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# Polymeric sensors at the crossroads of sustainability and scalability: low-temperature fabrication for environmental and health monitoring

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Modern industries are experiencing a dual transition: advancing toward sustainability (Industry 5.0) goals while simultaneously embracing Industry 4.0, characterized by Internet of Things (IoT)-driven smartification. This rapid expansion of interconnected devices is occurring in an era where conventional electronics remain fundamentally unsustainable, with persistent challenges in recycling, metal segregation, and circularity. This disconnect necessitates alternative material and fabrication strategies that can enable scalable sensor deployment without exacerbating environmental burdens. In this review, we analyze recent progress (over the last five years) in low-temperature fabricated polymer-driven sensors, focusing on their relevance for sustainable environmental and health monitoring. Advances across different polymer families and fabrication techniques are systematically examined, with evaluation from both sustainability and scalability perspectives. Special emphasis is placed on how these approaches address limitations of conventional high-temperature, resource-intensive processes and their applicability across sectors such as agriculture, pharmaceuticals, textiles, and chemicals. By examining current literature in light of the dual transition, the review identifies recent trends, outlines knowledge gaps, and highlights pathways for integrating polymer-based sensors into large-scale, environmentally responsible technologies.

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## 1. Introduction

Environmental pollution originating from industrial, agricultural, and urban activities presents increasing threats to human health and ecosystems on a global scale.[1] Consequently, continuous, real-time monitoring of contaminants in air, water, and soil, as well as physiological parameters through biomedical sensors, is vital for prompt intervention, public health management, and adherence to regulatory standards.[2] This requirement is particularly pressing for economically critical sectors such as agriculture, chemicals, textiles, electronics, and pharmaceuticals, that must sustain uninterrupted operations to meet continuous public demand.[3–6] The demand for sensors is a cross-cutting requirement driven by the increasing adoption of IoT platforms across all major manufacturing sectors.[7] The major industries have all embraced Industry 4.0,[8] the smartification era marked by extensive sensor deployment, data-driven automation and interconnectivity to optimize efficiency.

Despite the promise of smartification in Industry 4.0, the underlying reality is that current models often sideline sustainability concerns, leading to significant ecological and social consequences.[9] This situation results in escalating tension as organizations reach the boundaries of progress focused solely on technology. Automation often exacerbates energy consumption, the utilization of resources, and e-waste generation rather than mitigating environmental impacts. The shift to Industry 5.0 is essential to address sustainability deficits and promote worker well-being and responsible growth. This requires rethinking smart technologies to integrate digital innovation with sustainability, resilient resource management, and human involvement. The future of industry relies on aligning smartification with long-term ecological and social goals, avoiding unsustainable practices masked as technological advancement.[8,10] This simultaneous global shift towards sustainability (as shown in Fig. 1) necessitates a vast number of sensors to support these efforts.[11] At the same time, the pro-

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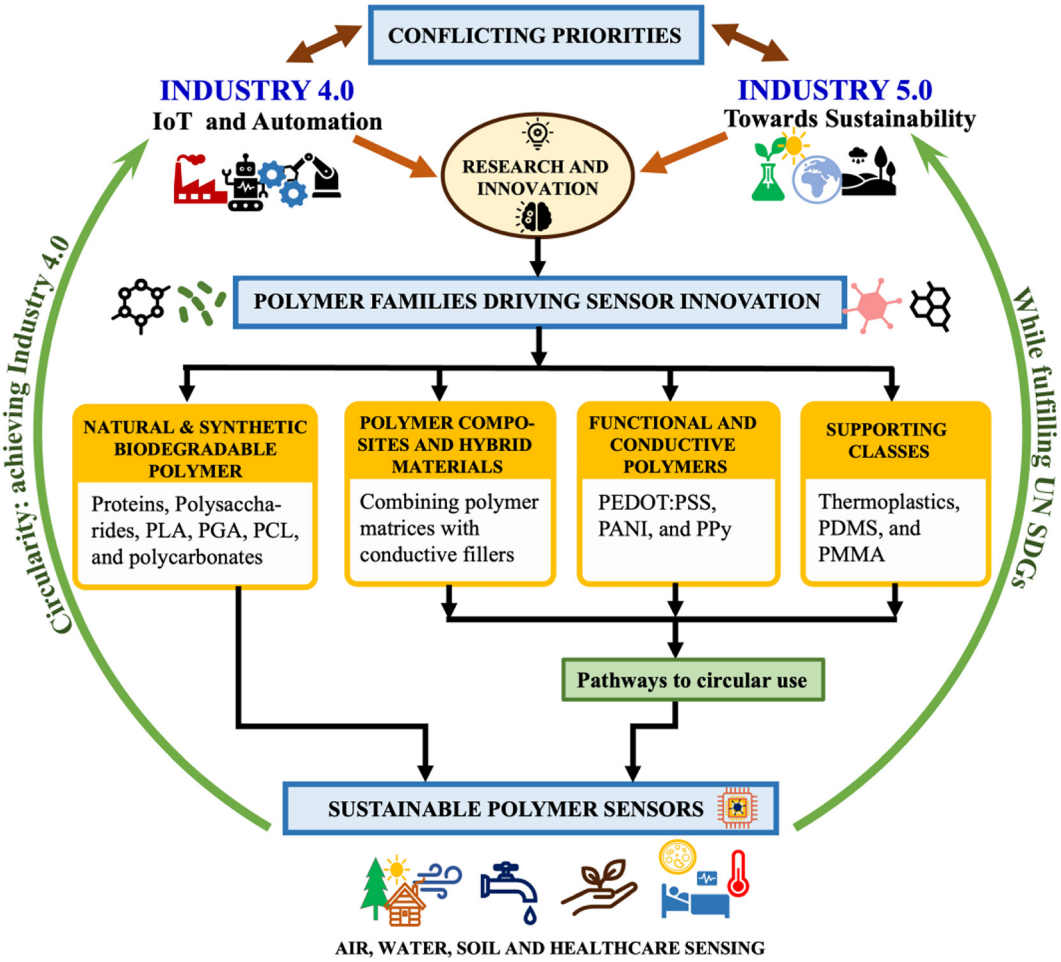


**Fig. 1** The conceptual diagram illustrates the dynamic interplay and conflicting priorities between ongoing Industry 4.0 technological innovation and the SDGs. It encapsulates recent advancements in research on diverse polymer families engineered for sensor applications, emphasizing their role in sustainable environmental and health monitoring. The schematic highlights the integration of recycled material recovery within the fabrication of polymer-based sensors, demonstrating how material circularity is preserved to align the lifecycle of sensing technologies with the objectives of the SDGs.

duction of these sensors may or may not be on a sustainable path, emphasizing the urgent need to prioritize environmentally responsible approaches to sensor development.[12]

Effectively addressing this surge in demand requires not only scalable sensors but also solutions that are tailored to the specific environmental and operational challenges of each industry. For example, the pharmaceutical industry requires ultra-precise sensors to detect contamination during drug manufacturing and maintain stringent quality control; the textile sector focuses on monitoring chemical effluents and dye pollutants to minimize environmental harm; the leather industry demands sensors for water quality and toxic substance detection to manage its wastewater impact effectively; and agriculture relies on sensors for soil and gas monitoring. Such sector-specific sensing needs, underscore the importance of developing customized sensor solutions tailored to the unique environmental profiles and operational challenges of each industry, while supporting sustainable and scalable deployment.

While sensors are essential for achieving sustainable development goals (SDGs)[13] such as responsible consumption and production (SDG 12), clean water and sanitation (SDG 6), industry innovation (SDG 9), climate action (SDG 13), and decent work and economic growth (SDG 8),[14] their production processes often involve significant carbon, water and ecological footprints. In other words, sensor manufacturing may not always follow a sustainable path, highlighting the urgent need for environmentally responsible development. This paradox underscores the necessity of aligning sensor innovation with sustainability principles.[15] In this context, low-temperature fabrication strategies, particularly those based on polymeric platforms and soft-chemistry approaches ("chimie douce"),[16] offer promising solutions. Such methods reduce resource consumption while enabling recyclability, scalability, and compatibility with flexible, large-area substrates.[17]

Current sensor technologies are still largely dominated by semiconductors such as silicon and metal oxides, valued for

their reliability, stability, and integration with established electronics infrastructure.[18] For instance, silicon is extensively used for high-precision sensing in industrial applications, and metal oxides are standard for gas sensing platforms. However, these materials face some major limitations: (1) the high-temperature, high-energy, and infrastructure-intensive processes required for their fabrication, typically in the 300–900 °C range with reliance on vacuum systems, cleanrooms and other resource-heavy infrastructure;[19–21] (2) the rigidity and limited compatibility of traditional substrates with emerging applications such as wearables or flexible electronics; and (3) the environmental burden associated with their lifecycle, including recyclability and electronic waste.[22] These limitations inflate costs, restrict scalability, and restrict widespread adoption in developing regions where infrastructure and capital investment are limited.[14]

In response, polymer-based sensing platforms have emerged as a compelling alternative, offering a fundamentally different processing and integration paradigm.[31] Unlike semiconductors that require high-temperature fabrication, polymers can be processed at temperatures often below 200 °C and in many cases near room temperature, through solution-based techniques such as drop-casting,[27,31–33] screen printing,[34] and ink-jet printing.[35] These methods eliminate dependence on cleanroom infrastructure, drastically reduce energy use, and allow rapid prototyping. Devices can be fabricated within hours rather than weeks, accelerating product development cycles and supporting localized, small-scale manufacturing. Importantly, polymer sensors can be seamlessly integrated with IoT platforms,[14,36] enabling real-time environmental monitoring. This integration supports smart agriculture, wearable health devices, and other Industry 4.0 applications, promoting data-driven decisions and operational efficiency.[37] The sustainability of polymer sensors, due to their recyclability and low embodied energy, further aligns with circular economy principles and global environmental goals.[11,15,22] However, to fully realize this potential, sensor development must evolve beyond conventional methods toward advanced materials design and system integration.

Advancing polymer sensors toward the next generation requires designs tailored to specific industrial effluents,[38] often achieved through combinatorial chemistry strategies using automation, robotics, and high-throughput experimentation to identify polymer combinations with enhanced sensitivity and selectivity. Complementing this, artificial intelligence (AI) and machine learning (ML) analyze vast datasets, reveal hidden patterns, and guide the design of novel sensing materials.[39,40] Computational tools enable integrated computational materials engineering (ICME) approaches to model and predict optimal material combinations and device architectures before fabrication.[41] The synergy of AI/ML with ICME accelerates optimization, improves accuracy, and reduces experimental overhead. Fig. 2 illustrates this framework, where combinatorial methods augmented with AI/ML guide the rational design of next-generation environmental sensors. For manufacturers in India and other developing economies facing tight margins, inflation, and regulatory pressures under Industry 4.0, such advances offer a practical path forward.[42] The convergence of materials science, computation, and smart manufacturing will support environmental sustainability, drives industrial growth, and promotes job creation, aligning with sustainable development goals to usher in an era of smart, resilient, and sustainable industries.[9,11,12]

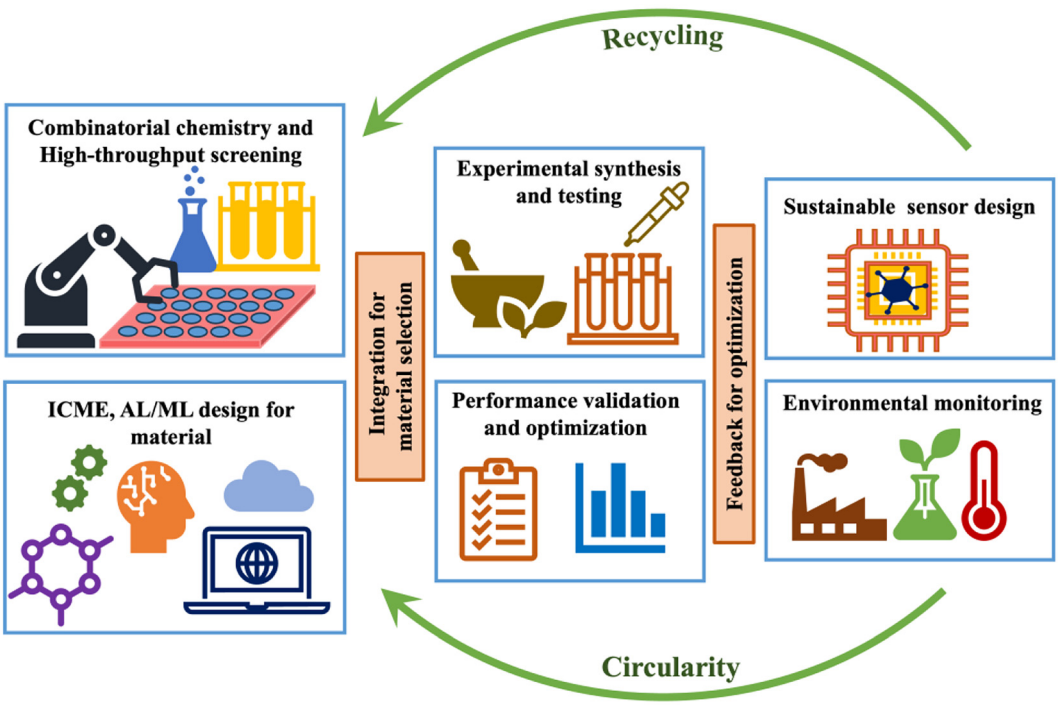


Fig. 2 Schematic representation of sensor design using combinatorial approaches integrated with AI and ML technologies.

Table 1 Sensor materials: contrasting silicon-based and polymer-based systems in terms of life cycle assessment (LCA)

| Sensor material/ system | Main attributes | Typical manufacturing features | LCA highlights (GHG, energy, *etc.*) | Ref. |
|---|---|---|---|---|
| Silicon-based sensor chips | Mature and standardized technology, long-term stability, rigid and brittle, limited flexibility, less suitable for wearable or large-area applications | High-temperature wafer fabrication (800–1200 °C),[23,24] photolithography, doping and deposition, cleanroom processing, specialized infrastructure | Major environmental hotspot due to high energy use in silicon wafer fabrication (35–60 kWh $kg^{-1}$);[25] recycling is complex and resource intensive, energy-intensive high-temperature manufacturing, high greenhouse gas footprint, complex and costly recycling | 19 and 26 |
| Polymer based sensors (conductive, bio-derived, functional *etc.*) | Flexibility, lightweight, electrical conductivity, chemical tunability, low power operation, ease of processing, selective sensing, and IoT integration capability | Solution based low-temperature (30–120 °C)[27,28] fabrication techniques (ink-jet printing, drop-cast, 3-D printing, electrospinning *etc.*) | Lower greenhouse gas emissions (25–42 $gCO_2$ eq. per sensor),[19] reduced energy consumption from low-temperature solution processing, compatibility with scalable printing and roll-to-roll fabrication, biodegradability and recyclability potential, extended device lifetimes through mechanical durability | 29 and 30 |

Although sustainability is often considered at a product's end-of-life, it is essential to integrate it throughout the entire lifecycle, from material selection to fabrication.[19] Life cycle assessment (LCA) studies show that bio-based and biodegradable polymers generally result in lower greenhouse gas emissions and non-renewable energy use than petrochemical-based options, especially when combined with renewable energy and responsible feedstock sourcing. However, some bio-based materials may involve higher land and water use, highlighting the need for holistic sustainability metrics.[43] In comparing inorganic, hybrid, and polymer-based sensor systems, polymer systems offer distinct advantages like lightweight structure, low-temperature processability, recyclability, and functional versatility. These advantages contribute to a diminished cradle-to-grave environmental impact in sensor applications.[44–48] Table 1 further illustrates these differences, comparing silicon- and polymer-based sensors in terms of attributes, manufacturing routes, and LCA impacts. This review examines the past 3–5 years of literature to identify how recent research, often implicitly, is moving toward these sustainable and scalable sensor technologies. It further focuses on developments in polymer-based, low-temperature fabricated sensors, evaluating material families and fabrication methods from sustainability and scalability perspectives. This approach highlights emerging trends, identifies knowledge gaps, and illustrates how current developments are advancing sensors that meet both Industry 4.0 requirements and global sustainability goals.

## 2. Recent advances in polymer-based sensors with focus on low-temperature fabrication, sustainability and scalability

Polymer-based sensors are increasingly recognized as sustainable for environmental monitoring.[15,17] These sensors benefit from energy-efficient, low-temperature fabrication processes and material advances.[31,33] Their chemical tunability and ease of processing make them suitable for scalable and eco-friendly devices.[11,12] Fig. 1 shows the various polymers used in environmental sensors. Polymers can be engineered with functional groups, tailored porosity, and mechanical resilience, enabling the selective detection of gases, ions, heavy metals, and biomolecules. Their selectivity is often guided by chemical theories such as the Pearson's Hard–Soft Acid–Base (HSAB) theory,[49] which explains that hard acids preferentially interact with hard bases and soft acids with soft bases, guiding selective binding between the functional groups of polymers and target analytes.

Unlike inorganic or silicon-based sensors that typically demand high-temperature, lithography-intensive fabrication steps, polymeric materials, enabled by soft chemistry (chimie douce) approaches, allow scalable processing under ambient conditions. This includes solution processing, printable inks, and roll-to-roll compatible methods such as drop casting, spin coating, and screen printing.[50,51] These fabrication methods will be discussed in detail in section 5. In addition to their ease of processing, polymers span a broad spectrum, including natural biodegradable polymers, synthetic biodegradable polymers, conductive polymers, functional polymers, and hybrid composites, supporting the design of sensors tailored to targeted detection requirements.[11,12] In the following subsections, we review the roles of these polymer classes in sensor development and highlight recent research validating their potential for scalable, eco-friendly sensor technologies.

### 2.1 Natural and synthetic biodegradable polymers

A crucial component of this sustainable trajectory is the use of biodegradable polymers, both natural and synthetic, which can lower the ecological footprint of sensors.[11,12] These materials are often processable at low-temperatures, further reducing energy consumption during fabrication. Natural bio-based polymers such as proteins (silk fibroin, gelatin, col-

lagen) and polysaccharides (chitosan, cellulose, alginate, starch, hemicellulose, lignin) are increasingly being explored as substrates, matrices, or active layers.[11,12,53] Their intrinsic biocompatibility, biodegradability, and chemical functionality support diverse applications such as environmental monitoring, biomedical diagnostics, and flexible wearable platforms.[54] In comparison, LCA of printed electronics reveal that conventional silicon-based sensor chips contribute the most to the environmental footprint of devices,[19] highlighting the potential of bioderived polymers to enable recyclable and eco-efficient sensor platforms.

As a representative example, Lee and co-workers fabricated flexible gas sensors in which cellulose films or cellulose nanofiber substrates were integrated with functional sensing layers, including chemical vapor deposition (CVD)-grown graphene and oxidized single-walled carbon nanotube bundles. These devices are manufactured *via* solution-processed fabrication and transfer methodologies conducted at comparatively low-temperatures, and they demonstrate pronounced sensitivity toward $NO_2$, detection limits in the parts-per-billion (ppb) range, and mechanically robust performance under bending deformation. The authors further demonstrate that the presence of polar functional groups, together with the tunable surface roughness of the cellulose support, significantly promotes gas adsorption and facilitates interfacial charge transfer, thereby yielding superior sensing performance relative to comparable silicon-based platforms.[55–57] Collectively, these studies demonstrate that natural cellulose substrates can concurrently facilitate mild, environmentally benign processing conditions and deliver competitive gas-sensing performance, thereby providing direct empirical support for the sustainability–performance relationship highlighted in this review.

Alongside these natural options, synthetic biodegradable polymers, such as polyglycolic acid (PGA), polylactic acid/poly-L-lactic acid (PLA/PLLA), poly(lactic-*co*-glycolic acid) (PLGA), poly(1,8-octanediol citrate) (POC), poly(glycerol sebacate) (PGS), polycaprolactone (PCL), polyhydroxybutyrate (PHB), polyhydroxyvalerate (PHV), polycarbonates (PC), polyphosphazenes (PPZ), polyurethane (PU), polydioxanone (PDO), polyvinyl alcohol (PVA), are equally important in advancing sustainable sensing. Their tunable molecular backbones allow controlled degradation, safe disintegration, and programmable functional properties, making them particularly attractive for transient, disposable, and wearable sensor systems.[58,59] These materials not only address the plastic waste crisis but also provide versatile platforms responsive to external stimuli like heat, pressure, and pH, as seen in smart biodegradable polymers such as PLA-based shape memory systems.[60] Comprehensive reviews highlight their applications across agriculture, biomedical devices, food packaging, textiles, and electronics.[61] However, relying on polymers alone may not always achieve the required sensitivity, stability, or multifunctionality.

