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Smart and Functional Polymers for Sustainable Applications in Health, Energy and Environment

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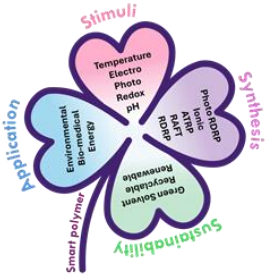
Abstract: The development of sustainable smart polymers has enabled materials capable of responding to diverse chemical, biological, and physical stimuli. This review highlights recent advances in controlled polymerization techniques-including ATRP, RAFT, RDRP, and photoinduced methods with emphasis on environmentally benign synthesis via green solvents and solvent-free routes. The integration of bio-based monomers, green catalysts, and circular design principles facilitates recyclability, biodegradability, and low toxic impact. Owing to their multifunctional behavior, these polymers exhibit significant potential in drug delivery, tissue engineering, flexible electronics, energy storage, energy conversion, and environmental remediation. Representative examples include thermo-responsive hydrogels, conductive polymer networks, self-healing elastomers, and adaptive separation membranes. Key challenges such as operational stability, scalability, and lifecycle management are discussed, underscoring the need for molecular-to-system level strategies. A holistic approach combining molecular design and circular economy frameworks will accelerate the translation of smart polymers into sustainable, high-performance technologies.



Keywords: *Smart polymer, stimuli-responsive, synthetic method, biomedical, energy*

Contents

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1. Introduction

Nature has long inspired many technological innovations.[1] Various natural materials exhibit responsive behaviors for instance, the leaves of *Mimosa pudica* that fold upon touch, chameleons that change color based on their surroundings and the Venus flytrap that swiftly reacts to physical touch.[2, 3] These phenomena motivate material scientists to study their mechanisms and develop advanced biomimetic materials and devices.[1,4] Smart and functional polymers, which have garnered a lot of interest in material science, are substances that respond to external stimuli and return to its initial condition after the stimulus is withdrawn.[5] Smart and functional polymers can dynamically detect environmental changes and adjust their physicochemical properties accordingly.[6] With carefully tailored molecular designs, these polymers can respond to various stimuli such as temperature, light, pH, and electric or magnetic fields.[7-9] By engineering them into different structures, their responsive features can be efficiently and flexibly utilized for a large range of practical applications like

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sensors,[10] actuators,[11] environmental remediation,[12] for controlled and triggered drug delivery,[13] and many other applications.

The need for novel materials that combine cutting-edge functionality with environmental sustainability has grown as society shifts toward a circular economy that prioritizes durability, reusability, recyclability, and biodegradability.[14] For example, in agricultural and medicinal applications, hydrogels that respond to temperature or pH and are made from natural polymers like chitosan, alginate, and cellulose offer environmentally benign substitutes for synthetic gels.[15] Smart and functional polymers are being used in environmental engineering to create reusable absorbents that can remove pollutants from water, including dyes, heavy metals, and microplastics.[16-19] Smart and functional polymers enable the creation of components in additive manufacturing and 3D printing that may alter their characteristics or structure over time in response to external stimuli.[20-22] Similar to this, smart and functional polymers allow for the development of flexible, energy-efficient gadgets that can adapt to the human body and react dynamically to physiological signals in wearable electronics and biomedical diagnostics.[23] These advancements highlight a clear shift in materials science toward developing functional materials with sustainable, stimuli-responsive frameworks.[7]

The creation of innovative polymerization techniques for functional monomers is the main force behind this progress. The creation of novel stimuli-responsive polymers (SRP) has been made possible by recent developments in a variety of reversible deactivation radical polymerization (RDRP) processes.[24] Various RDRP techniques such as single-electron transfer living radical polymerization (SET-LRP),[25] atom transfer radical polymerization (ATRP),[26] photo-RDRP,[17] electrochemically mediated ATRP (eATRP),[27] organometallic-mediated radical polymerization (OMRP),[28] reversible addition-fragmentation chain transfer (RAFT) polymerization,[29] nitroxide-mediated polymerization (NMP),[30] and iodine transfer polymerization (ITP)[31] are now widely employed to synthesize well-defined and structurally precise (co)polymers.

In this review, we highlight the recent advancements in smart and functional polymers, emphasizing various physical, chemical stimuli-responsive systems and their wide-ranging applications. After examining the basic properties that allow these polymers to carry out dynamic and adaptive tasks, it provides a summary of sustainable design techniques and the most recent advancements in material production. Special attention is given to their roles in environmental remediation, healthcare, and energy-related applications. The integration of such responsive polymeric materials into environmental systems shows great promise for advancing sustainability, intelligent, and eco-friendly technological solutions for the future.

