baby, A. Edjenguele, S. Sadhasivam, G. Palanisamy, S. S. Magdum, S. Thangarasu and T. H. Oh, *J. Mater. Chem. A*, 2025, **13**, 23248–23311.
40 A. Fattah-alhosseini, R. Chaharmahali, S. Alizad, M. Kaseem and B. Dikici, *Hybrid Adv.*, 2024, **5**, 100178.
41 J. Zikulnig, S. Carrara and J. Kosel, *Sci. Rep.*, 2025, **15**, 10866.
42 X. Hu, G. Li and J. C. Yu, *Langmuir*, 2010, **26**, 3031–3039.
43 C. Sidhoum, D. Ihiawakrim, M. Haouas, D. Constantin, F. Schosseler, M. Odziomek, K. Vertchik, A. Leforestier, C. Sanchez and O. Ersen, *Chem. Mater.*, 2025, **37**(15), 5454–5465.
44 L. Li, L. Han, H. Hu and R. Zhang, *Mater. Adv.*, 2023, **4**, 726–746.
45 I.-A. Pavel, S. Lakard and B. Lakard, *Chemosensors*, 2022, **10**, 97.
46 M. W. Alam, S. Islam Bhat, H. S. Al Qahtani, M. Aamir, M. N. Amin, M. Farhan, S. Aldabal, M. S. Khan, I. Jeelani, A. Nawaz, *et al.*, *Polymers*, 2022, **14**, 2164.
47 S. Tajik, H. Beitollahi, F. G. Nejad, Z. Dourandish, M. A. Khalilzadeh, H. W. Jang, R. A. Venditti, R. S. Varma and M. Shokouhimehr, *Ind. Eng. Chem. Res.*, 2021, **60**, 1112–1136.
48 Y. Wang, A. Liu, Y. Han and T. Li, *Polym. Int.*, 2020, **69**, 7–17.
49 F. Han, T. Wang, G. Liu, H. Liu, X. Xie, Z. Wei, J. Li, C. Jiang, Y. He and F. Xu, *Adv. Mater.*, 2022, **34**, 2109055.
50 Y. Chang, X. Qi, L. Wang, C. Li and Y. Wang, *Micromachines*, 2023, **14**, 2116.
51 V. P. Elanjeitsenni, K. S. Vadivu and B. M. Prasanth, *Mater. Res. Express*, 2022, **9**, 022001.
52 W. Walukiewicz, *Phys. B*, 2001, **302**, 123–134.
53 S. S. Kumar, K. Vidhya, T. Thomas and S. K. Kalpathy, *Polym. Adv. Technol.*, 2025, **36**, e70365.
54 S. K. Kalpathy, T. Thomas, K. V. Vidhya and S. S. Kumar, Polymer-Based Sensor and Method for Detecting Heavy Transition Metals, Indian Institute of Technology Madras (IIT Madras), 2023, Indian Patent 566801, Application No. 202341040751, https://iprsearch.ipindia.gov.in/PublicSearch/PublicationSearch, granted 15 June 2023.
55 I. Gualandi, M. Tessarolo, F. Mariani, L. Possanzini, E. Scavetta and B. Fraboni, *Polymers*, 2021, **13**, 894.
56 H. J. Salavagione, A. M. Díez-Pascual, E. Lázaro, S. Vera and M. A. Gómez-Fatou, *J. Mater. Chem. A*, 2014, **2**, 14289–14328.
57 A. Kovalchuk, K. Huang, C. Xiang, A. A. Martí and J. M. Tour, *ACS Appl. Mater. Interfaces*, 2015, **7**, 26063–26068.
58 S. Cichosz, A. Masek and M. Zaborski, *Polym. Test.*, 2018, **67**, 342–348.
59 B. F. Monea, E. I. Ionete, S. I. Spiridon, D. Ion-Ebrasu and E. Petre, *Sensors*, 2019, **19**, 2464.
60 C. M. Costa, V. F. Cardoso, P. Martins, D. M. Correia, R. Goncalves, P. Costa, V. Correia, C. Ribeiro, M. M. Fernandes, P. M. Martins, *et al.*, *Chem. Rev.*, 2023, **123**, 11392–11487.