For instance, silk fibroin (SF), a biocompatible and Food and Drug Administration (FDA)-approved material with tunable degradation, is a suitable candidate for transient implantable and wearable health monitoring devices.[58,62] However, their high crystallinity increases brittleness, and rapid enzymatic degradation with poor aqueous processability limits direct device fabrication. These limitations can be addressed by fabricating complete electronic systems on temporary substrates, which are later transferred to silk supports.[58] In addition, hybrid designs combining silk with conductive materials such as graphene allow silk to serve not only as a substrate but also as an electrically active component in sensors. Wang *et al.*[52] reported a self-healable, multifunctional electronic tattoo (E-tattoo) based on a graphene/SF/$Ca^{2+}$ (Gr/SF/$Ca^{2+}$) composite. The E-tattoo, fabricated through techniques such as screen printing or direct writing onto SF/$Ca^{2+}$ membranes, can be seamlessly affixed to the skin similar to a temporary tattoo as shown in Fig. 3 with the application of a single droplet of water, thereby aligning precisely with its microscopic topography while sensing strain, humidity, and temperature. Dynamic hydrogen and coordination bonds enable rapid self-healing (≈100% in 0.3 s). While silk-based bioplastics exemplify the advantages of biodegradable polymers, incorporating functional fillers and modifiers is crucial to tailor their properties and develop advanced multifunctional polymer composites for sensor applications. This drives the move toward polymeric composites, hybrid systems, and functional polymer modifications, where additives and synergistic materials are introduced to tailor sensor performance for highly customized applications.

Water uptake constitutes a critical parameter dictating the long-term operational stability of polymer-based sensors, particularly when hydrophilic or naturally derived biopolymers are used as the active matrix.[63] Moisture sorption can induce volumetric swelling, plasticization, and increased polymer chain mobility, thereby altering the mechanical integrity of the film as well as the associated mass-transport pathways. In electrochemical and ion-selective devices, the presence of absorbed water and interfacial water layers at the polymer–electrode interface can substantially modify ion transport characteristics, local dielectric permittivity, and interfacial charge-transfer kinetics. These alterations, in turn, give rise to signal drift, hysteresis phenomena, and diminished device-to-device reproducibility, particularly under conditions of varying ambient humidity or operation in aqueous environments.[64,65] To counteract moisture-induced instabilities in biopolymer-based biosensors, a range of strategies has been investigated, including chemical crosslinking to reduce free volume and suppress swelling, incorporation of hydrophilic matrices with more water-resistant constituents, and the engineering of biopolymer–nanomaterial composite architectures that restrict uncontrolled water uptake while preserving adequate analyte diffusion and binding accessibility. Thin passivation or barrier layers, such as hydrophobic or amphiphilic coatings and elastomeric encapsulants, have likewise been demonstrated to effectively mitigate water ingress and enhance signal stability, while only minimally affecting sensitivity.[66–69] These strategies, demonstrated across diverse biopolymer-based sensing platforms and functional polymer composites, establish practical

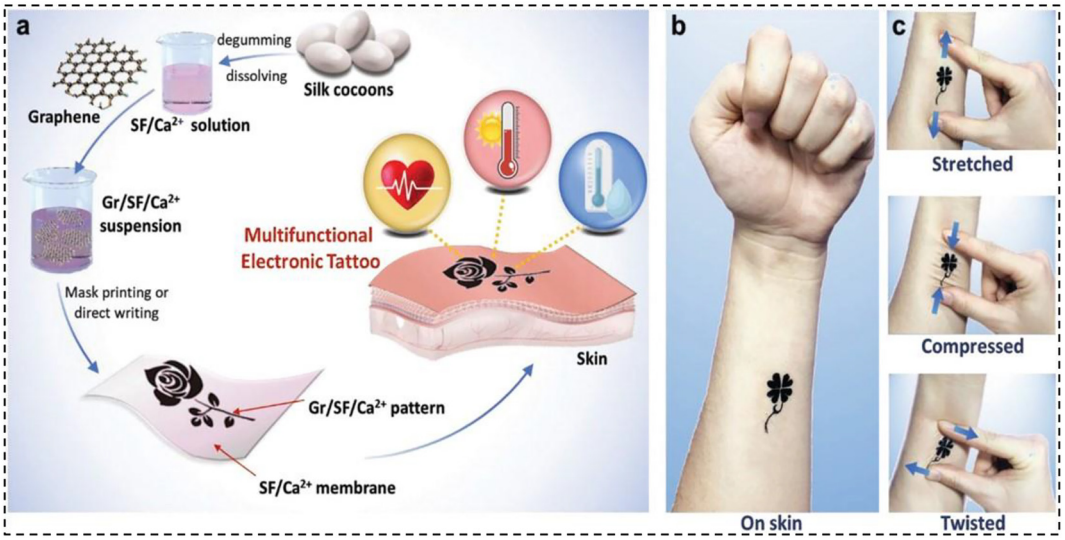


**Fig. 3** Fabrication and skin adhesion of the Gr/SF/$Ca^{2+}$ E-tattoo. (a) Schematic of the fabrication process. (b) Four-leaf clover E-tattoo on forearm. (c) Tattoo under stretch (top), compression (middle), and twist (bottom), showing conformal adhesion. (Reprinted with permission from Wang *et al.*, *Adv. Funct. Mater.*, 2019, Copyright 2019 Wiley-VCH.)[52]

design principles for improving the long-term durability, operational stability, and reliability of nature-derived polymer sensing platforms under realistic aqueous and high-humidity conditions.

### 2.2 Polymer composites and hybrid materials

Polymer-based hybrids and nanocomposites represent a versatile strategy to enhance the performance of sensors by combining polymer matrices with conductive fillers, such as graphene, carbon nanotubes (CNT), MXenes, or metallic nanoparticles, through approaches like solution blending, *in situ* growth, or layer-by-layer assembly, thereby improving both electrical and mechanical properties. These systems can be broadly categorized into: (i) polymer–polymer hybrids, where blending or copolymerization combines complementary traits like flexibility, processability, and biodegradability, yielding enhanced performance beyond what single polymers can achieve;[70] and (ii) polymer–nanomaterial composites, where incorporation of inorganic nanofillers (like MXenes or metal nanoparticles) or carbon-based nanofillers (like CNTs), significantly improves sensitivity, stability, and conductivity.[47]

Yang *et al.*[71] developed a flexible MXene/tissue paper (MTP) pressure sensor fabricated through solution-based process, exhibiting high sensitivity and a broad detection range. Its recyclability is enabled by using weighing paper instead of polyimide encapsulation, allowing silver electrodes to be recovered *via* incineration. As illustrated in Fig. 4, the incineration process leaves behind silver residues that can be collected, sonicated, and dried to produce reusable silver powder. Although the nano materials like MXenes are highly promising for sensor designs, their environmental impact remains a concern, which is partly mitigated by combining them with other materials *via* solution blending.[47] For instance, Sun *et al.* developed a MXene-based composite hydrogel (PBM hydrogel) by integrating PVA, and bacterial cellulose (BC) with MXene nanosheets through a repeated freeze–thaw process combined with dynamic borax cross-linking (as shown in Fig. 5i). The hydrogel exhibits excellent self-healing efficiency (97.8%) and strong self-adhesion, along with high sensing sensitivity (2.18) and rapid response time (10 ms) for detecting human movements, vocalization, and robotic motion. Notably, it demonstrates impressive biodegradability, fully degrading within 53 min in 3% $H_2O_2$ solution and over 56 days in phosphate-buffered saline (PBS), while maintaining cytocompatibility, highlighting its promise for wearable, eco-friendly sensor applications.[72] Similarly, Ali *et al.* demonstrated that the use of PLLA/Gly (poly(L-lactide acid)/glycine) in wearable piezoelectric sensors, fabricated *via* solution-based process involving spin-coating and mild drying, offers a significant advantage by minimizing electronic waste and eliminating the need for secondary surgeries in implantable devices. The film can be easily fabricated *via* a low-temperature spin-coating process and subsequently degrades completely in PBS at 37 °C within 5 days.[75]

Pan *et al.* developed a biodegradable cotton fiber-based piezoresistive textile for wearable biomonitoring using a scalable dip-coating method, where MXene flakes were tightly bound to cotton cellulose fibers at low temperatures (≤60 °C), resulting in a highly conductive textile with excellent hydrophilicity and abundant functional groups.[76] This low-temperature fabrication, including MXene coating, cotton degreasing, and drying, makes the process energy-efficient and compatible with biodegradable textiles. The resulting textile exhibited high sensitivity (17.73 $kPa^{-1}$), a broad pressure range (100 Pa–30 kPa), low detection limit (2 Pa), and fast response (80 ms), enabling reliable monitoring of physiological signals like swallowing, vocal vibrations, wrist pulse, and muscle contraction.

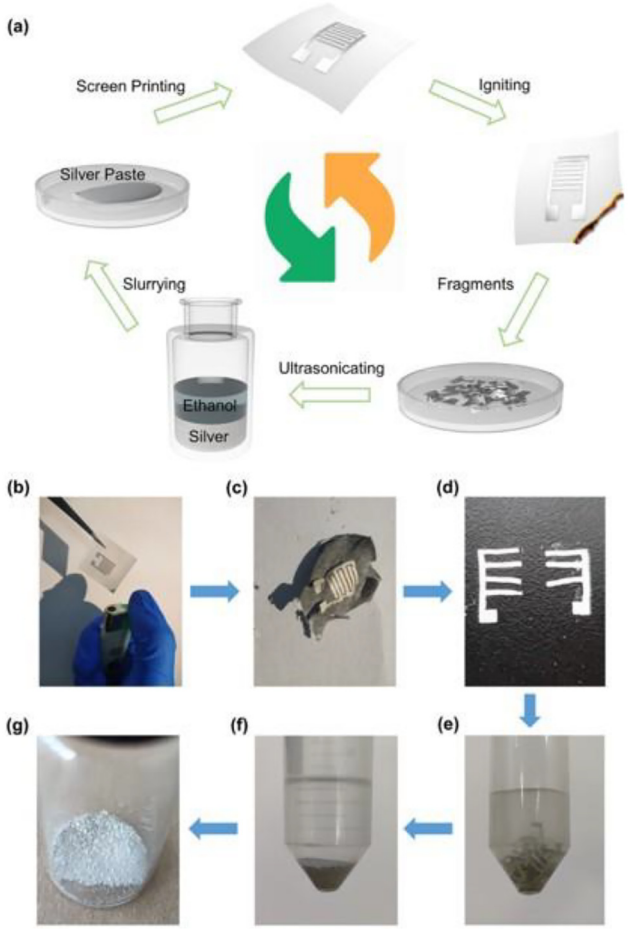


**Fig. 4** (a–g) Details the step-by-step recycling process of the Ag interdigital electrode from the all-paper-based MTP pressure sensor. (a) A schematic shows the overall recycling workflow: the sensor is burned, and the Ag electrode is recovered. (b) shows the intact printed paper sensor before burning, while (c) displays the sensor after burning, reduced to ash with the Ag electrode still present. (d) The fragmented Ag electrode is separated from the ash, and (e) shows the collection process using ethanol. The solution is then subjected to ultrasonic sonication, as seen in (f), to disperse the silver fragments. (g) shows the drying process, which yields reusable silver powder. This process offers a simple and effective method for reclaiming valuable materials, supporting sustainable sensor manufacturing.[71] (Reprinted with permission from Yang *et al.*, *Appl. Mater.*, 2021, Copyright 2021 American Chemical Society.)

Its degradability was confirmed *via* immersion in 2 M $H_2SO_4$ at 28 °C for 20 days, showing visible degradation. Complementing this, Wei *et al.*[73] introduced soy protein isolate (SPI)-based nanocomposite films enhanced with hydroxylated barium titanate (HBT) nanoparticles and glycerin (GL), fabricated through a solution-casting method. The optimized SPI-HBT0.5-GL0.5 film demonstrated high toughness (17.70 MJ $m^{-3}$), tensile strength (21.63 MPa), and conductivity (up to 0.912 S $m^{-1}$ under 48.2% moisture), while remaining translucent, biocompatible, and recyclable as shown in Fig. 5ii. These films were fabricated through a simple solution-casting method, which showed durability over 10000 cycles and fully degraded in PBS (pH 7.4, 37 °C). Further, Pozza *et al.* developed an electrospun PLA/poly(butylene adipate-co-terephthalate)(PBAT)/graphite sensor for detecting 2,4,6-trichlorophenol.[77] The biodegradable hybrid exhibits enhanced electrochemical performance with a low detection limit ($7.84 \times 10^{-8}$ mol $L^{-1}$). However, the use of toxic solvents (chloroform/dimethylformamide) and high-temperature calcination (500 °C) raises sustainability concerns, which could be mitigated by greener solvents (*e.g.* eco-friendly solution casting using ethyl acetate, water, ionic liquids) or solvent-free methods like melt electrospinning or three-dimensional (3D) printing.[78,79]

Liu *et al.*[74] developed a biodegradable piezoresistive sensor using electrospun PLGA/PVA nanofibers and Ag nanowire coated magnolia leaf veins. PVA NF films underwent rapid hydrolytic degradation into $CO_2$ and $H_2O$, while PLGA degrades more gradually into lactic and glycolic acids, both metabolically benign. The device exhibited 50% weight loss in 45 days, confirming its eco-friendly and biocompatible degradability. The study by Liu *et al.*[74] reports a biodegradable polyurethane (BPU)/CNT fiber-based strain sensor fabricated *via* wet spinning, achieving a wide sensing range (0–250%), high sensitivity (gauge factor up to 2468 at 250% strain), and stable performance over 3000 cycles. The BPU matrix, synthesized with polycaprolactone segments, demonstrated biodegradability with 19.45% weight loss in PBS after 42 days (as shown in Fig. 6). Notably, the study used carbon-based materials such as CNTs (similar to MXenes), which are not biodegradable and may pose toxicity risks to humans and the environment. To mitigate these issues, researchers have incorporated CNTs into biodegradable matrices such as polyurethane or SF hydrogels, which can partially degrade or limit CNT release, reducing environmental and biological hazards.[74,80] Surface modifications or doping with biocompatible materials, such as magnesium, further enhance degradability, reduce toxicity, and can even provide beneficial effects like promoting cell growth.[81–83] Polymer coatings like chitosan also improve biocompatibility and antibacterial properties. While these strategies do not fully degrade CNTs, they offer practical approaches to safely harness their functionality in sensors and biomedical devices.

Caratelli *et al.*[84] developed an origami paper-based electrochemical biosensor that combines enzyme-loaded paper-based analytical devices (PADs) with carbon black (CB)/CB-Prussian blue nanoparticles (PBNP) modified electrodes to detect pesticides in the airborne and liquid phases at ppb levels as shown in Fig. 7. While the disposable paper substrate highlights low-cost, eco-friendly fabrication, the study did not address recyclability or degradation of the active materials, leaving scope for future work toward sustainable reuse pathways. Recent advances suggest that this gap could be bridged; for instance, Kalleshappa and Pumera[85] showed that CB can be recovered from spent 3D-printed supercapacitors and reused as an additive in sodium-ion batteries, with performance comparable to fresh CB. Incorporating such strategies could allow paper-based biosensors to achieve rapid field detection while ensuring sustainable end-of-life management. In another work,

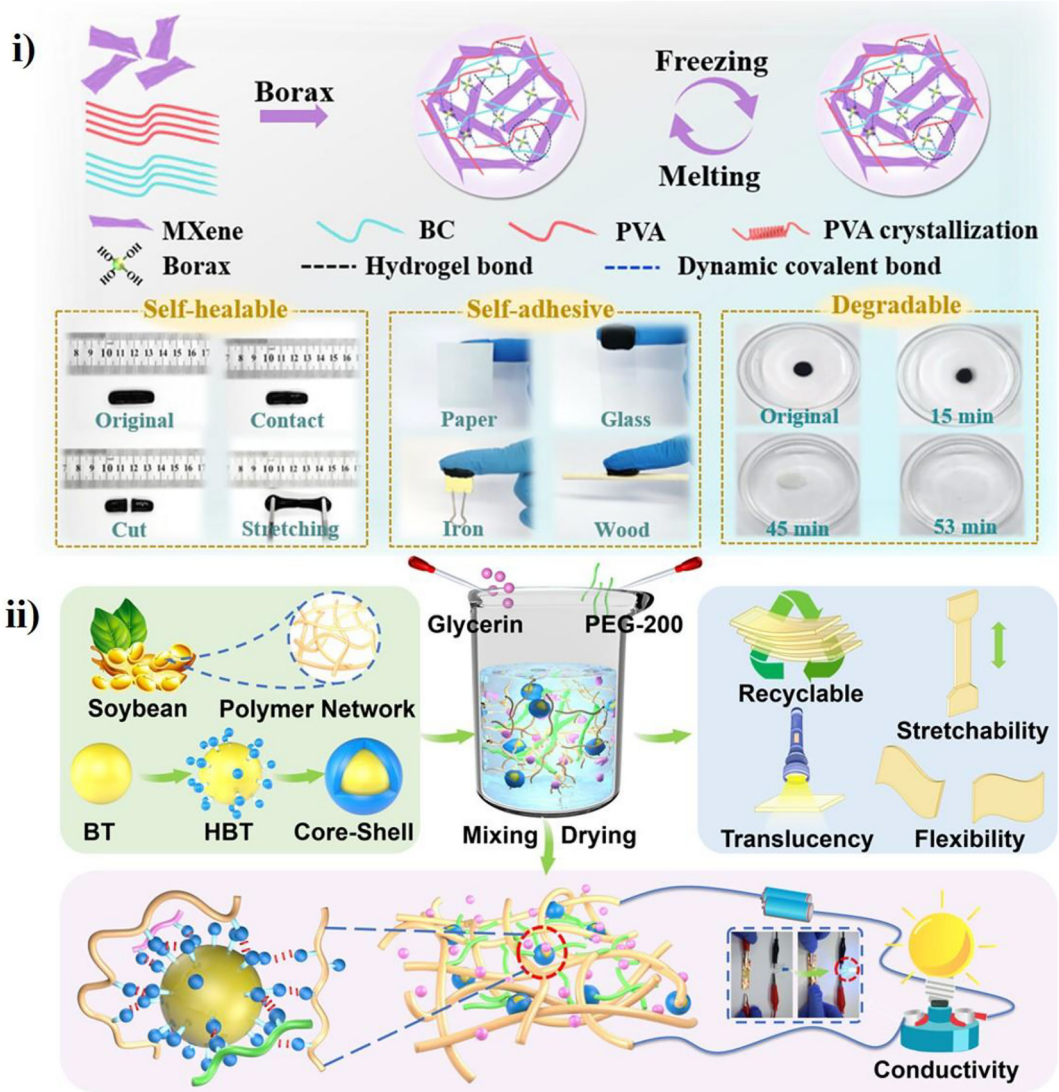


**Fig. 5** (i) Schematic of the PVA/BC/MXene hydrogel formation through dynamic cross-linking of MXene, PVA, BC, and borax *via* freeze–thaw cycles. The hydrogel exhibits self-healing (left), strong adhesion to various surfaces (middle), and rapid degradability in $H_2O_2$ solution (right).[72] (Reprinted with permission from Sun *et al.*, *Adv. Funct. Mater.*, 2023, Copyright 2023 American Chemical Society.) (ii) Schematic of the fabrication and features of SPI–HBT nanocomposite films. HBT nanoparticles are embedded in a soy protein polymer network with glycerin and PEG-200. After mixing and drying, the resulting film shows recyclability, flexibility, stretchability, translucency, and conductivity for use in wearable electronics.[73] (Reprinted with permission from Wei *et al.*, *Appl. Mater.*, 2021, Copyright 2021 American Chemical Society.)

Rani *et al.* presented a compelling example of sustainable sensor design by repurposing waste polypropylene (PP) into a porous, emulsion-templated scaffold for reversible $Cu^{2+}$ detection in water and blood.[86] This approach not only addresses the urgent issue of plastic waste management but also demonstrates how non-biodegradable polymers can be valorized into high-performance, reusable sensor platforms. The integration of spiropyran-based sensing allows for multi-modal detection with visible-light-triggered regeneration, enabling multiple sensing cycles without generating additional waste.

Reflecting on the diverse case studies presented, it is clear that most biodegradable polymers (*e.g.*, PLLA, PCL, PVA, SF, chitosan) have been explored primarily for biomedical applications because they must be biocompatible, degradable in the body, and safe for physiological use. In contrast, environmental monitoring applications require sensors that are not necessarily biocompatible but demand designs that ensure recyclability and sustainability throughout the entire lifecycle, from production to disposal (cradle-to-grave). Even if they are not fully biodegradable, polymer-based sensors should prioritize recyclability and reusability to enable truly sustainable biomedical/environmental sensing.