2. Smart and Functional Polymers

Polymers with responsive moieties exhibit reversible changes in their physicochemical properties when exposed to external stimuli such as pH, light, chemical factors such as redox, ionic strength, and biological elements like enzymes

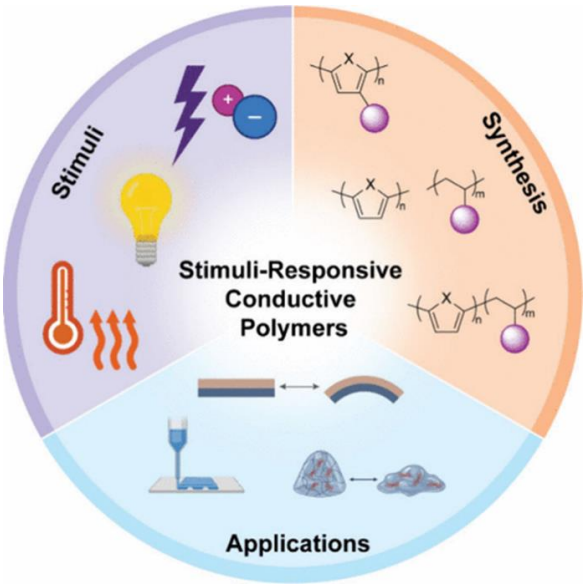

Figure 1. *Classification of SRPs. Reused with consent.[32] Copyright 2025, American Chemical Society.*

(Table 1). Recent advancements have led to the creation of multi-stimuli-responsive polymers, capable of responding to multiple inputs simultaneously, which enhances their tunability and adaptability for applications in tissue engineering controlled drug delivery, and smart coatings. Within the polymer network, these stimuli cause a variety of molecular-level modifications, including hydrophilicity, conformation, solubility, degradability, and even selective bond cleavage.[33,34] As a result, these reactions control the polymeric systems' overall mechanical, structural, and functional behavior.

Physical, chemical, and biological stimuli can be broadly categorized **(Figure 1)**. The dynamics and chain mobility of polymers are mostly influenced by physical stimuli. The polymer-solvent interface as well as intramolecular and intermolecular interactions are influenced by chemical stimuli. On the other hand, certain biochemical processes like enzymatic catalysis and receptor-ligand interactions are involved in biological stimuli like enzymes or biomolecules (like glucose).[2]

2.1. Thermo-Responsive Polymers

A well-known subclass of smart and functional polymers are thermo-responsive polymers also known as temperature-responsive polymers. Such polymers show reversible and adjustable changes in their physicochemical characteristics in response to temperature fluctuations. Because of this unique behaviour, they have been thoroughly investigated for a variety of uses, such as information processing, drug delivery,[35] tissue engineering,[36] catalysis,[37] and surface modification.[38]

The careful balance between hydrophilic and hydrophobic interactions inside the polymer chains is what causes the temperature-induced change in these polymers. The polymer's solubility and aggregation behaviour in a particular solvent are

Table 1. *Overview of major stimuli and their molecular response mechanisms in smart polymers.*

Stimulus	Responsive Mechanism	Typical Polymers (with Citations)
Temperature	LCST/UCST transition; coil-globule collapse due to disruption of H-bonding	PNIPAM, poly(vinyl ether)s, poly(oxazoline)s.[36-40,67]
pH	Protonation/deprotonation of acidic/basic groups leading to swelling/deswelling	PAA, PMAA, PDMAEMA.[24,68,69]
Light	Photoisomerization (trans-cis), reversible ring opening, DASA photo-switching	Azobenzene copolymers, spiropyran polymer, DASA block copolymers.[51,52,54,70]
Redox	Oxidation state variation of redox groups; disulfide cleavage	Ferrocene-containing polymers, TEMPO copolymers, disulfide hydrogels.[59,60]
Electric Field	Charge migration, conformational change, ion transport	PPy, PANi, PEDOT:PSS.[61]
Chemical Analyte	Reversible binding/complexation with analytes (e.g., diol, CO_2)	Boronic-acid polymers, CO_2-responsive amidine polymers.[62-64,71]

determined by this equilibrium. The lower critical solution temperature (LCST) and the upper critical solution temperature (UCST) are two important factors that determine the thermo-responsive behaviour. While polymers with a UCST show the opposite solubility tendency, those with an LCST are soluble below the transition temperature and insoluble above it.[24]

The breaking of hydrogen bonding connections between the polymer chains and surrounding solvent molecules as the temperature rises is the primary cause of the transition in LCST-type polymers. Phase separation, chain collapse, and an overall rise in hydrophobicity result from this. The process is reversible and controlled by thermodynamic principles; when the temperature rises, the Gibbs free energy of mixing ($\Delta G = \Delta H - T\Delta S$) changes from negative to positive. Poly(N-isopropylacrylamide) (PNIPAM),[39] polyvinylethers,[40] polyoxazolines,[41] are few examples of LCST-type polymers. They are flexible prospects for next-generation smart and functional polymers.[21]

2.2. Electro-Responsive Polymers

Electro-responsive polymers represent a broad class of electroactive polymers (EAPs) whose mechanical, optical, or electrical properties change in response to an applied electric field.[42] In the literature, the term EAP is sometimes used interchangeably with electrically conductive polymers; however, EAPs are not limited to conductive polymer systems. Instead, they encompass two fundamental categories that operate through distinct mechanisms: (1) Electronic Electroactive Polymers (EEAPs) and (2) Ionic Electroactive Polymers (IEAPs).