61 P. N. Immanuel, S.-J. Huang, Y. Adityawardhana and Y.-K. Yen, *Coatings*, 2023, **13**, 1326.
62 M. Gao, C.-C. Shih, S.-Y. Pan, C.-C. Chueh and W.-C. Chen, *J. Mater. Chem. A*, 2018, **6**, 20546–20563.
63 A. Gouda, N. Merhi, M. Hmadeh, T. Cecchi, C. Santato and M. Sain, *Global Challenges*, 2025, **9**, 2400240.
64 H. Gao, X.-M. Zeng and H.-G. Ni, *J. Environ. Manage.*, 2025, **395**, 127803.
65 P. Das, J.-C. P. Gabriel, C. Y. Tay and J.-M. Lee, *Chemosphere*, 2021, **269**, 129409.
66 G. Choi, S. Kim, B. Yang, J. Jung, U. H. Choi and C. Park, *Chem. Eng. J.*, 2024, **497**, 154730.
67 D. A. Ferreira-Filipe, A. Hursthouse, A. C. Duarte, T. Rocha-Santos and A. L. Patrício Silva, *Appl. Sci.*, 2025, **15**, 2122.
68 M. Aradoaei, A. R. Caramitu, M. V. Lungu, A. G. Ursan, R. C. Ciobanu, M. Aflori and A. Parfeni, *Polymers*, 2025, **17**, 2394.
69 M. I. Triantou and P. A. Tarantili, *E-waste: Management, Types and Challenges*, 2012, pp. 1–37.
70 E. Stenvall and A. Boldizar, *Recycling*, 2016, **1**, 89–100.
71 L.-H. Lee, *New Trends in Physics and Physucal Chemistry of Polymers*, Springer, 1989, pp. 185–196.
72 S. Barman and R. Chakraborty, *ACS Omega*, 2018, **3**, 18499–18509.
73 Y. Li, Y. Wu, K. Li, H. Lin, M. Wang, L. Zheng, C. Wu and X. Zhang, *Ind. Eng. Chem. Res.*, 2024, **63**, 5005–5027.
74 Y. Feng, Z. Zhang, D. Yue, V. O. Belko, S. A. Maksimenko, J. Deng, Y. Sun, Z. Yang, Q. Fu, B. Liu, *et al.*, *J. Mater. Res. Technol.*, 2024, **32**, 2891–2912.

75 P. Yang, Q. Zhou, X.-X. Yuan, J. M. Van Kasteren and Y.-Z. Wang, *Polym. Degrad. Stab.*, 2012, **97**, 1101–1106.
76 T. Türel, Ö. Dağlar, F. Eisenreich and Ž. Tomović, *Chem.–Asian J.*, 2023, **18**, e202300373.
77 A. E. Protsenko, A. N. Protsenko, O. G. Shakirova and V. V. Petrov, *Polymers*, 2023, **15**, 1559.
78 P. R. Jadhao, A. Preetam, R. Panda, S. Mishra, K. Pant and K. Nigam, *Solid Waste Management*, CRC Press, 2023, pp. 121–139.
79 Z. Yang, S. Zhang, H. Liang, E. He, Y. Wang, T. Lei, Z. Wu, Q. Chen, F. Zhou, Y. Wei, *et al.*, *Polym. Chem.*, 2024, **15**, 4784–4789.
80 A. Perumalla, T. Thomas and S. K. Kalpathy, *Opt. Mater.*, 2024, **152**, 115414.
81 J. Gan, A. Yang, Q. Guo and Z. Yang, *Adv. Devices Instrum.*, 2024, **5**, 0046.
82 S. Khuje, L. Zhu, J. Yu and S. Ren, *ACS Appl. Electron. Mater.*, 2024, **6**, 8226–8231.
83 K. S. Alblalaihid, S. A. Aldoihi and A. A. Alharbi, *Polymers*, 2024, **16**, 1560.
84 X. Wang, W. Huang, B. Yan, S. Zhou, X. Zhu, Z. Wang, Z. Cheng and G. Chen, *Waste Manage.*, 2025, **207**, 115135.
85 B. Caudle, T. T. Nguyen and S. Kataoka, *Green Chem.*, 2025, **27**, 1667–1678.
86 E. Schwartz, H. He, O. A. Ogunseitan and J. M. Schoenung, *Resour., Conserv. Recycl.*, 2025, **215**, 108019.
87 L. Klose, N. Meyer-Heydecke, S. Wongwattanarat, J. Chow, P. Pérez García, C. Carré, W. Streit, G. Antranikian, A. M. Romero and A. Liese, *Polymers*, 2023, **15**, 2653.