### 2.3 Functional and conductive polymers

Polymers with functional and conductive characteristics are central to advanced sensor technologies, offering versatility in

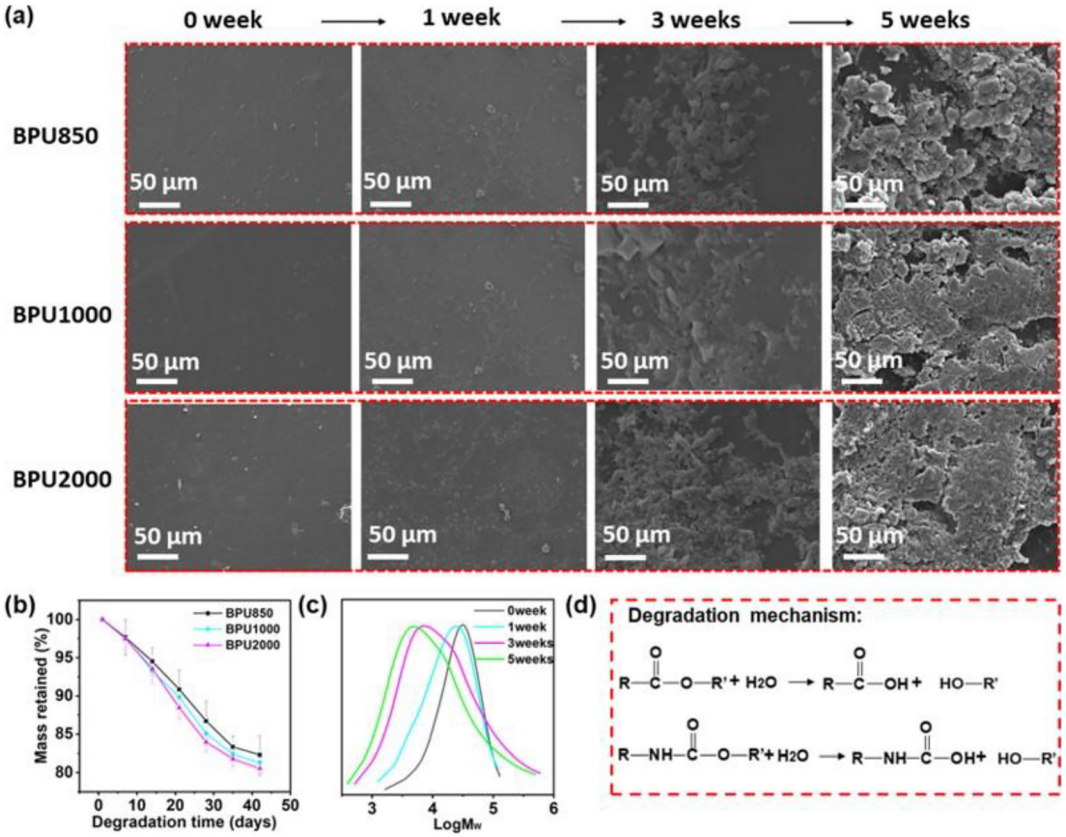


**Fig. 6** (a) SEM images show the surface morphology changes of BPU850, BPU1000, and BPU2000 films after degradation in PBS over 0, 1, 3, and 5 weeks, indicating progressive surface erosion. (b) The weight loss rates reveal increased degradation with time. (c) Gel permeation chromatography (GPC) curves of BPU2000 illustrate molecular weight reduction, confirming polymer breakdown. (d) A schematic illustrates the hydrolysis of ester and carbamate bonds responsible for degradation.[74] (Reprinted with permission from Liu *et al.*, *ACS Sustainable Chem. Eng.*, 2022, Copyright 2022 American Chemical Society.) (iii) (a–g) Details the step-by-step recycling process of the Ag interdigital electrode from the all-paper-based MTP pressure sensor. (a) A schematic shows the overall recycling workflow: the sensor is burned, and the Ag electrode is recovered. (b) shows the intact printed paper sensor before burning, while (c) displays the sensor after burning, reduced to ash with the Ag electrode still present. (d) The fragmented Ag electrode is separated from the ash, and (e) shows the collection process using ethanol. The solution is then subjected to ultrasonic sonication, as seen in (f), to disperse the silver fragments. (g) shows the drying process, which yields reusable silver powder. This process offers a simple and effective method for reclaiming valuable materials, supporting sustainable sensor manufacturing.[71] (Reprinted with permission from Yang *et al.*, *Appl. Mater.*, 2021, Copyright 2021 American Chemical Society.)

performance and responsiveness. Functional polymers are macromolecules with tailored chemical or physical properties that enable selective interactions with analytes, enhancing sensitivity and specificity in sensor applications.[87] They can transduce chemical or biological signals into measurable electrical, optical, or mechanical responses, which is crucial for accurate detection in complex matrices.[88] Among functional polymers, molecularly imprinted polymers (MIPs) and ion-imprinted polymers (IIPs) stand out due to their engineered recognition sites formed through templated synthesis, providing high affinity and selectivity towards target molecules or ions.[89] The controlled polymerization techniques including electropolymerization enable precise formation of these recognition sites.[90–92] Mwanza *et al.* highlight electropolymerization as a sustainable and scalable method for synthesizing molecularly imprinted polymers (eMIPs) in electrochemical sensors. Moreover, electropolymerization facilitates the synthesis of MIPs under more milder conditions, such as in aqueous environments and at room temperatures.[93] As a green alternative to conventional MIP synthesis routes, it offers minimal solvent use, lower energy demands, and precise control over polymer film formation, while also enabling polymer stripping and re-deposition, thus improving recyclability and material reuse. By focusing on environmental monitoring applications, their work demonstrates the potential of eMIPs to enhance sensor performance while supporting the principles of green chemistry.

Sanker *et al.* developed a smartphone-based inverse opal molecularly imprinted photonic crystal hydrogel sensor for colorimetric detection of bisphenol A (BPA) in water.[94] The sensor is highly reusable, maintaining performance for up to one month, with a rapid response (~4 minutes) and ultra-low detection limit (0.69 fM), while using a smartphone readout eliminates bulky instruments, making it portable and low-

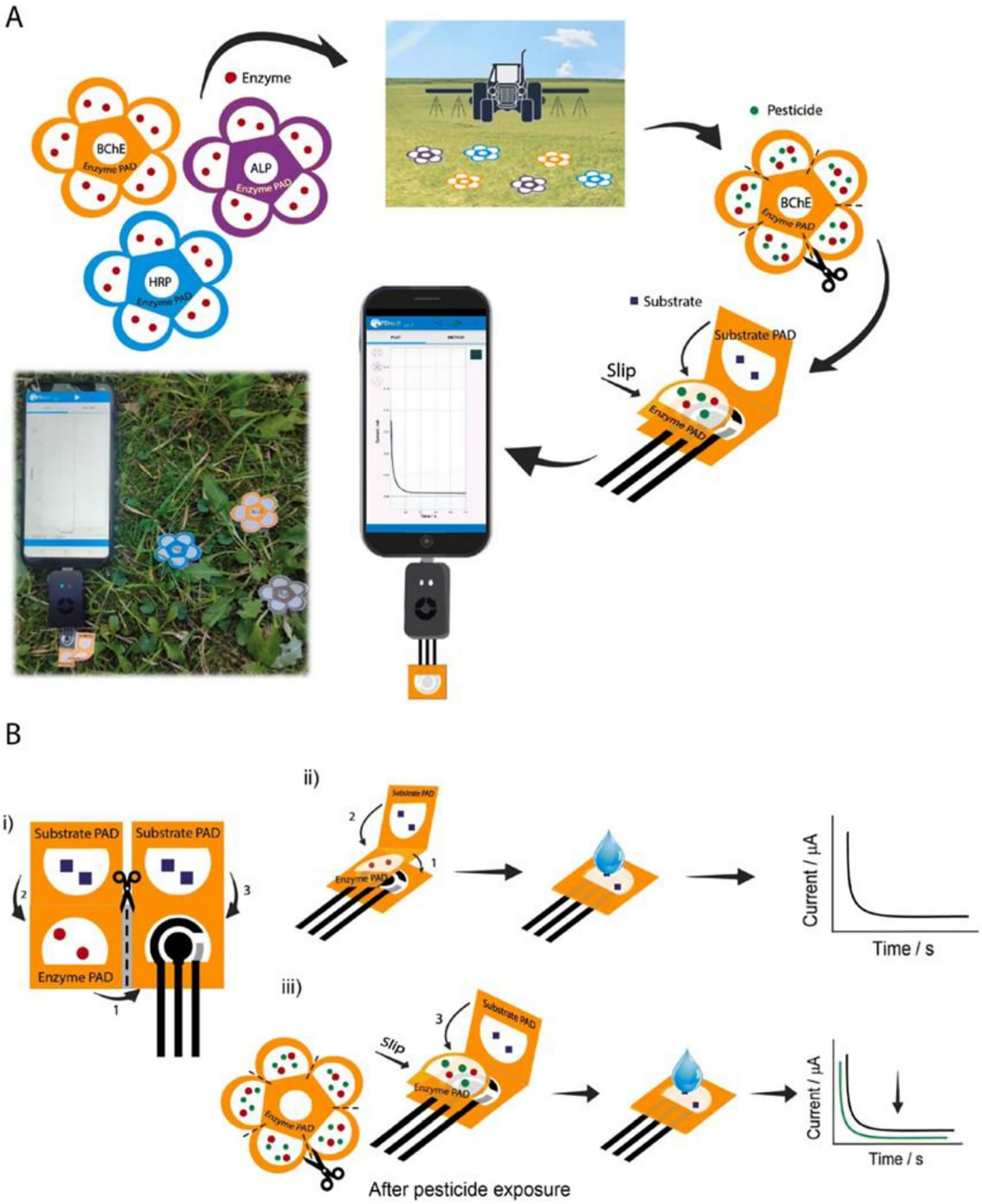


**Fig. 7** Figure illustrates the design and operation of the flower-inspired origami paper-based electrochemical biosensor for pesticide monitoring in the aerosol phase. Panel A shows the assembled device, where a flower-like paper pad, preloaded with enzymes, is coupled to a smartphone-controlled portable potentiostat, enabling user-friendly and on-site measurements. Panel B provides a schematic breakdown of the biosensor. It consists of an office paper-based screen-printed electrode integrated with three filter paper pads. The workflow is also depicted: (i) construction of the electrode-PAD assembly, (ii) measurement of baseline enzymatic activity in the absence of pesticide, and (iii) quantification of residual enzymatic activity following pesticide exposure. The inhibition of specific enzymes by pesticides forms the basis of detection, with signal readouts proportional to the concentration of analytes in the aerosol phase.[84] (Reprinted with permission from Caratelli *et al.*, *Biosens. Bioelectron.*, 2022, Copyright 2022 Elsevier B.V.)

cost. However, the use of polystyrene templates and organic solvents like xylene raises environmental concerns, and the multi-step fabrication may challenge large-scale production. Future efforts toward greener fabrication and longer sensor lifetimes could enhance scalability and sustainability. For instance, Qiu *et al.* developed a thermo-responsive, chitosan-based ion-imprinted hydrogel that selectively binds $La^{3+}$ ions and can be regenerated using only cold water, avoiding harsh acids.[95] This recyclable, water-based strategy reduces environmental impact and improves reusability, offering insights for designing greener polymer-based sensors.

While functional polymers primarily provide chemical specificity and structural versatility, conductive polymers introduce the additional capability of electron transport, making them indispensable for electrochemical and electronic sensor platforms. Conductive polymers such as poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS), polyaniline (PANI), and polypyrrole (PPy) are widely employed in electrochemical and resistive sensors owing to their intrinsic conductivity and room-temperature operation.[96] Beyond these, other classes of conducting polymers, including polythiophene, polycarbazoles, and polyaminonaphthalenes, further expand the design space, offering tunable electrical and mechanical properties that are particularly valuable for flexible and wearable sensing applications. However, most of these polymers are synthetically derived and inherently non-biodegradable, raising environmental concerns. Compounding this challenge, many sensor materials, particularly chemical-type sensors, are single-use, which further amplifies their ecological footprint.

To address these limitations, strategies are being developed to integrate conductive polymers into biodegradable or recyclable systems. For instance, PANI is a notable example: its π-conjugated backbone provides high electrical conductivity, multiple oxidation states, and good environmental stability, while its flexibility and compatibility with diverse substrates make it suitable for wearable electronics. Despite these advantages, PANI is not inherently biodegradable, but it can be engineered for sustainability through blending or copolymerization.[47] Lu *et al.*[97] reported a flexible, self-healable, and electrically conductive wearable strain sensor composed of PANI, phytic acid, and poly(2-acrylamido-2-methyl-1-propanesulfonic acid) (PAAMPSA). Remarkably, this sensor is completely water-soluble and can be recycled to produce new batches, demonstrating a pathway toward environmentally sustainable conductive polymer-based sensors.

### 2.4 Supporting classes

In sensor design, thermosets and elastomers cover a wide material range, including dynamic covalent systems like polyimine and vitrimers, synthetic elastomers such as Ecoflex, polydimethylsiloxane (PDMS), and polyurethane, as well as natural counterparts like natural rubber and dextrin. Conventional thermoset polymers (*e.g.*, epoxy resin, phenolic aldehyde resin) offer excellent mechanical and thermal stability due to their permanent crosslinked networks, making them ideal for electronic applications. However, their poor recyclability has long been a limitation, now addressed by dynamic covalent chemistries that enable reprocessing.[99] While vitrimers and polyimine enable recyclability through dynamic covalent bond exchange, elastomeric systems including Ecoflex, PDMS, polyurethane, natural rubber, and dextrin, offer stretchability and adaptability. Among them, natural rubber and dextrin are particularly notable for their biodegradability, making this class of materials highly suitable for tactile and wearable sensor systems.

Moreover, polymers have relatively low glass transition temperatures ($T_g$), which enable energy-efficient processing compared to rigid inorganic substrates.[100] For example, Qu *et al.*[100] discussed the structural advantages of polyethylene terephthalate (PET) and PP in maintaining mechanical flexibility during repeated bending cycles. Similarly, Batet *et al.*[36] reported the widespread use of PET and polyethylene (PE) substrates in low-cost resistive gas sensors and microfluidic devices, where recyclability reduces material waste in large-scale production. Thermoplastic polyurethane (TPU) and styrene-ethylene-butylene-styrene (SEBS) have also been incorporated into reprocessable strain sensors, offering both elasticity and reshaping capability, thereby extending device lifetimes through reuse cycles.[101,102] These studies highlight how thermoplastics not only provide structural support but also integrate recyclability into scalable sensor designs.

Zou *et al.*[98] developed polyimine-based electronic skin (e-skin) sensors by incorporating silver nanoparticles (AgNP) into a dynamic polyimine polymer to achieve conductivity. These e-skins demonstrated sensitivity to tactile, airflow, temperature, and humidity stimuli. Except for the airflow sensor, all sensors exhibited near-linear responses with sensitivities of 0.0067 $kPa^{-1}$ (tactile), 0.17% $°C^{-1}$ (temperature), and 0.22% (humidity), comparable to other e-skins. The reversible imine bonds enabled the crosslinked polyimine to dissolve in a diamine solution (Fig. 8), separating the polymer matrix from AgNP. The recycled solution was then re-polymerized with added terephthalaldehyde monomers and AgNP to form new conductive films. These recycled films maintained electrical conductivity and mechanical strength, Young's modulus showed only a slight increase after three recycling cycles (Fig. 8iii and iv), while resistivity remained stable (Fig. 8v). Overall, the study highlights efficient recycling and reshaping of polyimine-based e-skins without complex separation, demonstrating circular economy potential through material reuse. Similarly, Yue *et al.*[103] demonstrated epoxy-based vitrimer sensors embedded with CNT fillers that could be reshaped through hot pressing while retaining conductivity.

In contrast to dynamic covalent systems, which allow reshaping and closed-loop recycling, conventional epoxy resins pose a challenge due to their non-degradable, highly crosslinked networks. Their exceptional thermal stability and mechanical strength make them indispensable in electronic applications,[104,105] yet these very features hinder conventional recycling approaches. Recent developments in chemical recycling, including solvolysis,[106] glycolysis,[107] and supercritical fluid treatment,[108] have enabled partial depolymerization of cured epoxies into reusable monomers suitable for new composites or rigid sensing platforms. Building on these advances, Kalpathy *et al.* have patented a solvothermal depolymerization process that efficiently breaks down epoxy matrices into high-value products such as bisphenol A and *p*-isopropenyl phenol.[109] These recovered monomers can be repurposed for adhesives, coatings, and sustainable sensor materials.[110] Furthermore, the same work reports that glass fiber (silica) was recovered from printed circuit board (PCB) recycling, which holds potential for reuse with optically transparent resins to produce flexible, durable composites for applications

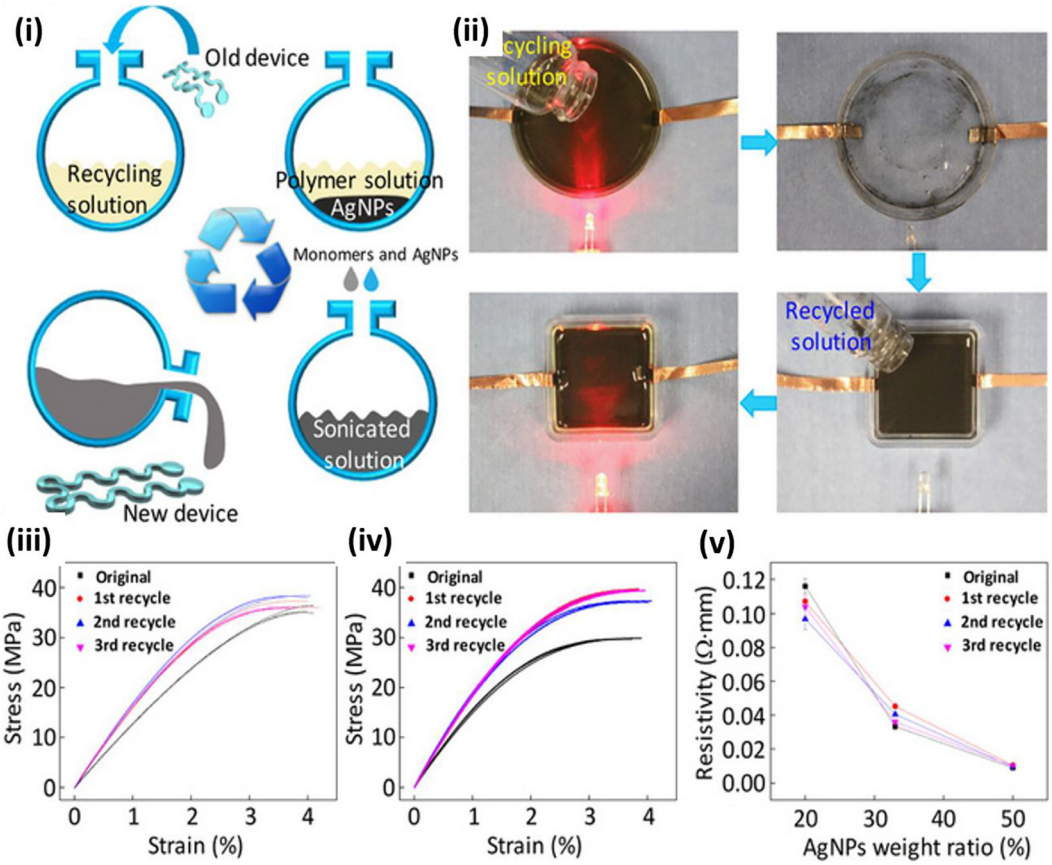


**Fig. 8** The recycling and testing of pure and conductive polyimine (thermoset) films. (i) depicts the overall recycling process; (ii) the light emitting diode (LED) circuit powered by the conductive film glows before recycling (top left) but switches off once the film dissolves (top right). The recovered solution is then transferred to a new Petri dish (bottom right), where it is polymerized into a fresh film that restores conductivity, lighting the LED again (bottom left). Mechanical testing results of pure (iii) and conductive (iv) films show properties before and after recycling, while (v) compares electrical resistivity of conductive films, demonstrating stability through recycling cycles.[98] (Adapted from Zou *et al.*, Sci. Adv., CC BY-NC 4.0.)

such as foldable electronics and polymer-based active surfaces.[111,112]

The diversity of polymers provides a rich design space for sensor development, where each class contributes unique functional, structural, or sustainable advantages. Conductive polymers and MIPs drive analyte selectivity and electrochemical responsiveness, biopolymers and hydrogels add biodegradability and biocompatibility, hybrids and nanocomposites deliver multifunctionality and stability, while thermoplastics and thermosets provide recyclable frameworks. Building upon these developments, the next section explores how advanced material discovery through combinatorial chemistry and high-throughput screening is accelerating the identification of novel functional polymers for future sensing applications.