EEAPs are materials in which actuation is driven by electronic processes such as dipole orientation, dielectric polarization, or electrostriction under an applied electric field.[43] Typical examples include dielectric elastomers, ferroelectric polymers, and piezoelectric fluoropolymers, which exhibit large reversible deformation without involving ion transport. EEAPs are generally high-performance elastomeric systems with fast response times and low energy consumption.

In contrast, IEAPs rely on ion migration and electrochemical reactions to generate deformation. Representative IEAPs include ionic polymer-metal composites (IPMCs), conducting polymer actuators based on poly(aniline) or poly(pyrrole), and ionic hydrogel systems, where solvent and ion movement across the polymer matrix produce bending or swelling under low operating voltage.[44] IEAPs offer high bending strain and operate in aqueous environments, making them useful for soft robotics and bio-interfacing.

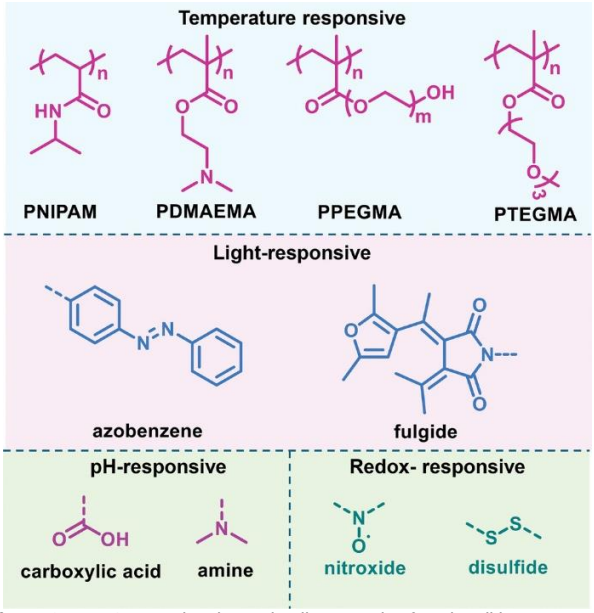

Figure 2. *Few SRP and various stimuli responsive functionalities. Reused with consent.[46] Copyright 2025, Wiley-VCH GmbH.*

2.3. Photo-Responsive Polymers

Light-responsive polymers, or photo-responsive polymers, change their physicochemical properties when exposed to light, making them essential in drug delivery, environmental sensing, and smart materials.[24] Their ability to transform structurally and behaviorally is controlled by the light's irradiation time, intensity, and wavelength, allowing for reversible and localized activation. Additionally, the formation or breakage of crosslinking bonds plays a major role in governing these stimulus-responsive activities. Key methods in developing these polymers include photoinduced isomerization and photochromism,[47] with examples such as spiropyran,[48] azobenzene,[49] and spirooxazine **(Figure 2)**.[50] These photoactive moieties enable significant macroscopic changes in shape, solubility, wettability, and mechanical properties through their modulation of molecular conformation and polarity in response to light.

The field of photo-responsive polymers has seen significant advancements, particularly with donor-acceptor Stenhouse adducts (DASAs), which act as visible light-responsive molecular photoswitches. DASAs can reversibly switch between a coloured open triene and a colourless closed cyclized form when exposed to visible light.[51] .Their incorporation into polymers is influenced by factors such as the polymer matrix's properties. These light-responsive systems are particularly promising for biomedical and soft-robotic applications due to their low phototoxicity and effective tissue penetration.[52] Research attempts to improve DASAs' chemical stability and responsiveness despite obstacles like photostability and switching kinetics, positioning them as essential elements in the creation of smart and functional polymers for a range of uses, such as optical data storage and targeted drug delivery **(Figure 3**).

2.4. pH-Responsive Polymers

A significant subclass of smart materials known as pH-responsive (or pH-sensitive) polymers can reversibly modify their physicochemical characteristics in response to variations in the pH of their surroundings, including solubility, conformation, swelling behaviour, and surface charge.[53] Due to its numerous uses in tissue engineering, regulated medication delivery,[54] environmental sensing, and biosensing systems, these polymers have attracted a lot of attention.[55]

The ionization or protonation-deprotonation of acidic or basic functional groups inside the polymer backbone or side chains is the main mechanism underlying pH responsiveness. Changes in pH cause the charge distribution to change, which causes electrostatic attraction or repulsion between polymer chains and, as a result, volume changes like swelling or shrinking. For example, at higher pH levels, the weak polyacid, poly(acrylic acid) (PAA) deprotonates, producing negatively charged carboxylate groups that resist one another and cause the polymer to swell.[56] On the other hand, the weak polybase poly(N,N-dimethylaminoethyl methacrylate) (PDMAEMA) is protonated in acidic environments, which causes chain contraction because of charge neutralization and intermolecular interactions.[57]

Their usage in cutting-edge biomedical and environmental technologies has been made possible by recent advancements in copolymer design and nanostructuring, which have further improved their sensitivity, mechanical strength, and biocompatibility.[58]