88 X. Zhu, Y. Duan, J. Lu, W. Xia, Y. Peng, J. Liu, W. Dong and M. Jiang, *Front. Microbiol.*, 2025, **16**, 1638208.
89 M. Santos, E. Araripe, L. Hohrenk-Danzouma and V. G. Z. Zeidler, *Sustainability Circularity NOW*, 2025, **2**, a25738285.
90 A. Turner and M. Filella, *Environ. Int.*, 2021, **156**, 106622.
91 L. Zhan, X. Zhao, Z. Ahmad and Z. Xu, *Chemosphere*, 2020, **245**, 125684.
92 E. Mayrhofer, L. Prielinger, V. Sharp, B. Rainer, C. Kirchnawy, C. Rung, A. Gruner, M. Juric and A. Springer, *Recycling*, 2023, **8**, 87.
93 J. Zou, Z. Chen, S.-J. Wang, Z.-H. Liu, Y.-J. Liu, P.-Y. Feng and X. Jing, *Polymers*, 2023, **15**, 2308.
94 L. Peng, J. Han, H. Zhang, L. Ren, K. Liu and J. Chen, *J. Cleaner Prod.*, 2025, **509**, 145623.
95 D. S. Achilias, M.-A. Charitopoulou and S. V. Ciprioti, *Polymers*, 2024, **16**, 2538.
96 D. Peti, J. Dobránsky and P. Michalík, *Polymers*, 2025, **17**, 603.
97 P. van den Tempel and F. Picchioni, *Recycling*, 2024, **10**, 1.
98 F. Kamran, H. Afshar and F. Shahi, *Polym. Eng. Sci.*, 2025, **65**(8), 3845–3879.
99 K. Dušek, D. Koc, P. Veselỳ, D. Froš and A. Géczy, *Adv. Sustainable Syst.*, 2025, **9**, 2400518.
100 V. C. Dinkar and V. Kumar, *Polym. Bull.*, 2025, 1–36.
101 Z. Zhang, A. K. Biswal, A. Nandi, K. Frost, J. A. Smith, B. H. Nguyen, S. Patel, A. Vashisth and V. Iyer, *Nat Sustainability*, 2024, **7**, 616–627.
102 X. Huang, Y. Wang, C. Ding, S. Zhang, X. Duan, H. Ji, J. Cai and Z. Wang, *ACS Appl. Polym. Mater.*, 2023, **6**, 126–140.
103 L. Chen, N. Ning, G. Zhou, Y. Li, S. Feng, Z. Guo and Y. Wei, *Polymers*, 2025, **17**, 571.
104 H. Yao, H. Yang, L. Jiang, W. Huang, Q. Jiang, B. Jiang and G. Zhang, *RSC Appl. Polym.*, 2025, **3**, 163–172.
105 S. Kumar, S. Krishnan and K. Prabakaran, *ACS Sustainable Resour. Manage.*, 2024, **1**, 2086–2107.
106 D. Hetemi and J. Pinson, *Chem. Soc. Rev.*, 2017, **46**, 5701–5713.
107 N. Kavitha, M. Elavarasan, R. Ramachandran, S. Uthayakumar, A. Chandramohan and K. Dinakaran, *Curr. Res. Green Sustainable Chem.*, 2022, **5**, 100316.
108 K. Zribi, J.-F. Feller, K. Elleuch, A. Bourmaud and B. Elleuch, *Polym. Adv. Technol.*, 2006, **17**, 727–731.
109 Q. Kang, Y. Lin and J. Tao, *Microelectron. Reliab.*, 2024, **152**, 115294.
110 HolyGrail 2.0: Digital watermarking technology, Alliance to End Plastic Waste, 2024, https://www.endplasticwaste.org/what-we-do/projects/aim-holy-grail-digital-watermarking, accessed 05 January 2026.