**Cross-cutting roles of polymers in sensor design.** Polymers often play multiple roles across sensor platforms due to their intrinsic versatility. Conductive polymers such as PANI or PEDOT:PSS can act as functional sensing elements or as components in composite materials with nanofillers (CNTs, MXenes, graphene) to enhance sensitivity, mechanical performance, and stability. Biodegradable polymers like PLGA, or SF provide tunable degradation, self-healing, and biocompatibility, while thermosets and elastomers contribute structural integrity. The same polymer may therefore contribute to different sensor classes, bridging functional, hybrid, and biodegradable designs. When polymers are non-degradable, sustainability can be effectively achieved through strategies such as recyclability, reprocessability, and recovery of embedded nanomaterials, thereby minimizing material waste and environmental impact. This convergence highlights that polymer classes are not mutually exclusive, and that their strategic integration enables the development of multifunctional, high-performance, and eco-compatible sensor platforms aligned with circular material design principles.

## 3. Advanced material discovery through combinatorial chemistry

The advent of combinatorial materials discovery signifies a transformative shift within the domain of polymer sensor

research, effectively bridging the gap between empirical trial-and-error methods and the precision of data-driven design approaches. Given the inherently rich and diverse chemistry of polymers, distinct functional groups can contribute to varying optical, electrical, or mechanical responses. In this regard combinatorial design methodologies would prove far more effective than conventional experimentation, as they can efficiently handle the vast permutations of potential compositions.[115] Through the rapid generation and screening of extensive libraries of materials, these methodologies expedite the identification of polymers possessing optimal properties for sensing applications. In contrast to sequential techniques, combinatorial strategies use parallel synthesis and high-throughput evaluation, enabling the exploration of expansive compositional and structural domains in significantly reduced timeframes, while concurrently minimizing material and energy consumption.[116] In recent years, this paradigm has garnered significant momentum, driven by the escalated demand for sustainable sensors that can be fabricated at low temperatures. This shift has necessitated precise control over material chemistry, processing techniques, and environmental compatibility.[117]

The expansive and largely unexplored chemical landscape of polymers offers both opportunities and challenges for advancements in sensor technology.[11,12] Combinatorial and high-throughput screening methodologies specifically tackle this complexity by facilitating the systematic construction of libraries, typically manifested as thin films or microarrays, with meticulously controlled compositional gradients. These platforms enable the concurrent evaluation of various polymer variants under standardized conditions, resulting in the generation of multidimensional datasets that establish correlations among structure, processing, and function.[118] Automated characterization tools facilitate the efficient assessment of sensitivity, selectivity, and stability, thereby reducing the dependence on fortuitous discovery. Notably, the integration of earth-abundant feedstocks and mild, solution-based processing techniques further augments the sustainability profile of these methodologies, aligning with the objectives of scalable and environmentally-friendly sensor design.[117,119,120]

Combinatorial methodologies have progressively transitioned from their initial applications in catalysis and materials science to become fundamental to contemporary sensor design. Maier *et al.*[121] elucidated the trajectory of high-throughput experimentation (HTE), which initially garnered prominence within the life sciences and subsequently permeated material science domains. Notwithstanding its extensive industrial adaptation the academic uptake of HTE has been comparatively slow. More recently, integration with ML has expanded the scope of combinatorial methods. Champa-Bujaico *et al.*[122] illustrated the use of AI tools in expediting the prediction and optimization of the properties of polymeric nanocomposites, thereby establishing a data-driven approach for the design of multifunctional and sustainable materials. Subsequent practical applications of these concepts have been realized within the realm of sensor materials. Roy *et al.*,[123] for example, employed combinatorial inkjet printing to assess various blends of polythiophenes, revealing that the systematic alteration of PEDOT:PSS and polystyrene-*graft*-3,4-ethylenedioxythiophene (P(S-EDOT)) compositions could enhance electrical conductivity for applications in temperature sensing.

Similarly, Fedorov *et al.*[124] documented the creation of microplotter-printed combinatorial libraries comprising metal oxides on chips, which facilitate "electronic olfaction" arrays with exceptional sensitivity to alcohol vapors at parts per million (ppm) levels. Expanding upon this foundational work, Gohel *et al.*[125] further elucidated that the integration of varied synthetic methodologies with additive manufacturing techniques can yield highly orthogonal multisensor systems for electronic noses, thereby providing remarkable selectivity in the classification of analytes. Parallel efforts by Roh *et al.* have amalgamated variations in combinatorial ligand and metal nodes with the integration of conductive polymers within metal–organic frameworks (cMOFs), resulting in the development of chemiresistive sensors characterized by enhanced recovery kinetics and cycling stability under ambient conditions.[126] Similarly, electrospinning under systematically varied conditions has yielded libraries of polymer nanofibers with tunable properties. These nanofibers directly enhance contaminant detection capabilities while minimizing resource use.[127] Taken together, these studies reflect a shift toward combinatorial paradigms that merge synthesis, printing, and informatics. This integration creates powerful platforms for accelerating the discovery and optimization of advanced polymer sensor materials. In addition to accelerating material discovery, these methodologies facilitate the design of sensors that balance sensitivity, scalability, and sustainability. Consequently, combinatorial approaches not only propel technological advancement but also correspond with the objectives of sustainable development, thereby establishing a foundation for future innovations in environmental and health sensing technologies.

A schematic illustration of integration of high-throughput combinatorial methodologies, computational modeling, open-source materials libraries, and collaborative networks are shown in Fig. 9(i). This approach enables new levels of discovery in the understanding and prediction of structure–property–process–composition relationships in materials.[113] Fig. 9(ii) shows a schematic overview of two high-throughput material synthesis and screening workflows, parallel combinatorial thin-film synthesis with spatially addressable sample arrays, and high-throughput screening of semiconductor thin films.[113,128] Taken together, these advances highlight how combinatorial chemistry, when combined with high-throughput experimentation and AI/ML-driven analytics, is revolutionizing polymer-based sensor design. Such approaches enable the rapid identification of sustainable polymers with minimal ecological footprint while maintaining high sensitivity and selectivity. As the demand for environmental monitoring escalates, the convergence of combinatorial material libraries, low-temperature fabrication methods, and data-driven discovery promises scalable, sustainable, and high-performance polymer-based sensors.[118,128,129]

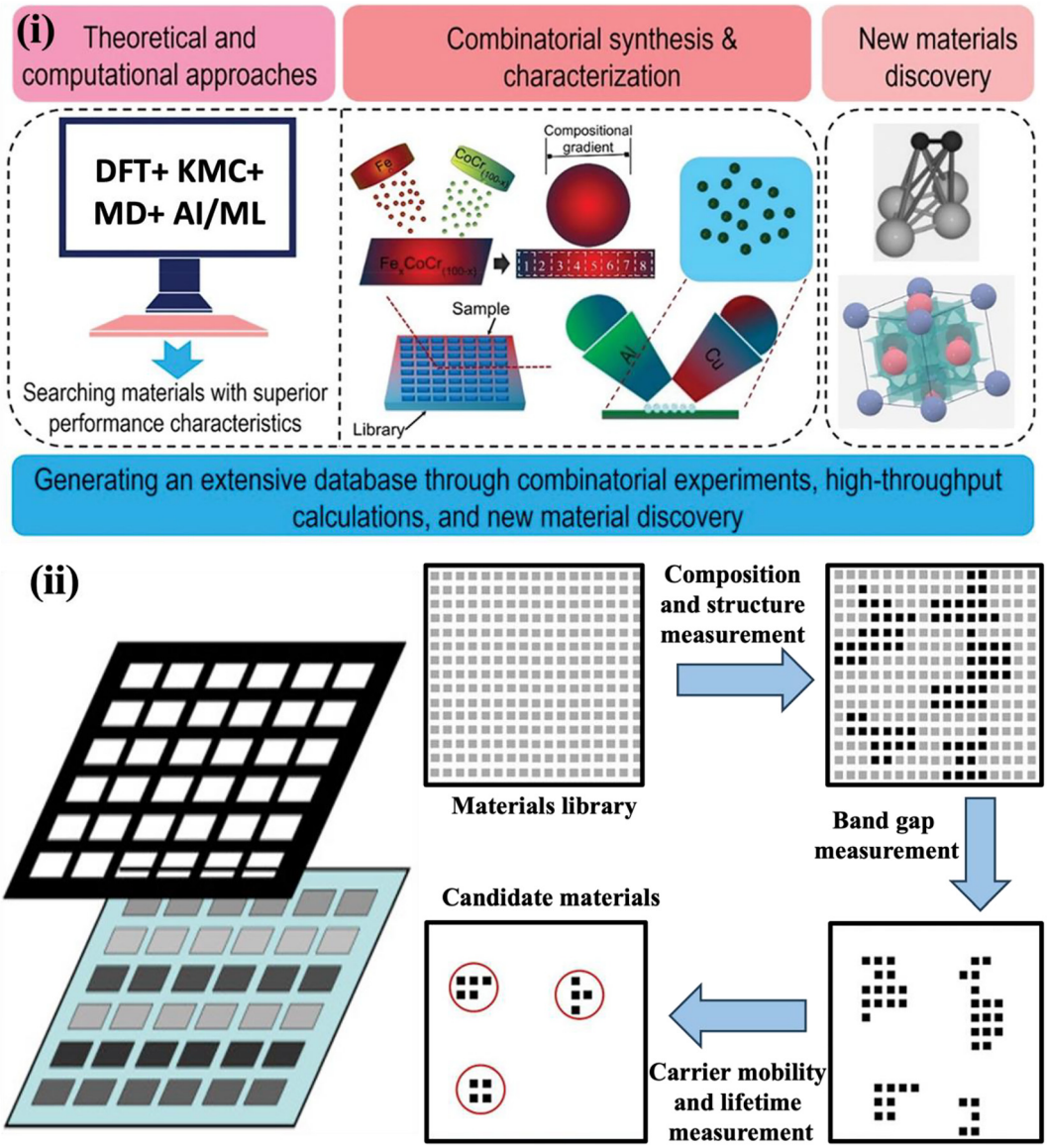


**Fig. 9** (i) Integration of high-throughput combinatorial methodologies, computational modeling (density functional theory (DFT), kinetic monte carlo (KMC), molecular dynamics (MD) and AI/ML), open-source materials libraries, and collaborative networks enables new levels of discovery in the understanding and prediction of structure–property–process–composition relationships in materials.[113] (Reproduced from Shahzad *et al.*, *Sci. Technol. Adv. Mater. Methods*, 2023, under CC BY license.) (ii) Schematic overview of two high-throughput material synthesis and screening workflows: left, parallel combinatorial thin-film synthesis with spatially addressable sample arrays; right, high-throughput screening of semiconductor thin films.[114] (Reproduced from Mao *et al.*, *J. Materiomics*, 2015, under CC BY-NC-ND 4.0.)

## 4. ICME and AI/ML-driven sensor design

While combinatorial approaches accelerate the discovery of suitable polymeric sensing materials, ICME and AI/ML frameworks extend this capability by enabling predictive modeling of material behavior, guiding optimal sensor architectures, and uncovering complex structure–property relationships often inaccessible through experiments alone. Importantly, combinatorial, ICME, and AI/ML approaches are not just alternatives, but complementary strategies for material discovery. By leveraging simulations and data-driven algorithms, ICME and AI/ML reduce experimental burden and enable the rational design of polymer-based environmental sensors. Within this paradigm, the materials science tetrahedron, first introduced by Flemings in 1986, provides a conceptual foundation by linking composition, structure, processing, and properties.[130–132] Extending this classical framework, the ML-driven materials tetrahedron (Fig. 10i) illustrates how data-

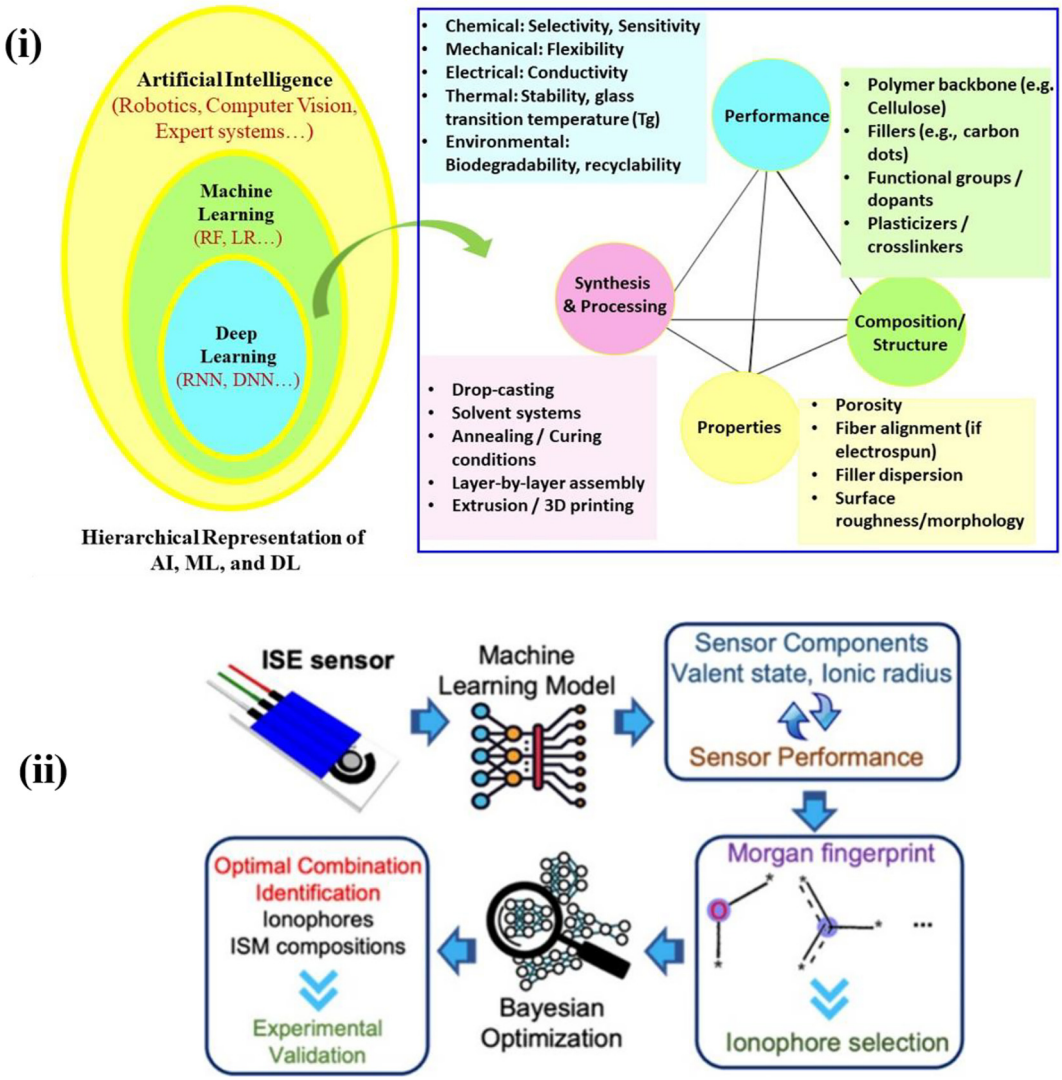


**Fig. 10** (i) Integrated view of AI-ML-DL hierarchy and ML-driven materials tetrahedron for polymer-based sensors materials, illustrating the interdependence of composition, structure, processing, and properties to guide rational design and performance optimization. (ii) Representation of the ML-Bayesian optimization workflow for designing optimized PVC-based ISE sensors.[136] (Reproduced from Huang *et al., Environ. Sci. Technol.*, 2021, CC BY 4.0, American Chemical Society.)

guided correlations across these domains can accelerate the design of sustainable polymer sensors. To operationalize these correlations, ML approaches are employed to model and predict sensor behavior under varying factors such as temperature, humidity, and pressure.

Classical methods such as random forests, support vector machines, and Gaussian processes are particularly valuable when datasets are small, while neural network architectures excel when handling large, complex data. For instance, multilayer perceptrons (MLPs) optimize mechanical strength and thermal stability based on filler type and processing conditions, convolutional neural networks (CNNs) aid structural design by analyzing composite configurations as images, recurrent neural networks (RNNs) capture time-dependent sensor responses under variable environments, and autoencoders uncover hidden relationships between fillers and performance, supporting application-specific composite design.[133] Beyond these, hybrid approaches such as Bayesian optimization, reinforcement learning, and evolutionary algorithms are increasingly explored to autonomously guide experimental workflows and accelerate the discovery of next-generation polymer sensors.[134,135]

In the Industry 4.0 landscape, AI-driven smart manufacturing and robotic systems, demonstrate how intelligent sensing and automation can enhance efficiency and precision.[137,138] In line with these advances, Quinn *et al.* team developed the PANDA (polymer analysis and discovery array) system in the year 2024, a self-driving laboratory that automates the electrodeposition and multi-modal characterization of polymer films. Their work specifically focused on optimizing the electrochro-

mic properties of electrodeposited PEDOT:PSS films using ML driven experimental design, combining robotics, electrochemistry, and optical methods to accelerate polymer materials discovery in a reproducible and efficient way.[139] In another work by Yuankai Huang and colleagues, an advanced polyvinyl chloride (PVC) based ion-selective electrode (ISE) sensors was developed for detecting metal ions in water, integrating ML and Bayesian optimization to enhance sensor performance. They combined ML and Bayesian optimization to predict and improve sensor performance, reducing the need for trial-and-error experiments.[136] Fig. 10ii illustrates the ML and Bayesian optimization framework developed for rational design of high-performance ISE cation sensors.

In another work, a large dataset from 20 years of published research was used to train ML models that could understand how different materials and compositions affect sensor accuracy. The chemical structure of sensor components was captured using a method called Morgan fingerprinting, which converts molecules into numbers that machines can understand. To find out which materials had the most impact on performance, they used SHAP (SHapley Additive exPlanations), a method that explains how much each input (like type of plasticizer or ion size) contributes to the model's prediction. Finally, Bayesian optimization was used to automatically suggest the best material combinations and fabrication conditions, making the whole sensor design process faster, cheaper, and more effective. In parallel, this approach mirrors the concept of polymer genomics, where AI and data-driven methods are used to uncover structure–property relationships in polymers. This enables the rational selection of materials with tailored mechanical and functional characteristics, particularly suited for low-temperature, sustainable sensor fabrication.[133]

Yue *et al.* developed a flexible, conductive yarn-based strain sensor featuring deliberately engineered microcrack architectures, which collectively enable ultrahigh sensitivity, a broad operational strain range, and outstanding mechanical durability. The device demonstrates pronounced environmental robustness, including resistance to both acidic and alkaline media as well as stable operation under submerged conditions. Such characteristics are particularly critical for practical deployment in wearable electronics and low-temperature sensing scenarios. Furthermore, the incorporation of ML methodologies facilitates advanced signal processing for gesture recognition and motion tracking, underscoring the increasing convergence of polymer-based sensing materials with AI-driven platforms.[140] Jia *et al.* developed a gradient-structured fibrous pressure sensor integrated with ML techniques for high-precision posture recognition and physiological monitoring. Their findings demonstrate that ML-assisted signal processing can substantially enhance the robustness, accuracy, and functional versatility of polymer-based wearable sensing systems.[141] Huang *et al.* reported the development of a multimodal conductive organohydrogel derived from chitosan-encapsulated MXene nanocomposites, which exhibits high stretchability, robust environmental tolerance, and intrinsic self-healing capability, and is further coupled with deep learning-assisted ball sports recognition. By integrating deep learning algorithms with multimodal sensor outputs, the system attained 100% classification accuracy for distinct ball sports activities, thereby underscoring the strong synergistic potential between advanced functional materials and ML techniques for next-generation intelligent wearable sensing platforms.[142] Collectively, these studies demonstrate that the convergence of advanced polymer-based sensing platforms with state-of-the-art ML and deep learning methodologies is essential for the realization of intelligent, high-precision, and multifunctional wearable sensing systems.