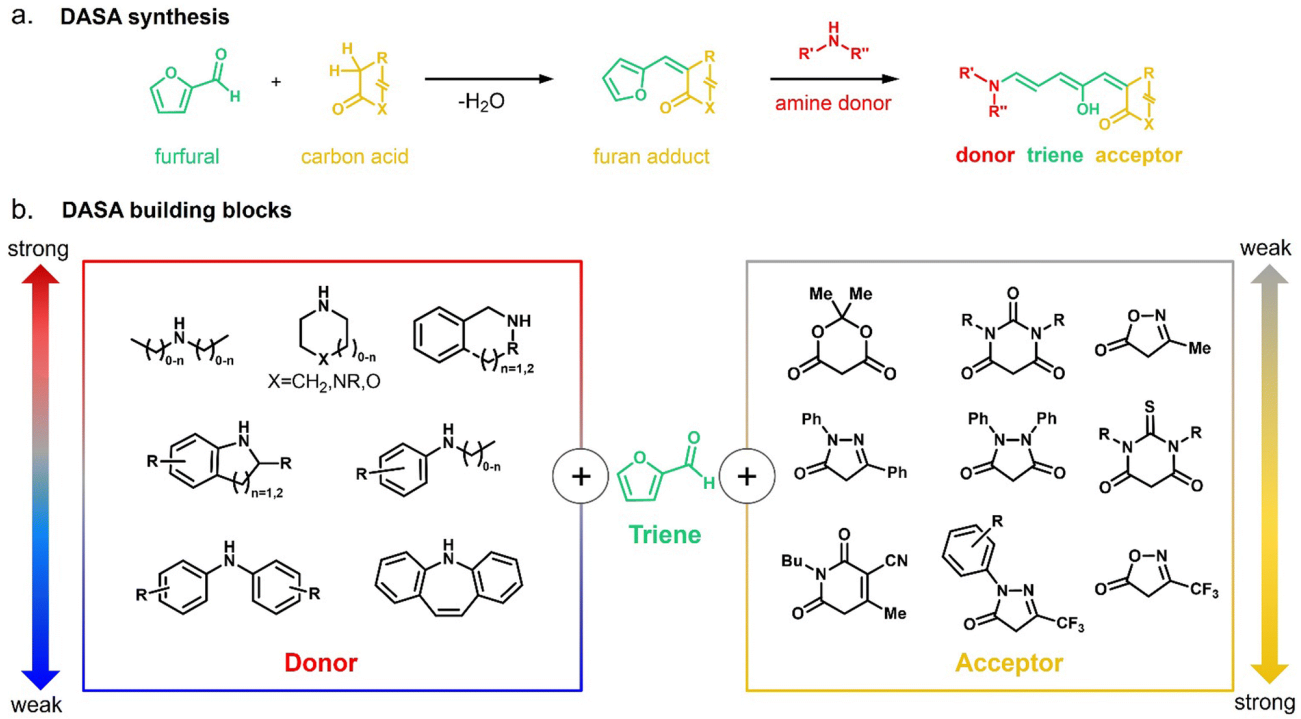

Figure 3. *Chemical structures of various carbon acid acceptors and secondary amine donors that were previously used in the synthesis of DASA. Reused with permission.[51] Available under a CC-BY license. Copyright 2023 Clerc et al.*

2.5. Redox-Responsive Polymers

In inorganic and coordination chemistry involving transition metal complexes, redox stimulation is an electrochemical process that modifies the oxidation state of redox-active groups in materials. Redox-responsive polymers, which incorporate redox-active moieties into their structures and enable reversible changes in their physicochemical properties, are the result of this process. Tetramethylpiperidine-1-oxyl (TEMPO) is famous for its redox reversibility and paramagnetic characteristics,[59] while other redox-sensitive groups, such as dithienylethene,[60] ferrocene, and disulphide units,[61] enable reversible switching in the polymer network. Because of these characteristics, redox-responsive polymers can be used in energy storage, catalysis, sensing, and stimuli-responsive materials applications where dynamic control of charge and molecular conformation is crucial.[59]

2.6. Chemo-Responsive Polymers

Chemo-responsive polymers, also known as chemical-responsive smart and functional polymers, reversibly change their chemical or physical properties in response to specific chemical stimuli. The nature and concentration of the interacting species determine these changes, which allow for dynamic adaptation for biosensing, medication administration, and environmental monitoring. Functional groups with chemical sensitivity can be added to provide chemo-responsive behaviour. For instance, because of their pH-dependent reversible transition between hydrophobic (neutral) and hydrophilic (anionic) states, boronic acid-functionalized polymers are diol-sensitive and frequently utilized in glucose detection.[62,63] Similarly, when exposed to CO_2, CO_2-responsive polymers with amidine or tertiary amine groups create reversible amidinium complexes that can be broken down by inert gases.[64] The design of sustainable and gas-responsive smart and functional polymers is based on this adjustable reversibility.