111 T. Rumetshofer and J. Fischer, *Polymers*, 2023, **15**, 1623.
112 J. Pawelec, Sorting Mixed Polymer Streams: How Optical Sorters Handle Complex Plastic Waste, 2025, https://meyer-corp.eu/article/sorting-mixed-polymer-streams-how-optical-sorters-handle-complex-plastic-waste/, accessed 05 January 2026.
113 A. Ludwig, *npj Comput. Mater.*, 2019, **5**, 70.
114 S. Basu Roy, A. Nabawy, A. N. Chattopadhyay, Y. Geng, J. M. Makabenta, A. Gupta and V. M. Rotello, *ACS Appl. Mater. Interfaces*, 2022, **14**, 27515–27522.
115 S. Baudis and M. Behl, *Macromol. Rapid Commun.*, 2022, **43**, 2100400.
116 T. A. Dickinson, D. R. Walt, J. White and J. S. Kauer, *Anal. Chem.*, 1997, **69**, 3413–3418.
117 K. Chang, C. Zhang and T. Liu, *Polym. Sci. Technol.*, 2025, **1**, 3–24.
118 G. Lu, T. Tian and Y. Wang, *Polymers*, 2024, **16**, 839.
119 Y.-S. Zhao, J. Huang, X. Yang, W. Wang, D.-G. Yu, H. He, P. Liu and K. Du, *Front. Bioeng. Biotechnol.*, 2025, **13**, 1533367.
120 R. A. Potyrailo, C. Surman and W. G. Morris, *J. Comb. Chem.*, 2009, **11**, 598–603.
121 K. Ferji, *Polym. Chem.*, 2025, **16**, 2457–2470.
122 H. Zhou, Y. Fang and H. Gao, *ACS Eng. Au*, 2023, **4**, 231–240.
123 W. Ge, R. De Silva, Y. Fan, S. A. Sisson and M. H. Stenzel, *Adv. Mater.*, 2025, **37**, 2413695.
124 X. Huang and S. Ju, *J. Appl. Phys.*, 2024, **135**, 171101.
125 A. A. Musa, A. Bello, S. M. Adams, A. P. Onwualu, V. C. Anye, K. A. Bello and I. I. Obianyo, *Polymers*, 2025, **17**, 893.
126 S. K. Sahu, V. Boggarapu and P. R. Sreekanth, *Mater. Today: Proc.*, 2024, **113**, 1–8.
127 S. Sahu, K. Tripathy, M. Bhattacharjee and D. Chopra, *Chem. Commun.*, 2024, **60**, 4382–4394.
128 A. Schade, M. Melzer, S. Zimmermann, T. Schwarz, K. Stoewe and H. Kuhn, *ACS Sustain. Chem. Eng.*, 2024, **12**, 12270–12288.

129 B. M. Stadler and J. G. de Vries, *Philos. Trans. R. Soc., A*, 2021, **379**(2209), 20200341.
130 O. G. Mountanea, E. Skolia and C. G. Kokotos, *Green Chem.*, 2024, **26**, 8528–8549.
131 J. Sun, J. Dong, L. Gao, Y.-Q. Zhao, H. Moon and S. L. Scott, *Chem. Rev.*, 2024, **124**, 9457–9579.
132 S. Zhang, K. Shao, C. Hong, S. Chen, Z. Lin, Z. Huang and G. Mureti, *J. Food Compos. Anal.*, 2023, **122**, 105477.
133 C. J. Bright, E. C. Nallon, M. P. Polcha and V. P. Schnee, *Anal. Chem.*, 2015, **87**, 12270–12275.
134 M. A. Salem, A. M. Khan, Y. K. Manea, H. A. Saleh and M. Ahmad, *ACS Omega*, 2022, **8**, 1220–1231.
135 M. N. Norizan, M. H. Moklis, S. Z. N. Demon, N. A. Halim, A. Samsuri, I. S. Mohamad, V. F. Knight and N. Abdullah, *RSC Adv.*, 2024, **14**, 9570.
136 G. Wang, M. Wang, M. Zheng, B. Ebo, C. Xu, Z. Liu and L. He, *ACS Appl. Nano Mater.*, 2023, **6**, 5871–5878.
137 H. Roh, D.-H. Kim, Y. Cho, Y.-M. Jo, J. A. Del Alamo, H. J. Kulik, M. Dincă and A. Gumyusenge, *Adv. Mater.*, 2024, **36**, 2312382.