Building upon these advances, recent investigations have further elucidated how the selection of polymer support classes and the implementation of ML-based analytics can be jointly optimized to enhance the sustainability, intelligence, and overall performance of sensing platforms. In a 2025 study, Xing *et al.* reported a flexible, multilayer polymer support architecture that integrates mechanically robust yet lightweight substrates with engineered interlayers, thereby enabling stable signal transduction under complex mechanical deformation while maintaining compatibility with low-temperature, large-area fabrication processes.[143] In parallel, a recent study by Xing *et al.*[144] demonstrated that the direct application of ML algorithms to raw signals obtained from polymer-based sensor arrays can autonomously extract robust discriminative features, compensate for environmental drift, and enhance recognition accuracy in complex physiological and behavioral monitoring scenarios.[144] In a complementary study, Liu *et al.*[145] developed a deep learning-assisted tactile sensing platform employing flexible, polymer-supported sensor arrays, which facilitates high-accuracy and robust object classification and password recognition even under repeated mechanical loading.[145] By rigorously integrating the structural design of the supporting polymer framework with convolutional neural network-based feature extraction and classification pipelines, this approach demonstrates how materials engineering and deep learning can be co-optimized to enable reliable, high-throughput tactile sensing in complex, multi-object environments. This work further substantiates the emerging paradigm of AI-enhanced polymer-based sensor architectures as a key technological foundation for secure and intelligent human–machine interfaces.

While ML offers transformative potential for polymer composite research, its adoption faces key hurdles such as limited high-quality datasets, inconsistent data standards, and the limited interpretability of deep learning (DL) models, which often act as "black boxes" by providing accurate predictions without clear scientific explanations. Addressing these challenges requires physics-informed ML and hybrid strategies that merge data-driven approaches with established simulations like finite element analysis (FEA) and molecular dynamics (MD).[146] In a recent review, Zhang *et al.* demonstrate how integrating ML into the ICME framework has accelerated superalloy design by streamlining the exploration of composition, microstructure property relationships. While ICME traditionally relies on computational thermodynamics and kine-

tics to guide material optimization, the authors explain that it is still difficult to explore all possible material combinations using simulations alone. To address this, deep learning models have been embedded into ICME workflows, enhancing computational accuracy and enabling high-throughput screening.[147] Another clear demonstration of how computational and data-driven approaches can systematically guide materials discovery is provided by Xu *et al.*,[148] where 779 625 compositions were computationally screened. And narrowed down to 12 high-performance candidates through ICME and AI/ML, with Support Vector Regression (SVR) models eliminating over 99.99% of less promising alloys. This integration of physics-based modeling and ML can drastically shorten the materials discovery cycle. Replicating such workflows for polymer-based sensor materials can enable rational composition selection, functional property prediction, and accelerated development of next-generation sustainable sensors.

## 5. Scalable low-temperature processing: printing, coating, and 3D printing

Solution-processable fabrication methodologies, including dip coating, screen printing, and inkjet printing, permit low-temperature processing, frequently at or near ambient conditions, thereby rendering them particularly advantageous for the scalable, cost-effective development of sensor platforms suitable for integration into IoT architectures.[153,154] Table 2 provides a comparative overview of representative low-temperature fabrication methodologies employed in the realization of polymer-based flexible sensors, detailing not only their respective processing temperature windows but also key manufacturability metrics, such as compatibility with mechanically compliant substrates, suitability for large-area and potentially roll-to-roll processing, and applicability to rapid prototyping workflows. Although each method exhibits particular limitations, such as intermittent alignment inaccuracies, constraints in material compatibility, and challenges related to process reproducibility, these drawbacks are relatively minor when evaluated against the considerable benefits they confer in terms of high throughput, enhanced design flexibility, and seamless integration with roll-to-roll or other additive manufacturing workflows. Importantly, all of these techniques operate at comparatively low processing temperatures, rendering them substantially more energy-efficient and cost-effective, as well as more compatible with lightweight polymeric substrates, than conventional silicon-based microfabrication approaches. Consequently, polymer materials, typically inexpensive and, in many cases, recyclable, can be reliably processed into flexible, large-area, and readily customizable sensing platforms that

**Table 2** Low temperature fabrication techniques and their advantages

| Technique | Key advantages | Limitations | Ref. |
|---|---|---|---|
| Drop casting | Simple, scalable, and material-efficient for small-scale prototyping | Limited by poor thickness control (1–100 μm)[27] and low reproducibility on large areas | 32, 149 and 150 |
| Dip coating | Simple, low-cost, and enables uniform large-area coatings with controllable surface coverage | Material- and time-intensive, with double-sided coating, uneven thickness (<50 nm),[151] and poor reproducibility on complex shapes | 149 and 152 |
| Screen printing | Rapid, low-cost, and scalable with good thickness control and reproducibility across diverse substrates | Limited resolution, ink sensitivity, and requires substrate pretreatment and precise alignment | 153–155 |
| Doctor-blade | Enables precise thickness control, large-area coating, minimal waste, and is suitable for both lab and industrial use | Requires accurate blade alignment and works best on flat surfaces, with limited application on uneven or 3D shapes | 156 and 157 |
| Flexography | High-speed, cost-effective technique ideal for mass production with good repeatability and optical coupling benefits | High equipment cost, limited ink options, large ink use, edge distortion, and possible damage to existing structures | 150, 158 and 159 |
| Gravure printing | High-resolution, low-cost, and fast technique suitable for fine microfluidic devices and single-pass barrier formation | Expensive cylinders, ink drying issues, limited functional inks, and high material consumption in RD | 158 and 160 |
| Ink-jet printing | Digitally controlled, non-contact, low-cost method with high precision, minimal waste, and versatile substrate/ink use | Poor adhesion on some substrates, droplet spreading, complex ink formulation and need for sintering | 159 and 161 |
| Spin coating | Fast, low-cost, and reproducible method with precise thickness control for uniform thin films | Limited to small, flat substrates, wastes material, and film quality depends on solution and spin conditions | 162 and 163 |
| Electro-spinning | Cost-effective, scalable method for producing high-surface-area, tunable fibers with easy integration and flexibility | Difficulty in achieving uniform fiber morphology over large areas | 164–166 |
| Solution-blow spinning | Cost-effective, high-throughput deposition of porous fiber mats directly onto flexible or non-planar substrates for wearable sensing | More difficult to control uniform fiber diameter and alignment over large areas, leading to variability between devices | 31 and 33 |
| 3D printing (additive manufacturing) | Rapid, scalable, and eco-friendly method for customizable, complex sensor designs with minimal waste | Limited in multi-material printing and often needs hybrid fabrication for desired properties | 167 and 168 |

satisfy the manufacturability and scalability requirements of emerging wearable electronics and IoT systems.

Recent case studies clearly illustrate how low-temperature fabrication enables the creation of flexible polymer sensors without sacrificing performance or scalability. For instance, Kumar *et al.*[27,32] developed a polymer-based sensor for detecting heavy metal ions in water. Drop-cast polymer films adsorb metals like copper, lead, and mercury, which are then analyzed using Fourier transform infrared (FTIR) spectroscopy to quantify contaminants down to nanomolar levels. This simple, low-resource method offers an alternative to complex techniques like inductively coupled plasma-optical emission spectroscopy (ICP-OES), making it suitable for use in rural or resource-limited settings. In another work, Al Shboul *et al.*[169] reported a fully printed flexible temperature sensor based on a polystyrene/graphite nanocomposite thermistor, fabricated using the doctor blade coating method.[169] The sensor showed excellent thermal stability, mechanical flexibility, and chemical resistance, maintaining performance even under harsh environmental conditions such as humidity, corrosive gases, and water immersion. It exhibited two distinct linear response regions (−10 to 10 °C and 20 to 60 °C) with high sensitivity and fast response/recovery times, making it well-suited for real-world applications such as breath monitoring, environmental sensing, and healthcare diagnostics.

Examples of low-temperature fabrication span multiple modalities, from drop-cast polymer films for contaminants detection, to screen-printed resistance-based temperature/pH sensors, and 3D-printed platforms for environmental monitoring. Printed temperature sensors are mostly resistance-based, where the sensor's electrical resistance changes with temperature. For which, conventional sensors typically rely on expensive metals such as platinum or on inks containing metallic micro- or nano-objects.[50] As a cost-effective alternative, Le Goupil *et al.* demonstrated that screen-printed sensors using silver particle inks achieve comparable performance while enabling low-temperature fabrication on flexible substrates like PET, poly(ethylene naphthalate) (PEN), and polyimide as shown in Fig. 11i.[170] These polymer-based sensors offer excellent scalability and ease of integration. Their seamless compatibility with IoT systems makes them ideal for next-generation wearable and disposable sensing applications. In another work, Katseli, Economou, and Kokkinos developed a 3D-printed electrochemical ring (e-ring) designed with Tinkercad.[171] Miniaturization and flexible integration were achieved using thermoplastic polymers such as a TPU holder and carbon-loaded PLA electrodes fabricated in a single low-temperature step. The working electrode is coated with electrodeposited gold for nonenzymatic glucose detection. As shown in Fig. 11iv, the e-ring connects *via* crocodile clips to a miniature potentiostat and smartphone app for wearable glucose monitoring.

Following this shift toward flexible, low-temperature, and environmentally conscious fabrication, researchers are now addressing the challenge of developing sensors on curved and irregular surfaces, where traditional high-temperature deposition techniques perform poorly due to poor adhesion, difficulty in maintaining uniform film thickness, and the limited compatibility of conventional deposition methods (like PVD/CVD) with non-planar geometries. Even in such demanding conditions, polymer-based materials stand out for their intrinsic flexibility, processability, and ability to conform seamlessly to diverse substrates. Cui *et al.* developed a screen-printing strategy using $CO_2$ laser-patterned polyimide stencils, which allowed for precise and conformal sensor formation on curved substrates.[172] While screen printing improves deposition on curved surfaces, Digital Light Processing (DLP) 3D printing takes fabrication further. DLP offers a polymer-centric, low-temperature approach ideal for scalable sensor development. Using photocurable polymers such as elastomers, hydrogels, and ionogels, DLP enables rapid prototyping of highly sensitive, conformal, and stretchable devices with microscale precision.[173] Its ability to spatially program mechanical and electrical properties through graded polymer architectures makes it especially promising for next-generation wearable and implantable sensors requiring customization, biocompatibility, and multifunctionality. Additive manufacturing (AM), particularly extrusion-based 3D printing, complements this by allowing the development of complex geome-

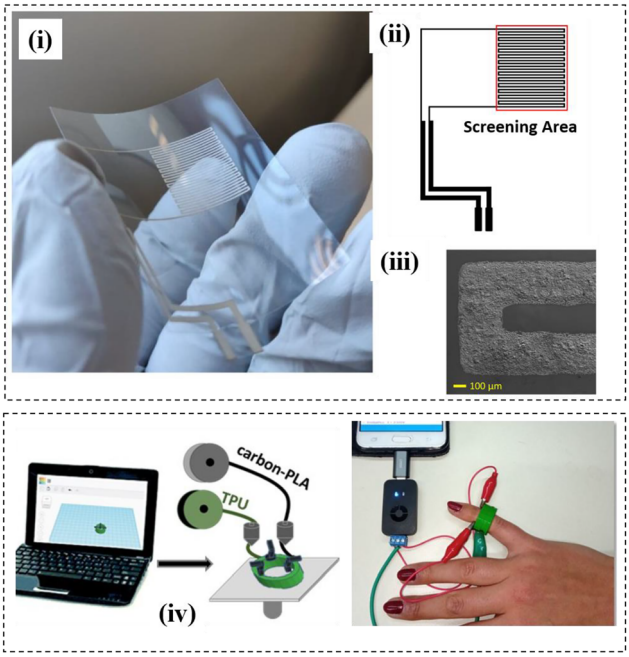


**Fig. 11** (i) Optical image of the sensor printed on flexible PET substrate. (ii) Schematic of the fully printed temperature sensor with a meandering silver particle conductive line in the sensing area. (iii) Scanning electron microscope (SEM) image showing the uniform silver particle line after a single printing run.[170] (Adapted from Goupil *et al.*, *ACS Omega*, 2023, Copyright 2023 American Chemical Society (CC BY-NC-ND 4.0)), (iv) design and setup of the 3D-printed electrochemical ring (e-ring), showing its flexible structure, integrated electrodes, and connection to a smartphone-controlled miniature potentiostat.[171] (Adapted with permission from Katseli *et al.*, *Anal. Chem.*, 2021, Copyright 2021 American Chemical Society.)

tries with minimal material waste using thermoplastics like PLA, PVDF, and ABS. These polymers often act not only as substrates but also as active sensing materials when combined with conductive fillers like CB or multiwalled carbon nanotubes (MWCNTs). Innovations such as PLA/MWCNT helices or recycled graphite-ABS composites enhance both functionality and sustainability.[168]

Taken together, screen-printing and additive manufacturing have revolutionized low-temperature fabrication of sensors. Screen-printing offers low-cost, large-scale production with versatile substrate compatibility, while 3D additive techniques enable rapid prototyping of complex, customized geometries.[153] In general, solution-based techniques highlight how researchers can leverage the versatility of plastics and polymer-based composites to enable low-temperature, scalable, and sustainable sensor fabrication across a wide range of substrates and geometries. Beyond conventional planar printing strategies, recent advances in 3D additive manufacturing technologies have substantially broadened the design space for polymer-based sensing platforms, in which mechanical compliance, breathability, and form-factor adaptability represent key performance determinants. As comprehensively reviewed by Liu *et al.* in their 2024 survey of flexible temperature sensors,[174] solution-processable polymers and polymer-based composites facilitate the realization of temperature sensing devices that integrate low-temperature fabrication with high mechanical flexibility, rapid thermal response, and conformal integration on curved or compliant substrates. Notably, a substantial proportion of these devices are fabricated *via* printing-based processing routes, thereby underscoring the pivotal role of additive manufacturing as an enabling technology for next-generation flexible and wearable thermal sensing platforms.

A compelling demonstration of the potential of low-temperature 3D-printed polymer-based sensors is presented by Sang *et al.*, who reported a fully 3D-printed bimodal electronic skin capable of concurrently detecting both pressure and temperature stimuli.[175] Through the implementation of multi-material *in situ* 3D printing of pressure-sensitive inks onto transparent, flexible substrates, the authors realized a tactile sensing density of 100 $cm^{-2}$, closely approximating that of human fingertips, while simultaneously preserving a linear temperature response across the biologically relevant range of 10–60 °C. This study demonstrates that low-temperature additive manufacturing enables the fabrication of mechanically compliant, multifunctional polymer-based sensor systems that are not achievable using conventional silicon-based microfabrication technologies. In parallel, 3D printing has emerged as a versatile and effective technology for environmental sensing, with particular relevance to water quality monitoring. Sun *et al.* conducted a comprehensive systematic review of 3D-printed sensors for water monitoring applications,[176] illustrating how polymer-based additive manufacturing facilitates the rapid and customizable fabrication of sensing platforms, electrodes, and fully integrated, additively manufactured sensor systems. Relative to conventional microfabrication methodologies, these approaches provide substantially reduced fabrication costs, expanded latitude in material selection, and more straightforward integration with fluidic architectures, thereby rendering them particularly advantageous for decentralized and single-use environmental monitoring applications.

Low-temperature additive manufacturing has additionally facilitated the development of mechanically robust, wearable sensors for monitoring human motion and physiological signals. Hou *et al.* reported the realization of conformal strain and humidity sensors produced by multi jet fusion (MJF) additive manufacturing of graphene nanoplate–carbon nanotube composite inks.[177] The printed sensors demonstrated pronounced mechanical robustness, stable and reproducible humidity sensitivity, and reliable strain-responsiveness, thereby facilitating accurate inference of joint kinematics and respiratory dynamics when integrated with ML algorithms. The intrinsically layer-by-layer fabrication process of MJF printing not only enhanced the mechanical durability of the devices but also maintained their functional integrity at low temperatures, thereby highlighting the suitability of polymer-based additive manufacturing as a scalable platform for health-monitoring technologies. Collectively, these case studies demonstrate that 3D printing of polymer-based sensors has progressed beyond its traditional role as a prototyping tool and is rapidly emerging as a robust and scalable manufacturing strategy for high-performance sensing platforms, particularly in the domains of environmental surveillance and health monitoring. By integrating extensive material versatility, structural programmability, and intrinsically energy-efficient fabrication, additive manufacturing serves as a complementary approach to screen-printing and other solution-based deposition techniques, thereby reinforcing the broader technological transition toward sustainable, mechanically compliant, and application-driven sensor platforms.

One of the foremost challenges in polymeric and hybrid sensors, especially for environmental monitoring, is interference from non-target species, signal crosstalk, and poor selectivity in complex matrices. To overcome these, very recent studies (2024–2026) have pivoted from conventional surface chemistry tweaks to advanced material design, functional interface engineering, algorithm-assisted signal discrimination, and hybrid architectures. For example, Yang *et al.* systematically investigated the adsorption behavior of heavy metal ions on paper substrates used in polymeric potentiometric sensors and found that 40–50% of ions were retained at low concentrations, resulting in super-Nernstian responses and significant interference. Based on these findings, they developed a corrective protocol using polynomial-fitted adsorption models to compensate for competitive ion uptake by the substrate, enabling accurate prediction of true Nernstian responses without surface modification. This approach yielded less than 10% deviation compared to ICP-OES analysis in real water samples.[181] Recent sensor designs increasingly exploit MIPs to enhance selectivity and suppress interference from co-existing species in complex environments. By tailoring the functional monomer and imprinting process, MIP-based

electrochemical and potentiometric sensors have demonstrated significantly improved discrimination against structurally similar interferents, effectively reducing nonspecific interactions that degrade signal quality.[182] Studies have shown that combining MIPs with advanced transducer layers (*e.g.*, graphene) or multifunctional monomer systems further stabilizes signal transduction and suppresses interfering species in mixed analyte conditions, confirming that rational MIP design is an effective strategy for interference control in next-generation polymeric sensors.[183–185] In parallel, ML-assisted signal analysis enables discrimination of overlapping analyte responses and compensation for environmental fluctuations without introducing additional toxic components.[186] These approaches collectively represent a shift toward smart materials and intelligent data processing as the frontier for mitigating interference in next-generation polymeric sensors.

## 6. Smart integration: IoT, smartphone platforms, and data intelligence

While combinatorial experimental approaches and ICME/AI/ML frameworks enable rapid discovery and predictive design of materials and devices at the laboratory scale, the full impact of these advances emerges only when sensors are integrated into smart platforms that connect them to end-users. Recent developments in the IoT, smartphone-based interfaces, and cloud/edge data intelligence have transformed stand-alone sensors into connected networks capable of real-time monitoring and decision-making.[187,188] This section discusses how polymer-based, low-temperature-fabricated sensors can be embedded within such digital ecosystems, bridging the gap between material innovation and practical deployment.

IoT facilitates wireless data transmission using protocols like ZigBee, Bluetooth Low Energy (BLE), LoRa (a low-power protocol enabling long-distance communication between sensors and gateways), Global System for Mobile Communications (GSM), and WiFi.[189] For instance, smart irrigation systems using low-cost soil moisture sensors and weather stations, integrated with IoT and cloud analytics, optimize water usage in agriculture.[190] IoT-enabled weather stations collect data like temperature, humidity, and wind speed, which when processed *via* cloud analytics and big data enable predictive irrigation control. AI and ML improve decision making by forecasting water needs and crop responses. Long-range communication protocols like LoRa and GSM ensure reliable data transmission even in remote areas. Combined with scalable cloud storage and real-time dashboards, these systems minimize resource use and empower even small-scale farmers with data-driven insights.

A compelling example of low-temperature, polymer-compatible sensor fabrication is the lab-on-a-glove biosensor by Wang and co-workers.[178] This stretchable system uses screen-printable, stress-enduring inks on nitrile polymer substrates to detect organophosphate threats, incorporating printed carbon and Ag/AgCl electrodes and a gel-based enzymatic layer. A miniaturized wireless potentiostat enables real-time voltammetric data transfer to smartphones, demonstrating the potential of scalable, low-cost wearable point-of-care (PoC) tools as shown in Fig. 12i. Complementing this, their ring-based wearable sensor integrates carbon and Prussian blue electrodes with a wireless potentiostat in a 3D-printed polymer ring as shown in Fig. 12ii, for real-time detection of explosives and nerve agents in vapor and liquid phases.[179] While analytically robust, future versions could benefit from smartphone integration, cloud analytics, and AI-driven data processing. Additionally, while the current fabrication involves screen-printing Ag/AgCl, carbon, and Prussian blue inks onto PET substrates with sequential curing at 85 °C, advancing toward fully additive, low-temperature, and scalable fabrication using printable polymer systems would enable more sustainable, high-throughput sensor production suitable for IoT-enabled field deployment.