2.7. Magnetic-Responsive Polymer Composite

Magnetic-responsive polymer composites are hybrid materials combining magnetic nanoparticles with polymer matrices, enabling remote and non-invasive control under magnetic fields.[9,65] Superparamagnetic iron oxide nanoparticles (Fe_3O_4, γ-Fe_2O_3) are commonly used for their strong magnetic response and stability, while metallic cobalt, nickel, or ferrites provide tunable magnetic and mechanical properties. These polymer composites can undergo controlled deformations like stretching, bending, rotation, or translation, and be guided to specific locations, making them valuable in drug delivery, cell manipulation, and theranostics.[65,66] Coupled with thermoresponsive polymers, magnetic induction can locally heat the matrix, triggering phase transitions for on-demand drug release or shape-memory actuation, enabling precise spatiotemporal control for biomedical and soft robotic applications.[66]

A clear understanding of these stimuli responsive principles lays the foundation for designing materials whose behaviour can be precisely tuned for targeted applications.

3. Synthesis Methods for Stimuli-Responsive Polymers (SRPs)

To translate these responsive features into practical material systems, advanced synthesis methods are essential for controlling polymer architecture, chain sequence, and functionality.

3.1. Conventional Radical Polymerization

Due to its ease of use and adaptability, free-radical polymerization (FRP) **(Table 2)** is the most popular technique for large-scale polymer and composite synthesis.[72] Nevertheless, it frequently lacks control, resulting in polymers with gel formation, low chain-end fidelity, and a wide molecular weight dispersion. FRP has been effectively used to create SRPs despite these disadvantages. For example, Maity *et al*.[73] created acrylate elastomers with self-healing, impact resistance, and strong adhesion through one-pot FRP of 4-vinylpyridine, acrylates, and acrylic acid, achieving enhanced mechanical strength via ionic and hydrogen bonding; Wang *et al*.[74] created semi-rigid polymers exhibiting liquid-crystalline

Table 2. *Comparison of controlled polymerization strategies for SRPs.*

Method	Control over Mw & Đ	Catalyst/Initiator	Solvent System	Typical Polymers Made	Pros	Cons
FRP	Low	Thermal initiators (AIBN, APS)	Bulk, solution	Acrylates, styrenics	Simple, scalable	Broad Đ, low end-group fidelity.[72]
ATRP	High	Cu/Fe complexes + ligand	Aqueous, organic	PMMA, PS, block copolymers	Excellent control, block copolymers	Metal residue, ligand cost.[76,80,89]
RAFT	High	RAFT chain-transfer agents	Wide range, incl. water	Stimuli-responsive block copolymers	Broad monomer scope, architectures	CTA removal/color contamination.[26,83]
Photo-RDRP	Very high	Organic photocatalysts, S-dots	Aqueous, ionic liquids	Functional block copolymers	Spatiotemporal control, metal-free	Light penetration, scale-up.[16,22]
CROP/AROP	High	Lewis acids, organocatalysts	Solvent-free, ionic liquids	Oxazolines, PVEs, degradable polyesters	Precise architecture, degradable	Moisture sensitivity, limited monomers.[88,90,91]

and temperature-responsive behaviour; and Connal *et al*.[75] synthesized PNIPAM-based copolymers with temperature sensitivity and metal-binding capacity.

3.2. Atom Transfer Radical Polymerization

Using transition metal catalysts to regulate polymer formation, ATRP is based on the atom transfer radical addition (ATRA) mechanism. Matyjaszewski and others' contributions made ATRP more environmentally friendly and adaptable for usage in industry and biomedicine by enabling ppm-level copper catalysts (via ARGET and ICAR ATRP), better control over polymer architecture, and wider applicability in aqueous and heterogeneous settings.[76,77] Alkyl/aryl halides function as initiators in ATRP, while ligands and transition metal halides (such as Cu^{+} and Fe^{2+}) create active radicals. Variants like photoATRP, eATRP,[78] and sonoATRP,[79] which offer fine spatial–temporal control, are made possible by stimuli like light, electricity, or ultrasound. The creation of porous and functional polymeric nanoparticles has been made possible by surface-confined ATRP (SC-ATRP).[80]

3.3. Photo and Thermal Reversible Deactivation Radical Polymerization

Polymer chemistry was transformed by RDRP, which allowed for controlled synthesis with exact molecular weights, topologies, and chain-end functions. Techniques like photoRDRP enable metal-free, light-driven polymerization via photo-organocatalysis, resulting in customized polymer topologies.[81] Ni-Co alloy nanoparticle-mediated RDRP,[82] which produces recyclable, multi-stimuli-responsive, and self-healing block copolymers. Whereas ionic liquid based photoRDRP systems that produce dual pH/thermal-responsive polymers are examples of recent advancements. Low-dispersity polymers and responsive block copolymers like PHEMA-*b*-PTBMA have been synthesized at room temperature using S-dot mediated RDRP.[22, 57] Furthermore, Ag-Pd nanocatalyst systems in recyclable ionic liquids improved sustainable photoRDRP by providing accurate control and recyclability that are perfect for the creation of smart and functional polymers.[16]