138 S. Dutta, W. Mandal, A. V. Desai, S. Fajal, G. K. Dam, S. Mukherjee and S. K. Ghosh, *Mol. Syst. Des. Eng.*, 2023, **8**, 1483–1491.
139 M. Hayat, N. Raza, S. Manzoor, Y. Irshad, R. Javaid, A. W. Rajput and F. K. Algethami, *RSC Adv.*, 2025, **15**, 21037–21050.
140 D. K. Kar, P. V., S. Si, H. Panigrahi and S. Mishra, *ACS Omega*, 2024, **9**(10), 11050–11080.
141 H. Zhang and G. Wang, *J. Fluoresc.*, 2025, 1–12.
142 L. Cheng, X. Chen, J. Gu, N. Kobayashi, H. Yuan and Y. Chen, *Fundam. Res.*, 2025, **5**, 919–922.
143 D. Zanella, M. Romagnoli, S. Malcangi, M. Beccaria, T. Chenet, C. De Luca, F. Testoni, L. Pasti, U. Visentini, G. Morini, *et al.*, *Anal. Bioanal. Chem.*, 2023, **415**, 2343–2355.
144 A. Serras-Malillos, B. B. Perez-Martinez, A. Iriondo, E. Acha, A. Lopez-Urionabarrenechea and B. Caballero, *RSC Adv.*, 2024, **14**, 9892–9911.
145 M. Girtan, R. Mallet, M. Socol and A. Stanculescu, *Mater. Today Commun.*, 2020, **22**, 100735.
146 Z. Cui, W. Duan, Z. Lu, L. Huang, H. Che, B. Gou, Z. Xu, H. Liang, J. Huang, D. Mao, *et al.*, *J. Alloys Compd.*, 2025, **1013**, 178566.
147 M. J. Hossain, B. T. Tabatabaei, M. Kiki and J.-W. Choi, *Int. J. Precis. Eng. Manuf. Green Technol.*, 2025, **12**, 277–300.
148 R. G. Ferreira, A. P. Silva and J. Nunes-Pereira, *ACS Sens.*, 2024, **9**, 1104–1133.
149 M. U. Ali Khan, R. Raad, F. Tubbal, P. I. Theoharis, S. Liu and J. Foroughi, *Polymers*, 2021, **13**, 357.
150 A. B. Botelho Junior, U. K. Sultana and J. Vaughan, *Management of Electronic Waste: Resource Recovery, Technology and Regulation*, 2024, pp. 234–288.
151 M. Delfi, M. Ghomi, A. Zarrabi, R. Mohammadinejad, Z. B. Taraghdari, M. Ashrafizadeh, E. N. Zare, T. Agarwal, V. V. Padil, B. Mokhtari, *et al.*, *Prosthesis*, 2020, **2**, 12.
152 R. D. Maalihan, M. R. B. Domalanta, A. C. C. Corrales and E. B. Caldona, *Polym. Compos.*, 2025, **46**, 5857–5881.
153 S. F. Ahmed, S. Shuravi, S. Afrin, S. J. Rafa, M. Hoque and A. H. Gandomi, *arXiv*, 2023, preprint, arXiv:2309.03420, DOI: 10.48550/arXiv.2309.03420.
154 A. Schulte, M. Lamb-Scheffler, P. Biessey and T. Rieger, *Chem. Ing. Tech.*, 2023, **95**, 1268–1281.
155 D. Steegborn, M. Renner and P. Biessey, *J. Sustainability*, 2025, **1**(2), 1–20.
156 S. Ghasemi, M. Sibi, D. C. Webster and G. Pourhashem, *J. Cleaner Prod.*, 2024, **469**, 143148.
157 P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, 2000.
158 M. Krasnodębski, *Stud. Hist. Philos. Sci.*, 2024, **103**, 85–94.
159 T. Tong and M. Elimelech, *Environ. Sci. Technol.*, 2016, **50**, 6846–6855.
160 M. Date, V. Patyal, D. Jaspal, A. Malviya and K. Khare, *J. Water Process Eng.*, 2022, **49**, 103129.