In another study by Song *et al.*, a wireless self-powered gas sensor network was developed for smart home applications, using Pd-decorated 3D$SnO_2$ nanostructures that achieved ultra-low detection limits (as low as 1 ppb) for gases such as $H_2$, formaldehyde, toluene, and acetone. The system, termed SINGOR (self-powered integrated nanostructured gas sensor), integrates solar energy harvesting, low-power Bluetooth communication, and mobile app-based data visualization to enable real-time, remote monitoring and localization of hazardous gases using ML algorithms.[180] The system layout is illustrated in Fig. 12c, which depicts sensor deployment within a smart home, along with key components including a lithium-ion battery, Pd/$SnO_2$ sensors fabricated on anodic aluminum oxide (AAO) substrates, signal processing circuitry, and a Bluetooth module. These elements are compactly assembled on a PCB, supporting autonomous and energy-efficient operation. While the study successfully demonstrates a robust IoT-based sensing platform, the gas sensors themselves were fabricated using high-temperature annealed Pd/$SnO_2$ thin films *via* atomic layer deposition on AAO templates. Although the operation of the SINGOR system, once deployed, is ultra-low-power, consuming only 4.3 μW per sensor, the fabrication process is complex and energy-intensive. These factors limit scalability, posing challenges for practical IoT-enabled sensor deployment in resource-conscious settings. To overcome such limitations, the convergence of low-temperature polymer-based sensor fabrication with smartphone-based readouts and energy-efficient IoT integration represents a sustainable and scalable alternative. This approach paves the way for next-generation sensing systems that are smart, affordable, adaptable, and environmentally responsible.

Supporting this trend toward sustainable, low-energy sensor technologies, Stefano Mariani and colleagues have developed a biodegradable, seed-inspired soft robot (I-SeedPel) for autonomous visual humidity sensing, leveraging hygro-mechanical motion to correlate structural changes with ambient humidity.[191] Fabricated entirely from biodegradable polymers such as PCL, polyethylene oxide (PEO), and cellulose nanocrystals


**Fig. 12** (i) Schematic of a wearable glove biosensor system featuring screen-printed stretchable electrodes, a swipe-based sampling pad, and a flexible wireless electrochemical module for real-time detection of organophosphate compounds.[178] (Reproduced with permission from Mishra *et al.*, *ACS Sens.*, 2017, **2**, 553–560. https://pubs.acs.org/doi/10.1021/acssensors.7b00051); (ii) schematic of a ring-type wearable sensor with flexible polymer substrate and integrated wireless module for real-time detection.[179] (Reproduced with permission from Sempionatto *et al.*, *ACS Sens.*, 2017, **2**, 1470–1478. https://pubs.acs.org/doi/10.1021/acssensors.7b00603 Copyright © 2017 American Chemical Society.) (iii) Illustrates the layout and components of the SINGOR system (a) shows the spatial deployment of the sensor array within a smart home environment for real-time gas leakage detection. (b) depicts remote gas monitoring through a smartphone interface enabled *via* Bluetooth. (c) highlights the modular integration of key components, including a solar energy module, lithium-ion battery, and a 3D Pd/$SnO_2$ gas sensor array.[180] (Adapted with permission from Song *et al.*, *ACS Nano*, 2021, Copyright 2021 American Chemical Society.)

(CNC), the device uses low-temperature additive manufacturing techniques, combined with coaxial electrospinning. These accessible, energy-efficient fabrication methods enable the integration of functional materials into soft robotic architectures. This approach demonstrates how polymer-based systems can seamlessly merge with bioinspired robotics to create sustainable, battery-free, and visually readable sensors for distributed environmental monitoring, offering mechanical adaptability and environmental compatibility.

Recent polymer-based wearable systems further demonstrate how the integration of on-device processing, cloud connectivity, and AI/ML analytics enables not only efficient data transmission but also advanced health signal interpretation and actionable insights. For example, ML algorithms have been shown to significantly enhance the real-time analysis and clinical relevance of data from flexible wearable sensors, improving accuracy in personalized health monitoring and pattern recognition tasks.[192–194] Promphet *et al.* developed a wearable sweat glucose sensing system, where a flexible electrochemical sensor strip modified with CNTs and cellulose nanofibers transmits data *via* Bluetooth to a smartphone app for real-time diabetes screening, and ML was used to optimize

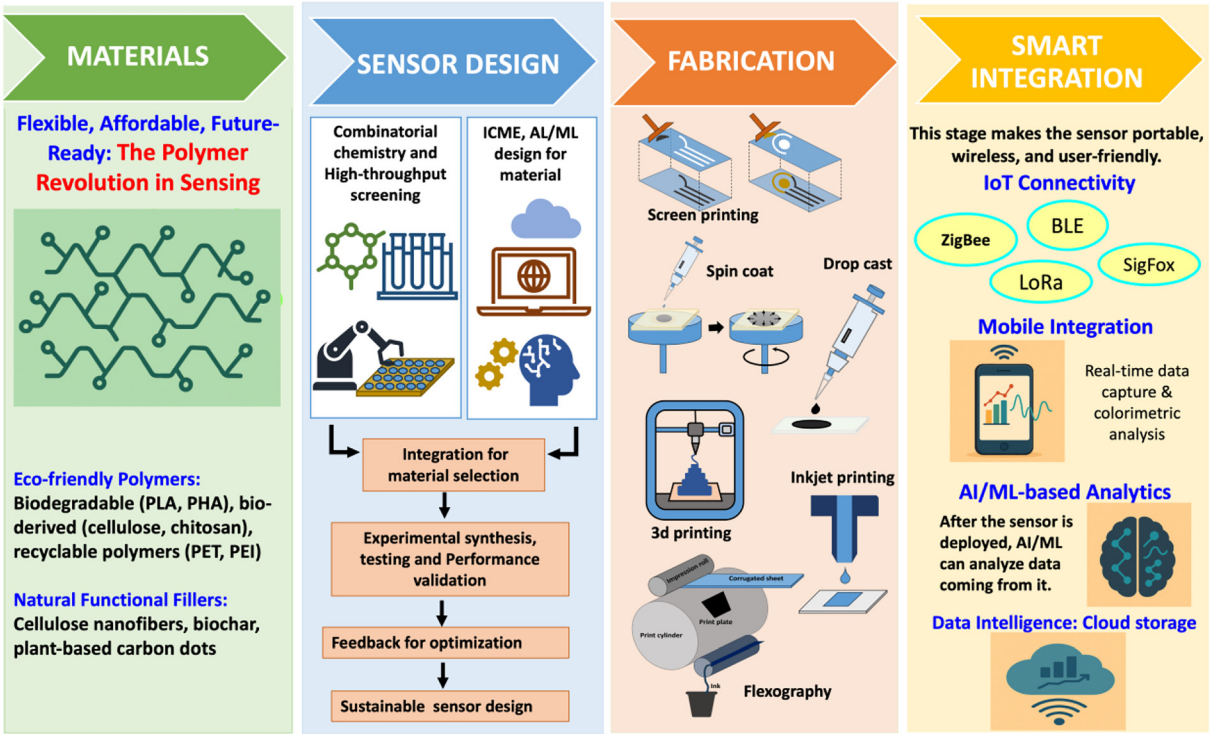


**Fig. 13** Roadmap illustrating sustainable polymer sensor development, highlighting the progression from materials and design to fabrication and intelligent IoT integration.

the signal response and sensing parameters for accurate monitoring in complex biofluids.[195] Farahmandpour and Kordrostami developed a paper-based wearable Bio-FET array for sweat glucose, pH, and temperature sensing using MXene-based composites. ML algorithms were used to process the sensor data, calibrate glucose readings against pH and temperature variations, and correct for environmental and physiological fluctuations, enabling precise and reliable real-time glucose estimation.[196] These developments underscore the potential of polymers as an ideal platform for future sensor technologies, owing to their low-temperature processability, design versatility, and compatibility with soft, smart, and sustainable systems, while AI/ML-enabled IoT integration allows sensor data to be transformed into real-time, actionable insights across a range of applications. This overall progression is captured in Fig. 13, which presents a future-facing roadmap for advancing polymer-based sensors, from sustainable material discovery to AI-driven design, low-temperature fabrication, and IoT integration.

## 7. Performance landscape of low-temperature polymer sensors *versus* silicon-based counterparts

Although sensor performance constitutes a key quantitative metric, it must be evaluated relative to the constraints and objectives of the target application. Distinct sensing domains, including environmental monitoring, wearable health diagnostics, point-of-care testing, and industrial surveillance, impose heterogeneous performance requirements with respect to sensitivity, spatial and temporal resolution, response time, and long-term operational stability. In numerous applied contexts, polymer-based sensors already achieve limits of detection and analytical accuracies that are commensurate with practical monitoring requirements and existing regulatory thresholds.[197–199] Moreover, the combination of adequate performance with low cost, mechanical flexibility, and ease of deployment is frequently of greater practical importance, particularly in distributed, real-time, and large-area monitoring applications. Consequently, a direct one-to-one comparison of performance metrics, without explicit consideration of application-specific requirements, may fail to accurately reflect the practical significance and suitability of polymeric sensors. In this context, polymer-based platforms should be regarded as complementary technologies that augment, rather than supplant, conventional semiconductor technologies.

Table 3 summarizes the key performance metrics of the highlighted polymer-based sensors and compares them with conventional silicon-based counterparts specifically in heavy metal and glucose sensing applications. This comparison indicates that, although polymeric sensors may exhibit limitations in long-term stability, ultra-low detection limits, and operational robustness under harsh conditions, they offer distinct advantages in terms of low-temperature, solution-based fabri-

Table 3 Performance comparison of polymer and semiconductor sensing platforms over heavy metal and glucose sensoring application domains

| | Heavy metal ion sensing | | | Glucose sensing | | |
|---|---|---|---|---|---|---|
| Sensors | Polymer based | | Semiconductor based | Polymer based | | Semiconductor based |
| Sensor type description | Fluorescence paper-strip sensor ($Fe^{3+}$ detection in water) | Fluorescent thin film sensor – rapid trace $Cu^{2+}$ detection in agriculture | FET aptasensor ($Hg^{2+}$ detection in aqueous solution) | Colorimetric enzymatic polymer film sensor | Fluorescence-based imprinted polymer sensor | Metal–oxide semiconductor ($NiO@In_2O_3$) heterojunction-based non-enzymatic glucose sensor |
| Material system | Cd(II) coordination polymer coated on PVDF | PPYBA (poly (pyrene boric acid)) and porous degradable substrate; 3D hydrogel network | $MoS_2$–carbon dot (CD) nanohybrid transistor with $Hg^{2+}$ aptamer | Chitosan (CS)/glucose oxidase (GOx) films | Carbon quantum dots (CQDs) embedded in a MIP copolymer matrix as free-standing polymer microbeads or thin film | $NiO@In_2O_3$ hollow nanofibers on ITO glass (p–n heterojunction) |
| Detection limit | $4.0 \times 10^{-8}$ M (40 nM) $Fe^{3+}$ | 1.81 nM for $Cu^{2+}$ (high specificity *vs.* other metal ions/anions) | 0.65 aM in the linear range of 1 aM to 10 pM with high sensitivity | 2 μM (spectrophotometric measurement); 33 μM (smartphone colorimetric) | ~29.4 nM, extendable to ~2.5 nM under optimized conditions | 2 nM |
| Long-term stability | Stable for 6 cycles and easily recyclable | The substrate demonstrates rapid degradation, aligning with zero-waste electronics | Very high electrical stability over repeated cycles; consistent sensing response | Stable for 4 weeks at 4 °C and ~10 reuses without loss of activity | Good over several usage cycles and several days in controlled buffer conditions | Very good, but substrate cracking risk under mechanical stress |
| Operating/fabrication temp. | Solvothermal synthesis & low-temp. coating; at room temp. | Electropolymerization and solution casting (low temperature) | Probe sonicator operating at 400 W; high-energy intensity process | Room temp. drop casting | Solution-based and imprinting at room temperature; CQDs are dispersed and templated into polymer network *via* aqueous-phase polymerization | Two calcinations at 500 °C (electrospinning precursor → NiO → $NiO@In_2O_3$) |
| Flexibility/IoT integration | Paper-strip format inherently flexible; compatible with portable optical readers | Can be integrated with portable intelligent sensing platforms for agricultural monitoring | Mechanical flexibility is limited due to semiconductor channel; rigid layers, and fabrication complexity | High; flexible polymer films; smartphone integration for detection | Highly compatible with smartphone-based imaging and IoT-enabled PoC systems | Poor: rigid ITO substrate, limited wearable/IoT compatibility |
| Ref. | 200 | 201 | 202 | 203 | 204 | 205 |

Remarks: polymeric sensors, despite often exhibiting lower intrinsic sensitivity and somewhat reduced long term drift stability compared with semiconductor based FET platforms, offer compelling advantages in terms of softness, flexibility, scalability and compatibility with low temperature, solution based fabrication. Overall, polymer-based sensors are closest to replacing silicon in applications where (i) the required accuracy is modest, (ii) the sensing interface must be soft, conformal, biodegradable or recyclable, and (iii) distributed or large-area coverage is more important than micron-level spatial resolution or ppm-level accuracy.

cation, reduced infrastructure requirements, mechanical flexibility, and facile integration with portable and IoT-enabled systems, as illustrated in Fig. 14. These attributes make polymeric sensors particularly suitable for resource-limited settings and emerging smart monitoring platforms. Recent advances involving nano-engineered hydrogels, MIPs, surface-functionalized polymers, and polymer-supported nanocomposites have substantially enhanced analyte recognition and signal transduction, enabling sub-nanomolar to nanomolar detection in several applications.[206,207]

Ashraf *et al.* developed an electrochemical MIP sensor for dydrogesterone detection in human plasma by simple electropolymerization of poly(methacrylic acid-*co*-methyl methacrylate) on screen-printed gold electrodes, achieving a sub-nanomolar detection limit of 370 pM with good selectivity and operational stability.[208] Such studies clearly demonstrate the growing capability of advanced polymeric architectures to deliver high analytical performance while retaining low-cost and scalable fabrication. Although polymer-based sensors are unlikely to fully replace semiconductor platforms in the near future for ultra-high-precision applications, their continued technological maturation, coupled with supportive industrial practices and policy frameworks, positions them as promising and sustainable candidates for large-scale, decentralized, and IoT-integrated sensing systems in environmental and biomedical monitoring.

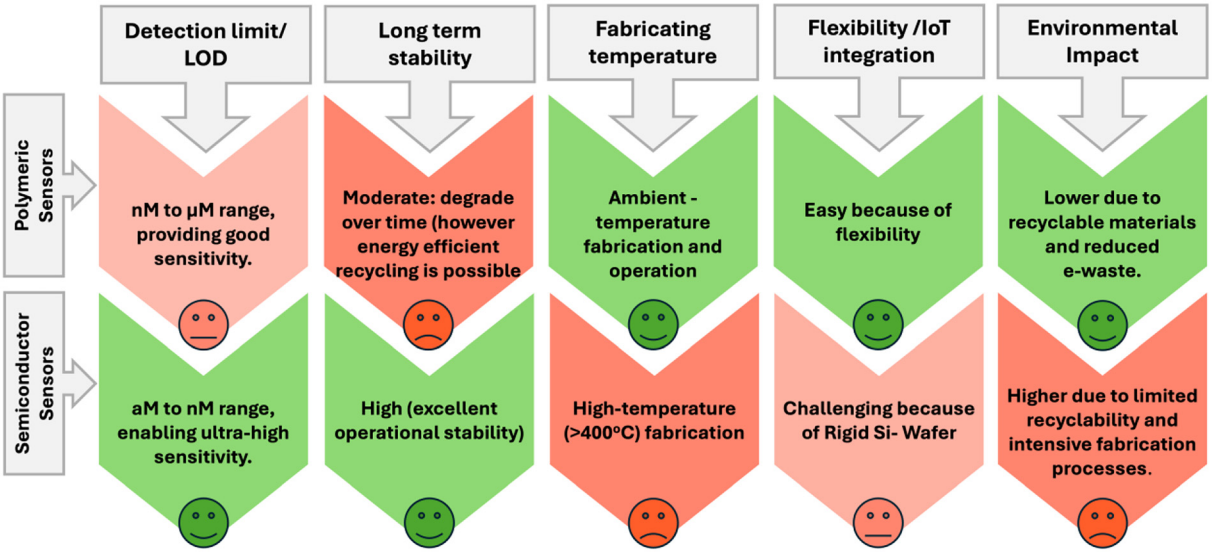


**Fig. 14** Comparative evaluation of polymer-based sensors relative to conventional silicon-based devices indicates that polymer platforms generally achieve detection limits within the nM–µM concentration regime. These systems are typically fabricated at low temperatures (<120 °C), exhibit superior mechanical flexibility, and are amenable to scalable, low-cost manufacturing processes, thereby facilitating their integration into IoT sensing architectures. Although polymer-based sensors may face long-term stability challenges, their recyclability requires relatively low energy input, improving overall sustainability. Compared to silicon-based platforms, this contributes to lower environmental impact and promotes material circularity.

## 8. Future perspective: transitioning from industry 4.0 to industry 5.0 through sustainable polymer sensor platforms

The advent of digitalization and IoT-driven automation within the Industry 4.0 framework has led to an increase in sensor deployments. However, this advancement presents sustainability challenges, particularly for developing nations with limited infrastructure and resources. Traditional semiconductor sensors, characterized by their significant energy consumption and inflexible production requirements, are not ideally suited for scalable applications in fields such as biomedical, agriculture, and pharmaceuticals, where there is a demand for real-time and cost-efficient monitoring. The transition to Industry 5.0 represents a strategic approach by prioritizing sustainable material selection along with the principles of circularity. The implementation of low-temperature, recyclable, and IoT-integrated polymer sensor systems furnishes a versatile and energy-efficient solution that facilitates closed-loop material recovery and promotes environmental stewardship, thus converting the linear models characteristic of Industry 4.0 into the regenerative paradigms of Industry 5.0.

Recent advances in combinatorial material discovery, AI/ML-guided micro-design of experiments, and scalable fabrication methods including 3D printing and solution processing enable rapid development and deployment of customized sensors tailored to resource-constrained environments. Techniques such as drop casting and inkjet printing facilitate application-specific fabrication that aligns with the Industry 5.0 goals of adaptability, recyclability, and circularity. Prioritizing localized recycling and upcycling infrastructures leveraging e-waste and agro-waste further enhances supply chain resilience and national self-reliance. Achieving sustainable automation across critical sectors requires integrating smart circular sensor technologies with adaptive manufacturing and localized material recovery, ensuring alignment with Industry 5.0 and the SDGs, while democratizing innovation and fostering social equity.

### 8.1 Sustainability beyond fabrication: the role of valorization

The versatility of polymer-based sensors extends far beyond deployment; however, true sustainability in this domain demands looking beyond fabrication alone. A critical, often overlooked factor is end-of-life management, where significant challenges remain:

- Recycling of polymer electronics is burdensome and economically unattractive
- Industries lack incentives to invest in recycling without clear value recovery mechanisms
- This is where valorization becomes essential. Unless recycled materials are: upgraded (*e.g.*, through additive processing) or converted into higher-value products, large-scale adoption of circular practices is unlikely to materialize.

Concepts such as urban mining, which have been traditionally linked to metals, are increasingly being applied to polymers and other industrial residues, thereby reclassifying them as valuable secondary resources rather than waste. By integrating valorization strategies throughout the life cycles of sensors, it is possible to:

• Bridge the gap between lab-scale demonstrations and industrial adoption

• Incentivize circular design from the outset

• Promote interdisciplinary innovation in materials science, sustainability, and manufacturing

This framing underscores a core principle: technological breakthroughs alone are insufficient unless paired with economic and environmental incentives.

### 8.2 Proof-of-concept: circular sensors in practice

• This conceptual framework is transitioning into practical applications. In particular, Crapnell *et al.*[209] demonstrated an approach aligned with the principles of a circular economy by recycling mixed material 3D printed devices to produce new functional filaments. Through thermal mixing and carbon black supplementation, they regenerated conductive and nonconductive filaments, which were subsequently reprinted into fully recycled electrochemical cells. The recycled devices maintained electroanalytical performance comparable to that of the original platforms for acetaminophen detection, highlighting how the sensor materials themselves can be valorized through additive manufacturing and recycling. Such examples illustrate the feasibility of embedding circularity directly into polymer sensor technologies, thereby aligning material innovation with scalable sustainability goals.