3.4. Reversible Addition Fragmentation Chain Transfer Polymerization

A potent controlled/living radical polymerization technique for creating polymers with exact topologies, limited dispersity, and distinct end groups is RAFT polymerization.[83] It makes it possible to create sophisticated functional materials with adjustable characteristics. For instance, RAFT was used to create thermo-responsive poly(N-acryloylpiperidine-*random*-N-acryloylpyrrolidine) copolymers with adjustable LCST (3–47 °C), while multifunctional star-shaped copolymers with triple stimuli responsiveness (pH, light and temperature) showed pH-triggered drug release and self-assembly into nanoaggregates.[54] These advancements demonstrate RAFT's adaptability in creating complex polymeric systems for smart and functional polymers and healthcare applications.[84]

3.5. Cationic and Anionic Polymerization

The regulated synthesis of SRPs is made possible by cationic ring-opening polymerization (CROP), which starts cyclic monomers via cationic species. Recent advancements include photo- and electrochemically switchable devices that provide exact control over the structure of polymers in mild, metal-free environments. CROP has created sophisticated copolymers with redox responsiveness and tunable self-assembly, such as PTEVE-*b*-PPEGMA and PSt-*b*-PTEVE.[85, 86] Anionic ring-opening polymerization (AROP), on the other hand, produces polymers with regulated molecular weights and dispersity. Degradable self-immolating networks, hybrid

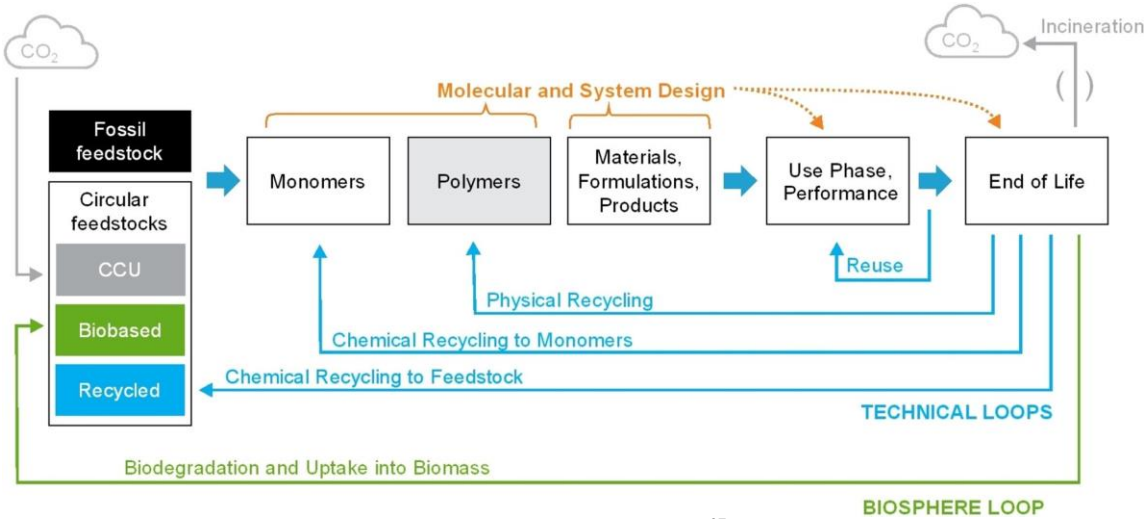

Figure 4. *Value chain and life cycle of polymers. Reused with consent.*[97] *Copyright 2022, Wiley-VCH GmbH*

thermo-responsive magnetic polymers, and multi-stimuli-responsive block copolymers that combine redox, pH, and thermo-responsive units are examples of developments.[87] For responsive materials, coatings, and biomedical applications, these developments in cationic and anionic polymerization broaden the design of smart and functional polymers.[88]

4. Sustainable Polymer Design Strategies

Building on these molecular-level design capabilities, integrating sustainability principles into polymer development has become equally critical to ensure long-term environmental compatibility. When careful selection of polymer classes, renewable monomers, and environmentally responsible synthetic approaches are done it reduces ecological impact across the material's lifecycle. Decisions are guided by green chemistry principles, emphasizing low toxicity, energy efficiency, and waste minimization.

Transitioning to bio-based feedstocks such as agricultural residues, plant oils, carbohydrates, and waste-derived chemicals lowers dependence on fossil resources and helps reduce the carbon footprint. Sustainable polymerization methods including enzymatic catalysis, organocatalysis, and solvent-free or aqueous processes further enhance resource efficiency and minimize hazardous reagent use.[92] Integrating these strategies with systems-level considerations ensures that materials remain functional in service while enabling responsible, resource-efficient recovery.[93] Sustainable polymer design is thus a comprehensive approach combining responsible sourcing, green synthesis, targeted functionality, and intentional reintegration into material cycles **(Figure 4)**.