• In another work Carvalho *et al.*[210] developed a sustainable magnetic electrochemical biosensor for SARS-CoV-2 detection using recycled materials such as graphite from spent batteries and polystyrene from disposable cups. The fabrication process, based on 3D printing and the principles of circular economy, achieved a recyclability rate of 98.5% and allowed a relatively low material cost of USD 0.2 per biosensor. This work highlights how valorization of waste materials can drive affordable, eco-friendly, and scalable sensor technologies suited for mass deployment, especially in resource-limited settings.

• Zhang *et al.*[211] conducted a comprehensive review of recent advancements in the electrochemical recycling of polymeric materials, highlighting its capacity to convert plastic waste into valuable monomers and building blocks under relatively mild conditions. Contrary to conventional thermal techniques, electrochemical methodologies facilitate selective depolymerization and functionalization by using electrons as clean reactants, frequently driven by renewable energy sources. This approach fosters closed-loop recycling by retrieving high-purity monomers, which can be repolymerized into new materials, thereby effectively valorizing plastic waste streams that typically present recycling challenges. This approach addresses critical challenges in plastic recycling and serves as an exemplar of how innovative and sustainable technologies can facilitate the shift toward circular economies and more prudent resource management.

## 9. Conclusion

The landscape of sustainable sensor technologies is being rapidly reshaped by the versatile advantages of polymer-based platforms. Significantly, this advancement occurs within the context of emerging conflicts between the goals of Industry 4.0 and Industry 5.0. Industry 4.0 drives extensive digitalization and automation, which frequently results in increased resource consumption and generation of electronic waste. In contrast, Industry 5.0 focuses on human-centric innovation and sustainability. These conflicting priorities highlight the challenge of aligning rapid industrial innovation with the long-term objectives of the SDGs and circular economy principles. This review highlights polymers that are particularly well-suited for sustainable sensor design, emphasizing that, regardless of class, they should ideally support recyclability or reuse.

The landscape of sustainable sensor technologies is being rapidly reshaped by the versatile advantages of polymer-based platforms. This review highlights polymers that are particularly well-suited for sustainable sensor design, emphasizing that, regardless of class, they should ideally support recyclability or reuse.

Polymer-based sensors offer a rare opportunity to:

• Align industrial innovation with environmental stewardship

• Empower regions traditionally left out of high-tech manufacturing

• Build sensor systems that are not just smart, but responsible, circular, and inclusive

If harnessed strategically, this shift could redefine the way we design, deploy, and retire sensing technologies, from linear production to regenerative ecosystems. One pathway toward realizing such regenerative systems lies in the adoption of biodegradable and bio-derived polymers. Natural biopolymers such as chitosan, alginate, silk fibroin, starch, and bacterial cellulose, together with synthetic biodegradable polymers like PLA, PLLA, and PVA, provide controlled end-of-life management through biodegradation or compostability, making them especially relevant for biomedical applications where safety and degradability are critical. For environmental monitoring, non-biodegradable polymers, including thermoplastics such as PET, PE, TPU, and SEBS, as well as thermosets and elastomers, can be employed, provided strategies exist to recover, recycle, or repurpose them at the end of their lifecycle. Conductive polymers like PEDOT:PSS and PANI, and the incorporation of nanofillers such as CNTs, MXenes, or graphene, can enhance sensitivity, mechanical robustness, and functional performance across both biodegradable and non-biodegradable polymer systems. Collectively, these approaches demonstrate that polymers can serve multiple roles, including structural support, active sensing elements, or biodegradable matrices, while supporting circularity principles. This versatility enables the development of environmentally responsible sensor platforms for biomedical, wearable, and environmental applications.

Leveraging the inherent adaptability of polymers, combinatorial approaches integrated with AI/ML and ICME frameworks enable rapid prediction and optimization of polymer compositions, nanofiller combinations, and sensor architectures. These data-driven strategies accelerate material discovery and

allow precise tailoring of sensor performance to specific biomedical, environmental, or wearable applications. Complementing this, polymers are uniquely compatible with low-temperature fabrication techniques, including solution processing, additive manufacturing, and bio-inspired assembly. Chimie douce-inspired strategies, which exploit chemical cross-linking, supramolecular interactions, and dynamic bonding, facilitate the construction of functional sensor architectures without the energetic penalties of conventional semiconductor processing. Together, these advances make polymer-based sensors highly scalable, economically viable, and environmentally responsible, providing a versatile platform for sustainable sensing technologies.

Smart integration of these sensors into IoT-enabled infrastructures offers a pathway where sustainability and Industry 4.0 converge rather than diverge. By embedding recyclable, biodegradable, or compostable sensors into wearables, smart packaging, environmental monitoring, and healthcare platforms, industries can simultaneously meet the demands of data-rich automation and the SDGs. Taken together, the evidence underscores that polymer-based sensors, realized through low-temperature, energy-efficient fabrication, are not merely alternatives but essential drivers of the transition toward Industry 5.0. Their adoption ensures that the very tools enabling digital automation evolve into technologies that prioritize human well-being and ecological responsibility, actively reinforcing the global commitment to a greener, smarter future.

## Author contributions

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

## Conflicts of interest

There are no conflicts to declare.

## Data availability

Data will be made available on request.

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## References

1 L. V. Martoni, N. O. Gomes, O. N. Oliveira Jr., S. A. Machado and P. A. Raymundo-Pereira, *Microchem. J.*, 2024, **197**, 109780.
2 L. V. Martoni, N. O. Gomes, T. M. Prado, M. L. Calegaro, O. N. Oliveira Jr., S. A. Machado and P. A. Raymundo-Pereira, *J. Environ. Chem. Eng.*, 2022, **10**, 107556.
3 A. Khan, H. Aziz, N. Khan, M. Hasan, S. Ahmed, I. Farooqi, A. Dhingra, V. Vambol, F. Changani, M. Yousefi, *et al.*, *Int. J. Environ. Sci. Technol.*, 2021, 1–12.
4 D. M. Yacout and M. Hassouna, *Environ. Monit. Assess.*, 2016, **188**, 1–13.
5 F. Uddin, *Cellulose*, 2021, **28**, 10715–10739.
6 V. K. Gaur, P. Sharma, R. Sirohi, M. K. Awasthi, C.-G. Dussap and A. Pandey, *J. Hazard. Mater.*, 2020, **398**, 123019.
7 B. Robert and S. K. Kalpathy, *J. Water Process Eng.*, 2025, **75**, 107992.
8 M. Golovianko, V. Terziyan, V. Branytskyi and D. Malyk, *Procedia Comput. Sci.*, 2023, **217**, 102–113.
9 S. C. Teixeira, T. V. de Oliveira, N. d. F. F. Soares and P. A. Raymundo-Pereira, *Food Chem.*, 2024, 142652.
10 S. Huang, B. Wang, X. Li, P. Zheng, D. Mourtzis and L. Wang, *J. Manuf. Syst.*, 2022, **64**, 424–428.
11 S. C. Teixeira, N. O. Gomes, T. V. de Oliveira, N. F. Soares and P. A. Raymundo-Pereira, *Anal. Chem.*, 2025, **97**, 14875–14884.

12 S. C. Teixeira, N. O. Gomes, T. V. de Oliveira, P. Fortes-Da-Silva, N. d. F. F. Soares and P. A. Raymundo-Pereira, *Biosens. Bioelectron.: X*, 2023, **14**, 100371.
13 United Nations, *Sustainable Development Goals*, 2015, https://sdgs.un.org/goals, accessed: 2025-05-07.
14 V. Chaudhary, P. Gaur and S. Rustagi, *Sustainable Mater. Technol.*, 2024, e00952.
15 N. O. Gomes, S. C. Teixeira, M. L. Calegaro, S. A. Machado, N. d. F. F. Soares, T. V. de Oliveira and P. A. Raymundo-Pereira, *Chem. Eng. J.*, 2023, **472**, 144775.
16 C. Sanchez, L. Rozes, F. Ribot, C. Laberty-Robert, D. Grosso, C. Sassoye, C. Boissiere and L. Nicole, *C. R. Chim.*, 2010, **13**, 3–39.
17 S. C. Teixeira, N. O. Gomes, M. L. Calegaro, S. A. Machado, T. V. de Oliveira, N. d. F. F. Soares and P. A. Raymundo-Pereira, *Biomater. Adv.*, 2023, **155**, 213676.
18 G. F. Fine, L. M. Cavanagh, A. Afonja and R. Binions, *Sensors*, 2010, **10**, 5469–5502.
19 J. Zikulnig, S. Carrara and J. Kosel, *Sci. Rep.*, 2025, **15**, 10866.
20 S. E. Moon, N.-J. Choi, H.-K. Lee, J. Lee and W. S. Yang, *ETRI J.*, 2013, **35**, 617–624.
21 X. Hu, G. Li and J. C. Yu, *Langmuir*, 2010, **26**, 3031–3039.
22 B. Robert, S. S. Kumar, T. Thomas and S. K. Kalpathy, *J. Mater. Chem. A*, 2026, DOI: 10.1039/d5ta09015f.
23 Z. Ma, Y. Liu, L. Deng, M. Zhang, S. Zhang, J. Ma, P. Song, Q. Liu, A. Ji, F. Yang, *et al.*, *Nanomaterials*, 2018, **8**, 77.
24 T. Zhao, X. Yu, W. Xu, Y. He, Z. Qu, R. Shen, R. Wang, H. Guo, H. Sun, Z. Li, *et al.*, in *2024 IEEE International Electron Devices Meeting (IEDM)*, 2024, pp. 1–4.
25 C. Ballif, F.-J. Haug, M. Boccard, P. J. Verlinden and G. Hahn, *Nat. Rev. Mater.*, 2022, **7**, 597–616.
26 B. von Vacano, H. Mangold, G. W. Vandermeulen, G. Battagliarin, M. Hofmann, J. Bean and A. Künkel, *Angew. Chem., Int. Ed.*, 2023, **62**, e202210823.
27 S. S. Kumar, K. Vidhya, T. Thomas and S. K. Kalpathy, *Polym. Adv. Technol.*, 2025, **36**, e70365.
28 C. Príncipe, S. M. Jorge, M. Matos, L. Santos, J. Morgado and A. Charas, *Org. Electron.*, 2024, **125**, 106987.
29 A. K. Mohanty, F. Wu, R. Mincheva, M. Hakkarainen, J.-M. Raquez, D. F. Mielewski, R. Narayan, A. N. Netravali and M. Misra, *Nat. Rev. Methods Primers*, 2022, **2**, 46.
30 R. Banerjee and S. S. Ray, *Macromol. Mater. Eng.*, 2022, **307**, 2100794.
31 N. O. Gomes, R. T. Paschoalin, S. Bilatto, A. R. Sorigotti, C. S. Farinas, L. H. C. Mattoso, S. A. Machado, O. N. Oliveira Jr. and P. A. Raymundo-Pereira, *ACS Sustainable Chem. Eng.*, 2023, **11**, 2209–2218.
32 S. K. Kalpathy, T. Thomas, K. V. Vidhya and S. S. Kumar, Polymer-based sensor and method for detecting heavy transition metals, *Indian Patent* 566801, 2023, Application No. 202341040751, granted 15 June 2023; Indian Institute of Technology Madras (IIT Madras), https://iprsearch.ipindia.gov.in/PublicSearch/PublicationSearch.
33 R. T. Paschoalin, N. O. Gomes, G. F. Almeida, S. Bilatto, C. S. Farinas, S. A. Machado, L. H. Mattoso, O. N. Oliveira Jr. and P. A. Raymundo-Pereira, *Biosens. Bioelectron.*, 2022, **199**, 113875.
34 G. Martinelli, M. C. Carotta, M. Ferroni, Y. Sadaoka and E. Traversa, *Sens. Actuators, B*, 1999, **55**, 99–110.
35 G. Barandun, L. Gonzalez-Macia, H. S. Lee, C. Dincer and F. Güder, *ACS Sens.*, 2022, **7**, 2804–2822.
36 D. Batet and G. Gabriel, *ChemSusChem*, 2025, **18**, e202401101.
37 S. Mansoor, S. Iqbal, S. M. Popescu, S. L. Kim, Y. S. Chung and J.-H. Baek, *Front. Plant Sci.*, 2025, **16**, 1587869.
38 P. Ehizuenlen and S. Apeh, *NIPES-J. Sci. Technol. Res.*, 2023, **5**, 133–140.
39 K. Ferji, *Polym. Chem.*, 2025, **16**, 2457–2470.
40 T. Yue, J. He and Y. Li, *Acc. Mater. Res.*, 2025, **6**, 1033–1045.
41 W. Y. Wang, J. Li, W. Liu and Z.-K. Liu, *Comput. Mater. Sci.*, 2019, **158**, 42–48.
42 A. T. Rosário and J. C. Dias, *Sensors*, 2023, **23**, 1165.
43 N. O. Gomes, M. L. Calegaro, L. H. C. Mattoso, O. N. Oliveira Jr., S. A. Machado and P. A. Raymundo-Pereira, *ACS Appl. Nano Mater.*, 2024, **7**, 27520–27530.
44 H. Jung, G. Shin, H. Kwak, L. T. Hao, J. Jegal, H. J. Kim, H. Jeon, J. Park and D. X. Oh, *Chemosphere*, 2023, **320**, 138089.
45 K. Yadav and G. C. Nikalje, *PeerJ*, 2024, **12**, e18013.
46 R. I. Muazu, P. Yaseneva, N. Shah and M.-M. Titirici, *J. Environ. Chem. Eng.*, 2024, **12**, 114387.
47 A. Ajeev, T. Warfle, S. Maslaczynska-Salome, S. Alipoori, C. Duprey and E. K. Wujcik, *Chem. Sci.*, 2025, **16**, 9056–9075.
48 R. R. Larder and F. L. Hatton, *ACS Polym. Au*, 2022, **3**, 182–201.
49 R. G. Pearson, *Surv. Prog. Chem.*, 1969, **5**, 1–52.
50 A. M. Al-Amri, *Chemosensors*, 2025, **13**, 285.
51 A. Qadir, S. Shafique, T. Iqbal, H. Ali, L. Xin, S. Ruibing, T. Shi, H. Xu, Y. Wang and Z. Hu, *Sens. Actuators, A*, 2024, **370**, 115267.
52 Q. Wang, S. Ling, X. Liang, H. Wang, H. Lu and Y. Zhang, *Adv. Funct. Mater.*, 2019, **29**, 1808695.
53 R. R. Silva, P. A. Raymundo-Pereira, A. M. Campos, D. Wilson, C. G. Otoni, H. S. Barud, C. A. Costa, R. R. Domeneguetti, D. T. Balogh, S. J. Ribeiro, *et al.*, *Talanta*, 2020, **218**, 121153.
54 Z. Zhang, B. Feng, J. Yan, W. Zhao and J. Sun, *Green Chem.*, 2025, **27**, 1604–1619.
55 J. Hur, S. Park, J. H. Kim, J. Y. Cho, B. Kwon, J. H. Lee, G. Y. Bae, H. Kim, J. T. Han and W. H. Lee, *ACS Sustainable Chem. Eng.*, 2022, **10**, 3227–3235.
56 S. Park, J. Ahn, J. H. Kim, J. T. Han, W. H. Lee and H. Kim, *Cellulose*, 2023, **30**, 1045–1055.
57 Y. Kim, S. Kim, W. H. Lee and H. Kim, *Cellulose*, 2020, **27**, 1685–1693.
58 E. S. Hosseini, S. Dervin, P. Ganguly and R. Dahiya, *ACS Appl. Bio Mater.*, 2020, **4**, 163–194.
59 Z. Zhai, X. Du, Y. Long and H. Zheng, *Front. Electron.*, 2022, **3**, 985681.

60 Q.-H. Chan, S. A. Alias, S. W. Quek, C. Y. Ng and K. I. Ku Marsilla, *Polym.-Plast. Technol. Mater.*, 2023, **62**, 1273–1289.
61 M. Meghana, C. Nandhini, L. Benny, L. George and A. Varghese, *Polym. Bull.*, 2023, **80**, 11507–11556.
62 A. Reizabal, C. M. Costa, L. Pérez-Álvarez, J. L. Vilas-Vilela and S. Lanceros-Méndez, *Adv. Funct. Mater.*, 2023, **33**, 2210764.
63 Y. Wang, W. Cai, Y. Zhang, J. Ji, H. Zheng, D. Yan and X. Liu, *Discover Nano*, 2024, **19**, 176.
64 M. Wang, R. Myllylä, J. Hiltunen, S. Uusitalo and L. Hakalahti, *2011 International Workshop on Biophotonics*, 2011, pp. 1–3.
65 R. De Marco, J.-P. Veder, G. Clarke, A. Nelson, K. Prince, E. Pretsch and E. Bakker, *Phys. Chem. Chem. Phys.*, 2008, **10**, 73–76.
66 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.
67 E. Olson, J. Blisko, C. Du, Y. Liu, Y. Li, H. Thurber, G. Curtzwiler, J. Ren, M. Thuo, X. Yong, *et al.*, *Nanoscale Adv.*, 2021, **3**, 4037–4047.
68 X. Zhou, H. Zang, Y. Guan, S. Li and M. Liu, *Nanomaterials*, 2023, **13**, 2639.
69 J. Jeong, M. Shin, S. M. Kang and M. Seo, *NPG Asia Mater.*, 2025, **17**, 24.
70 J. Praveenkumara, P. Madhu, T. G. Y. Gowda, M. Sanjay and S. Siengchin, *J. Text. Inst.*, 2022, **113**, 1231–1239.
71 L. Yang, H. Wang, W. Yuan, Y. Li, P. Gao, N. Tiwari, X. Chen, Z. Wang, G. Niu and H. Cheng, *ACS Appl. Mater. Interfaces*, 2021, **13**, 60531–60543.
72 S. Sun, R. Yuan, S. Ling, T. Zhou, Z. Wu, M. Fu, H. He, X. Li and C. Zhang, *ACS Appl. Mater. Interfaces*, 2024, **16**, 7826–7837.
73 Y. Wei, S. Jiang, X. Li, J. Li, Y. Dong, S. Q. Shi, J. Li and Z. Fang, *ACS Appl. Mater. Interfaces*, 2021, **13**, 37617–37627.
74 Z. Liu, C. Li, X. Zhang, B. Zhou, S. Wen, Y. Zhou, S. Chen, L. Jiang, S. Jerrams and F. Zhou, *ACS Sustainable Chem. Eng.*, 2022, **10**, 8788–8798.
75 M. Ali, S. M. Hoseyni, R. Das, M. Awais, I. Basdogan and L. Beker, *Adv. Mater. Technol.*, 2023, **8**, 2300347.
76 H. Pan, G. Chen, Y. Chen, A. Di Carlo, M. A. Mayer, S. Shen, C. Chen, W. Li, S. Subramaniam, H. Huang, *et al.*, *Biosens. Bioelectron.*, 2023, **222**, 114999.
77 M. C. Pozza Junior, A. G. Rosenberger, F. F. da Silva, D. C. Dragunski, E. C. Muniz and J. Caetano, *Environ. Technol.*, 2024, **45**, 2388–2401.
78 J. Sharifi, G. Rizvi and H. Fayazfar, *Materials*, 2024, **17**, 5782.
79 A. Lima, N. Pereira, C. Ribeiro, S. Lanceros-Mendez and P. Martins, *ACS Sustainable Chem. Eng.*, 2022, **10**, 4122–4132.
80 S. Zhang, Z. Zhou, J. Zhong, Z. Shi, Y. Mao and T. H. Tao, *Adv. Sci.*, 2020, **7**, 1903802.
81 S. Abazari, A. Shamsipur, H. Bakhsheshi-Rad, M. Keshavarz, M. Kehtari, S. Ramakrishna and F. Berto, *J. Mater. Res. Technol.*, 2022, **20**, 976–990.
82 A. Francis, S. Abdel-Gawad and M. Shoeib, *J. Coat. Technol. Res.*, 2021, **18**, 971–988.
83 M. Zhao, R. Su, L. Ji, Y. Zhang, H. Wu, Z. Wen and C. Dai, *J. Nanomater.*, 2023, **2023**, 5012576.
84 V. Caratelli, G. Fegatelli, D. Moscone and F. Arduini, *Biosens. Bioelectron.*, 2022, **205**, 114119.
85 B. Kalleshappa and M. Pumera, *J. Mater. Chem. A*, 2025, **13**, 795–807.
86 S. Rani, I. Kathuria, A. Kumar, D. Kumar, A. Kumar, S. Kumar, B. Nandan and R. K. Srivastava, *Environ. Res.*, 2023, **228**, 115928.
87 K. Spychalska, D. Zajac, S. Baluta, K. Halicka and J. Cabaj, *Polymers*, 2020, **12**, 1154.
88 Y. Liu, P. Fan, Y. Pan and J. Ping, *Chem. Rev.*, 2025, **125**, 8246–8318.
89 P. E. Hande and A. B. Samui, *Smart Polymers*, CRC Press, 2022, pp. 245–261.
90 C. Branger, W. Meouche and A. Margaillan, *React. Funct. Polym.*, 2013, **73**, 859–875.
91 J. Niu, M. Du, W. Wu, J. Yang and Q. Chen, *J. Sep. Sci.*, 2024, **47**, 2400353.
92 Y. Huang and R. Wang, *Curr. Org. Chem.*, 2018, **22**, 1600–1618.
93 C. Mwanza, W.-Z. Zhang, K. Mulenga and S.-N. Ding, *Green Chem.*, 2024, **26**, 11490–11517.
94 S. S. S. Sanker, S. Thomas, D. P. Jacob, V. Suniya, S. Nalini and K. Madhusoodanan, *Analyst*, 2025, **150**, 3730–3739.
95 Y. Qiu, K. Ding, L. Tang, Z. Qin, M. Li and X. Yin, *Int. J. Mol. Sci.*, 2022, **23**, 10542.
96 J. Stejskal, *Chem. Pap.*, 2020, **74**, 1–54.
97 Y. Lu, Z. Liu, H. Yan, Q. Peng, R. Wang, M. E. Barkey, J.-W. Jeon and E. K. Wujcik, *ACS Appl. Mater. Interfaces*, 2019, **11**, 20453–20464.
98 Z. Zou, C. Zhu, Y. Li, X. Lei, W. Zhang and J. Xiao, *Sci. Adv.*, 2018, **4**, eaaq0508.
99 X. Tao, S. Liao and Y. Wang, *EcoMat*, 2021, **3**, e12083.
100 T. Qu, G. Nan, Y. Ouyang, B. Bieketuerxun, X. Yan, Y. Qi and Y. Zhang, *Polymers*, 2023, **15**, 4268.
101 Z. Zhou, W. Tang, T. Xu, W. Zhao, J. Zhang and C. Bai, *Sensors*, 2024, **24**, 4793.
102 T. Jamatia, J. Matyas, R. Olejnik, R. Danova, J. Maloch, D. Skoda, P. Slobodian and I. Kuritka, *Polymers*, 2023, **15**, 1618.
103 L. Yue, V. S. Bonab, D. Yuan, A. Patel, V. Karimkhani and I. Manas-Zloczower, *Glob. Chall.*, 2019, **3**, 1800076.
104 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.
105 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.
106 P. Yang, Q. Zhou, X.-X. Yuan, J. M. Van Kasteren and Y.-Z. Wang, *Polym. Degrad. Stab.*, 2012, **97**, 1101–1106.
107 T. Türel, Ö. Dağlar, F. Eisenreich and Ž. Tomović, *Chem. – Asian J.*, 2023, **18**, e202300373.
108 A. E. Protsenko, A. N. Protsenko, O. G. Shakirova and V. V. Petrov, *Polymers*, 2023, **15**, 1559.