4.1. Renewable Feedstock

High greenhouse gas emissions during the extraction and processing of fossil fuels are one of the major environmental effects of traditional petrochemical-based polymer manufacture.[94] Producing one ton of polyethylene can release between 1.8 to 3.2 tons of CO_2 equivalents,[95] and Hazardous byproducts from the manufacturing process can contaminate soil, water, and air.[96] Moreover, the extremely slow degradation of conventional polymers leads to persistent plastic pollution and microplastic accumulation in ecosystems and food chains, posing risks to wildlife and human health. These issues emphasize the importance of adopting renewable feedstocks and sustainable polymer design to reduce environmental harm.

Some of the widely used synthetic biodegradable polymers include polyesters such as Polylactic acid (PLA), Polyhydroxyalkanoates (PHAs) **(Figure 5)**.

To lessen long-term ecological effects, synthetic biodegradable polymers are deliberately designed to break down in the environment, usually through microbial enzymatic activity. Polyester-based systems are among the most popular approaches.

4.2. Green Synthesis Approaches

Growing environmental awareness in the late 1980s, led to introduction of green chemistry principles by Anastas and Warner, which provided guidelines for reducing environmental impact in chemical and polymer processes.[98] The commercialization of PLA from renewable feedstocks by companies like NatureWorks in the late 1980s–1990s further demonstrated the viability of biodegradable polymers.[99] These innovations established the foundation for modern green polymer synthesis focused on sustainability and reduced environmental impact. Several green strategies for polymer synthesis are as follows:

4.2.1. Enzymatic Catalysis

Enzymatic catalysis represents an important green approach in polymer synthesis due to its ability to operate under exceptionally mild reaction conditions. Enzymes like lipases,[100] peroxidases[101], and laccases[102] are used in enzyme-catalyzed polymerization to promote polymer synthesis in conditions similar to ambient temperature and pressure, greatly lowering energy consumption and environmental effect.

4.2.2. Organocatalysis

In polymer chemistry, organocatalysis has grown in importance as a method that allows for the moderate and controlled execution of polymerization reactions.[103] Organocatalysts have been applied across multiple polymerization types, providing precise activation of monomers and chain ends to obtain well-defined macromolecular structures.[104]

4.2.3. Solvent-Free / Green Solvent Polymerization

The transition toward green solvent systems has become a major focus in sustainable polymer synthesis. Ionic liquids, characterized by negligible vapor pressure, high thermal stability, and tunable solvation properties, have emerged as effective alternatives to conventional volatile organic solvents. Their non-volatile nature minimizes environmental emissions and reduces health hazards typically associated with solvent-based polymerization processes.[105] Furthermore, ionic liquids can be recovered and recycled during or after polymerization,

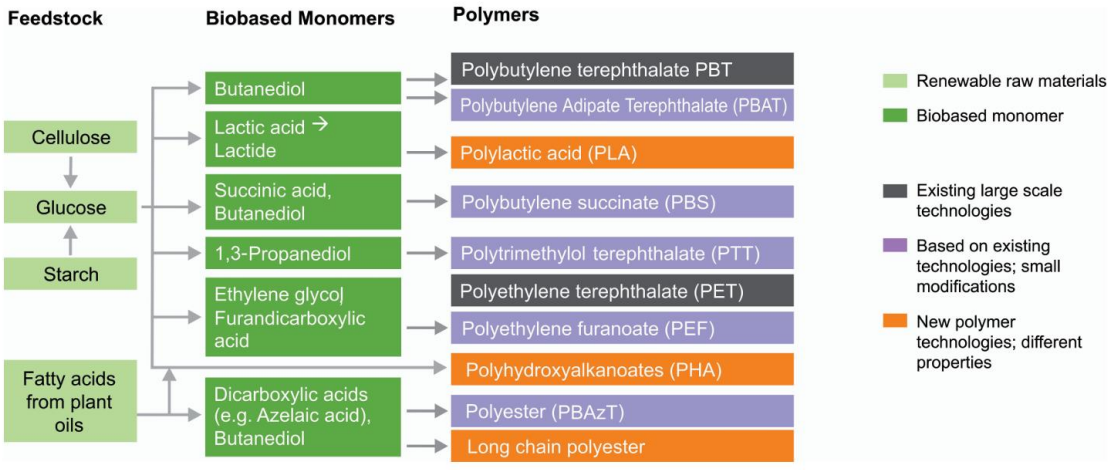

Figure 5. *Different pathways in a life cycle assessment. Reused with consent.*[97] *Copyright 2022, Wiley-VCH GmbH*

thereby enhancing process efficiency and reducing waste, which contributes to improved overall sustainability.[106]

4.3. Recyclability and Upcycling Strategies

Sorting through material recovery facilities (MRFs), where waste streams are divided into categories including post-industrial waste (PIW), post-consumer waste (PCW), municipal solid waste (MSW), and ocean plastics, is usually the first step in managing plastic trash.[107] PIW generally exhibits higher purity and homogeneity compared to other waste types, making it more amenable to closed-loop industrial recycling. In contrast, PCW and MSW often contain mixed polymers and contaminants, reducing recyclability and leading to significant material loss. To overcome these limitations, several chemical recycling technologies have been developed. Thermal degradation processes, such as pyrolysis, convert mixed plastic waste into pyrolysis oil, which can be upgraded via catalytic treatment or steam cracking to produce olefins and aromatics suitable for manufacturing new polymers **(Figure 6)**.[108] It is also possible to depolymerize polyesters and polycarbonates chemically or enzymatically, for example through glycolysis, to recover their monomers for repolymerization.[109] These emerging recycling and upcycling approaches aim to retain material value and support a more circular polymer economy.