109 S. K. Kalpathy, T. Thomas, R. Ravendran, M. M. Bhunia and S. Kumar, *Debromination of Waste Printed Circuit Board*, Indian Patent Application No. 202541002887, 2025, Indian Institute of Technology Madras (IIT Madras).
110 S. Jahanshahi, A. Pizzi, A. Abdulkhani and A. Shakeri, *Polymers*, 2016, **8**, 143.
111 S. Khuje, L. Zhu, J. Yu and S. Ren, *ACS Appl. Electron. Mater.*, 2024, **6**, 8226–8231.
112 K. S. Alblalaihid, S. A. Aldoihi and A. A. Alharbi, *Polymers*, 2024, **16**, 1560.
113 K. Shahzad, A. I. Mardare and A. W. Hassel, *Sci. Technol. Adv. Mater.: Methods*, 2024, **4**, 2292486.
114 S. S. Mao and P. E. Burrows, *J. Materiomics*, 2015, **1**, 85–91.
115 S. Baudis and M. Behl, *Macromol. Rapid Commun.*, 2022, **43**, 2100400.
116 F. Wieberger, T. Kolb, C. Neuber, C. K. Ober and H.-W. Schmidt, *Molecules*, 2013, **18**, 4120–4139.
117 A. D. A. Bin Abu Sofian, X. Sun, V. K. Gupta, A. Berenjian, A. Xia, Z. Ma and P. L. Show, *Energy Fuels*, 2024, **38**, 1593–1617.
118 A. Ludwig, *npj Comput. Mater.*, 2019, **5**, 70.
119 U. Lange, N. V. Roznyatovskaya and V. M. Mirsky, *Anal. Chim. Acta*, 2008, **614**, 1–26.
120 S. Basak and A. Bandyopadhyay, *ACS Appl. Eng. Mater.*, 2024, **2**, 1190–1208.
121 W. F. Maier, *ACS Comb. Sci.*, 2019, **21**, 437–444.
122 E. Champa-Bujaico, P. García-Díaz and A. M. Díez-Pascual, *Int. J. Mol. Sci.*, 2022, **23**, 10712.
123 A. L. Roy, C. Beaumont, M. Leclerc and K. Walus, *Flexible Printed Electron.*, 2023, **8**, 014002.
124 F. S. Fedorov, N. P. Simonenko, V. Trouillet, I. A. Volkov, I. A. Plugin, D. P. Rupasov, A. S. Mokrushin, I. A. Nagornov, T. L. Simonenko, I. S. Vlasov, *et al.*, *ACS Appl. Mater. Interfaces*, 2020, **12**, 56135–56150.
125 V. R. Gohel, M. Chetyrkina, A. Gaev, N. P. Simonenko, T. L. Simonenko, P. Y. Gorobtsov, N. A. Fisenko, D. A. Dudorova, V. Zaytsev, A. Lantsberg, *et al.*, *Lab Chip*, 2024, **24**, 3810–3825.
126 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.
127 Y. Cho, J. W. Beak, M. Sagong, S. Ahn, J. S. Nam and I.-D. Kim, *Adv. Mater.*, 2025, 2500162.
128 K. A. Fransen, S. H. Av-Ron, T. R. Buchanan, D. J. Walsh, D. T. Rota, L. Van Note and B. D. Olsen, *Proc. Natl. Acad. Sci. U. S. A.*, 2023, **120**, e2220021120.
129 N. Masanabo, B. Orimolade, A. O. Idris, T. T. Nkambule, B. B. Mamba and U. Feleni, *Environ. Sci. Pollut. Res.*, 2023, **30**, 14062–14090.
130 M. C. Flemings, *Trans. Iron Steel Inst. Jpn.*, 1986, **26**, 93–100.
131 M. E. Deagen, L. C. Brinson, R. A. Vaia and L. S. Schadler, *MRS Bull.*, 2022, **47**, 379–388.
132 C. C. Sun, *J. Pharm. Sci.*, 2009, **98**, 1671–1687.
133 L. Mirtskhulava, *Sustainability in Polymer Technology and Plastic Engineering*, 2025, pp. 19–34.
134 R. Ma, H. Zhang and T. Luo, *ACS Appl. Mater. Interfaces*, 2022, **14**, 15587–15598.
135 R. J. Dalal, F. Oviedo, M. C. Leyden and T. M. Reineke, *Chem. Sci.*, 2024, **15**, 7219–7228.
136 Y. Huang, S. Zhong, L. Gan and Y. Chen, *ACS ES&T Eng.*, 2024, **4**, 1702–1711.
137 T. K. Patra, *ACS Polym. Au*, 2021, **2**, 8–26.
138 G. Samblani and D. P. Bhatt, *Intelligent Manufacturing and Industry 4.0*, CRC Press, 2025, pp. 217–236.
139 H. Quinn, G. A. Robben, Z. Zheng, A. L. Gardner, J. G. Werner and K. A. Brown, *Mater. Horiz.*, 2024, **11**, 5331–5340.
140 X. Yue, Q. Li, Z. Wang, L. Duan, W. Yang, D. Pan, H. Liu, C. Liu and C. Shen, *Nano Res.*, 2026, **19**, 94908084.
141 G. Jia, X. Yue, L. Duan, R. Yin, C. Pan, H. Liu, C. Liu and C. Shen, *Adv. Fiber Mater.*, 2025, 1–16.
142 M. Huang, S. Liu, Y. Chi, J. Li, H. Sun, L. Dong, H. Liu, C. Liu and C. Shen, *Soft Sci.*, 2025, **5**, 24.
143 D. Xing, Z. Wang, M. Zhang, S. Liu, W. Yang, R. Yin, H. Liu, C. Liu and C. Shen, *Adv. Funct. Mater.*, 2025, e29907.
144 D. Xing, Z. Wang, S. Liu, W. Yang, R. Yin, C. Liu, C. Shen and H. Liu, *ACS Sens.*, 2025, **11**, 371–383.
145 S. Liu, X. Yue, S. Liu, W. Yang, H. Liu, C. Liu and C. Shen, *J. Mater. Sci. Technol.*, 2025, **260**, 241–252.
146 M. Karuppusamy, R. Thirumalaisamy, S. Palanisamy, S. Nagamalai, E. E. S. Massoud and N. Ayrilmis, *J. Mater. Chem. A*, 2025, **13**, 16290–16308.
147 J. Zhang, H. Gao, Y. Liu and J. Wang, *JOM*, 2025, **77**, 106–124.
148 B. Xu, H. Yin, X. Jiang, C. Zhang, R. Zhang, Y. Wang and X. Qu, *Comput. Mater. Sci.*, 2022, **202**, 111021.
149 W. Wu, *Sci. Technol. Adv. Mater.*, 2019, **20**, 187–224.
150 H. M. Soe, A. Abd Manaf, A. Matsuda and M. Jaafar, *Sens. Actuators, A*, 2021, **329**, 112793.
151 S. Lindholm, *Development of a polymeric dip coating procedure for nanosplasmonic fiber optic sensors*, Master's thesis, Chalmers University of Technology, Gothenburg, Sweden, 2020.
152 T. T. N. Hoa, N. Van Duy, C. M. Hung, N. Van Hieu, H. H. Hau and N. D. Hoa, *RSC Adv.*, 2020, **10**, 17713–17723.
153 L. O. Orzari, C. Kalinke, H. A. Silva-Neto, D. S. Rocha, J. R. Camargo, W. K. Coltro and B. C. Janegitz, *Anal. Chem.*, 2025, **97**, 1482–1494.
154 X. Gong, K. Huang, Y.-H. Wu and X.-S. Zhang, *Sens. Actuators, A*, 2022, **345**, 113821.
155 A. Hayat and J. L. Marty, *Sensors*, 2014, **14**, 10432–10453.
156 G. C. Patil, *Simple Chemical Methods for Thin Film Deposition: Synthesis and Applications*, Springer, 2023, pp. 509–530.
157 A. Berni, M. Mennig and H. Schmidt, *Sol-gel technologies for glass producers and users*, Springer, 2004, pp. 89–92.

158 D. Maddipatla, B. B. Narakathu and M. Atashbar, *Biosensors*, 2020, **10**, 199.
159 T. Wolfer, P. Bollgruen, D. Mager, L. Overmeyer and J. G. Korvink, *Procedia Technol.*, 2014, **15**, 521–529.
160 K. Kim, J. Kim, B. Kim and S. Ko, *Int. J. Precis. Eng. Manuf.-Green Technol.*, 2018, **5**, 369–374.
161 X. Wang, M. Zhang, L. Zhang, J. Xu, X. Xiao and X. Zhang, *Mater. Today Commun.*, 2022, **31**, 103263.
162 H. Syafutra and R. Siskandar, *et al.*, *Thin Film Processes-Artifacts on Surface Phenomena and Technological Facets*, IntechOpen, 2017.
163 M. Sadegh-cheri, *J. Chem. Educ.*, 2019, **96**, 1268–1272.
164 C. Zhou, N. Shi, X. Jiang, M. Chen, J. Jiang, Y. Zheng, W. Wu, D. Cui, H. Haick and N. Tang, *Sens. Actuators, B*, 2022, **353**, 131133.
165 B. Robert and G. Nallathambi, *Colloid Interface Sci. Commun.*, 2020, **37**, 100275.
166 W. Han, Y. Wang, J. Su, X. Xin, Y. Guo, Y.-Z. Long and S. Ramakrishna, *Sci. China Technol. Sci.*, 2019, **62**, 886–894.
167 R. M. Cardoso, C. Kalinke, R. G. Rocha, P. L. Dos Santos, D. P. Rocha, P. R. Oliveira, B. C. Janegitz, J. A. Bonacin, E. M. Richter and R. A. Munoz, *Anal. Chim. Acta*, 2020, **1118**, 73–91.
168 M. J. Hossain, B. T. Tabatabaei, M. Kiki and J.-W. Choi, *Int. J. Precis. Eng. Manuf.-Green Technol.*, 2025, **12**, 277–300.
169 A. Al Shboul, M. Ketabi, J. H. Ngai, D. Skaf, S. Rondeau-Gagné and R. Izquierdo, *ACS Omega*, 2025, **10**, 3878–3889.
170 F. Le Goupil, G. Payrot, S. Khiev, W. Smaal and G. Hadziioannou, *ACS Omega*, 2023, **8**, 8481–8487.
171 V. Katseli, A. Economou and C. Kokkinos, *Anal. Chem.*, 2021, **93**, 3331–3336.
172 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.
173 J. Yi, S. Yang, L. Yue and I. M. Lei, *Microsyst. Nanoeng.*, 2025, **11**, 51.
174 L. Liu, Y. Dou, J. Wang, Y. Zhao, W. Kong, C. Ma, D. He, H. Wang, H. Zhang, A. Chang, *et al.*, *Adv. Sci.*, 2024, **11**, 2405003.
175 S. Sang, Z. Pei, F. Zhang, C. Ji, Q. Li, J. Ji, K. Yang and Q. Zhang, *ACS Appl. Mater. Interfaces*, 2022, **14**, 31493–31501.
176 Y. Sun, D. Li, Y. Shi, Z. Wang, S. I. Okeke, L. Yang, W. Zhang, Z. Zhang, Y. Shi and L. Xiao, *Sensors*, 2023, **23**, 2366.
177 Y. Hou, M. Gao, J. Gao, L. Zhao, E. H. T. Teo, D. Wang, H. J. Qi and K. Zhou, *Adv. Sci.*, 2023, **10**, 2304132.
178 R. K. Mishra, L. J. Hubble, A. Martín, R. Kumar, A. Barfidokht, J. Kim, M. M. Musameh, I. L. Kyratzis and J. Wang, *ACS Sens.*, 2017, **2**, 553–561.
179 J. R. Sempionatto, R. K. Mishra, A. Martín, G. Tang, T. Nakagawa, X. Lu, A. S. Campbell, K. M. Lyu and J. Wang, *ACS Sens.*, 2017, **2**, 1531–1538.
180 Z. Song, W. Ye, Z. Chen, Z. Chen, M. Li, W. Tang, C. Wang, Z. Wan, S. Poddar, X. Wen, *et al.*, *ACS Nano*, 2021, **15**, 7659–7667.
181 M. Yang, R. Silva, K. Zhao, R. Ding, J. L. C. Foo, L. Ge and G. Lisak, *Analyst*, 2024, **149**, 4351–4362.
182 J. Wang, R. Liang and W. Qin, *Anal. Chim. Acta*, 2024, **1298**, 342412.
183 E. M. Moaaz, A. S. Fayed, E. M. Abdel-Moety and M. R. Rezk, *RSC Adv.*, 2025, **15**, 18475–18489.
184 E. M. Moaaz, A. S. Fayed, M. R. Rezk and E. M. Abdel-Moety, *Sci. Rep.*, 2025, **15**, 30892.
185 E. Han, M. Bao, Y. Li and J. Cai, *Food Chem.*, 2025, 147084.
186 M. A. Belal, S. Hajra, S. Panda, K. R. Kaja, M. M. M. Abdo, A. Abd El-Moneim, D. Janas, Y. K. Mishra and H. J. Kim, *J. Mater. Chem. A*, 2025, **13**, 5447–5497.
187 R. Y. Hassan, *Sensors*, 2022, **22**, 7539.
188 S. Mansouri, S. Boulares, S. Chabchoub, Y. Alharbi and A. Alqahtani, *Microchem. J.*, 2025, 112670.
189 B. Zong, S. Wu, Y. Yang, Q. Li, T. Tao and S. Mao, *Nano–Micro Lett.*, 2025, **17**, 54.
190 K. Obaideen, B. A. Yousef, M. N. AlMallahi, Y. C. Tan, M. Mahmoud, H. Jaber and M. Ramadan, *Energy Nexus*, 2022, **7**, 100124.
191 S. Mariani, L. Cecchini, N. M. Pugno and B. Mazzolai, *Mater. Des.*, 2023, **235**, 112408.
192 X. Xiao, J. Yin, J. Xu, T. Tat and J. Chen, *ACS Nano*, 2024, **18**, 22734–22751.
193 N. Yadav, Q. Zhang, D. Qi, A. Yadav and H. Zheng, *Nanoscale Adv.*, 2025, **7**, 4803–4819.
194 S. Chen, S. Fan, Z. Qiao, Z. Wu, B. Lin, Z. Li, M. A. Riegler, M. Y. H. Wong, A. Opheim, O. Korostynska, *et al.*, *Adv. Mater.*, 2025, 2500412.
195 N. Promphet, C. Thanawattano, C. Buekban, T. Laochai, P. Lormaneenopparat, W. Sukmas, P. Rattanawaleedirojn, P. Puthongkham, P. Potiyaraj, W. Leewattanakit, *et al.*, *Anal. Chim. Acta*, 2024, **1312**, 342761.
196 M. Farahmandpour and Z. Kordrostami, *Sci. Rep.*, 2025, **15**, 16219.
197 C. Virumbrales, R. Hernández-Ruiz, M. Trigo-López, S. Vallejos and J. M. García, *Sensors*, 2024, **24**, 3852.
198 W. Tang, J. Han, W. Zhang, H. Li, J. Chen, W. Song and L. Wang, *Analyst*, 2024, **149**, 5617–5637.
199 G. G. Yang, D.-H. Kim, S. Samal, J. Choi, H. Roh, C. E. Cunin, H. M. Lee, S. O. Kim, M. Dinca and A. Gumyusenge, *ACS Sens.*, 2023, **8**, 3687–3692.
200 Y. Zhang, L. Gao, S. Ma and T. Hu, *Spectrochim. Acta, Part A*, 2022, **267**, 120525.
201 Y. Li, S. Zhang, Y. Tang, W. Zhou, G. Zhang, J. Xu and L. Zhang, *Microchem. J.*, 2025, **209**, 112820.
202 S. Mansouri Majd, F. Ghasemi, A. Salimi and T.-K. Sham, *ACS Appl. Electron. Mater.*, 2020, **2**, 635–645.
203 A. Skonta, M. G. Bellou, T. E. Matikas and H. Stamatis, *Biosensors*, 2024, **14**, 299.
204 D. K. Dang, V. T. K. Xuyen, Q. T. H. Ta and L. T. Nhiem, *RSC Adv.*, 2025, **15**, 40698–40708.
205 C. Zhang, X. Xu, B. Li, H. Li, X. Tan, P. J. Jesuraj and W. Xie, *Microchem. J.*, 2025, **208**, 112401.

206 M. Ardalani, M. Shamsipur and A. Besharati-Seidani, *J. Electroanal. Chem.*, 2020, **879**, 114788.
207 Y. García, M. Vera, D. González, E. Vélez-Peña, B. Sellergren and V. A. Jiménez, *ACS Omega*, 2025, **10**, 20649–20660.
208 S. Ashraf, T. Hussain, S. Z. Bajwa, A. Mujahid and A. Afzal, *J. Mater. Chem. B*, 2024, **12**, 6905–6916.
209 R. D. Crapnell, E. Sigley, R. J. Williams, T. Brine, A. Garcia-Miranda Ferrari, C. Kalinke, B. C. Janegitz, J. A. Bonacin and C. E. Banks, *ACS Sustainable Chem. Eng.*, 2023, **11**, 9183–9193.
210 C. L. C. Carvalho, S. Q. Nascimento, T. Bertaglia, L. C. Faria, E. R. Manuli, G. M. Pereira, W. C. da Silva, C. M. Costa, J. F. Maestu, S. Lanceros-Méndez, *et al.*, *ACS Sens.*, 2025, **10**, 1970–1985.
211 W. Zhang, L. Killian and A. Thevenon, *Chem. Sci.*, 2024, **15**, 8606–8624.