5. Smart and Functional Polymers for Health Applications

These structurally controlled smart and functional polymers have emerged as cutting-edge materials in biomedicine. They offers innovative solutions that surpass traditional materials and therapies through their exceptional biocompatibility, biodegradability, and stimulus-responsive versatility for diverse medical applications like tissue regeneration, controlled drug delivery, and diagnostic advancements.[110, 111]

5.1. Drug Delivery

In recent decades, smart and functional polymers have become vital to pharmaceutical chemistry due to their extensive use in drug delivery systems.[112, 113] Polymeric

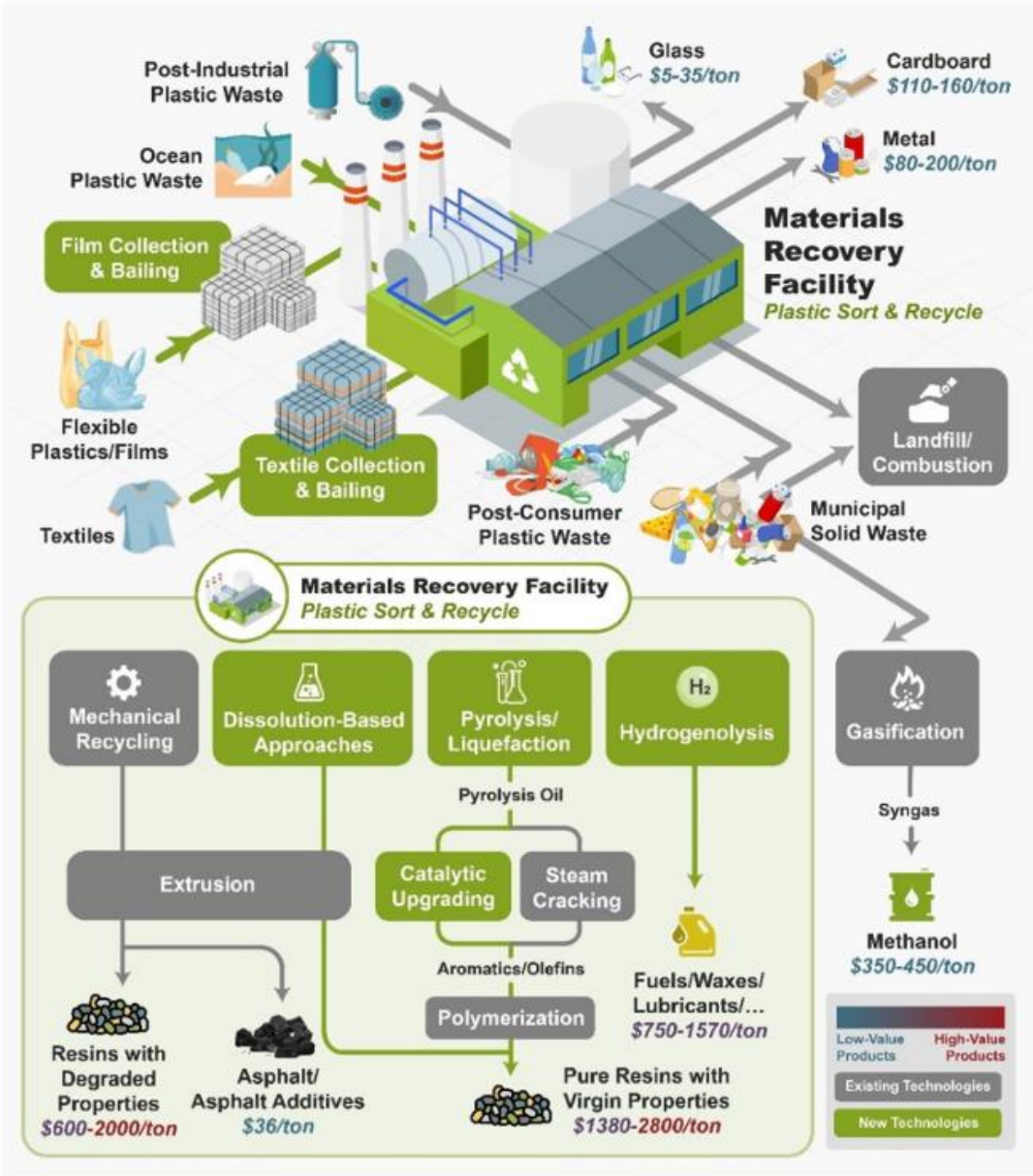

Figure 6. *Summary of current management system of waste plastics. Reused with permission.[107] Available under a CC-BY license. Copyright 2022 Li et al.*

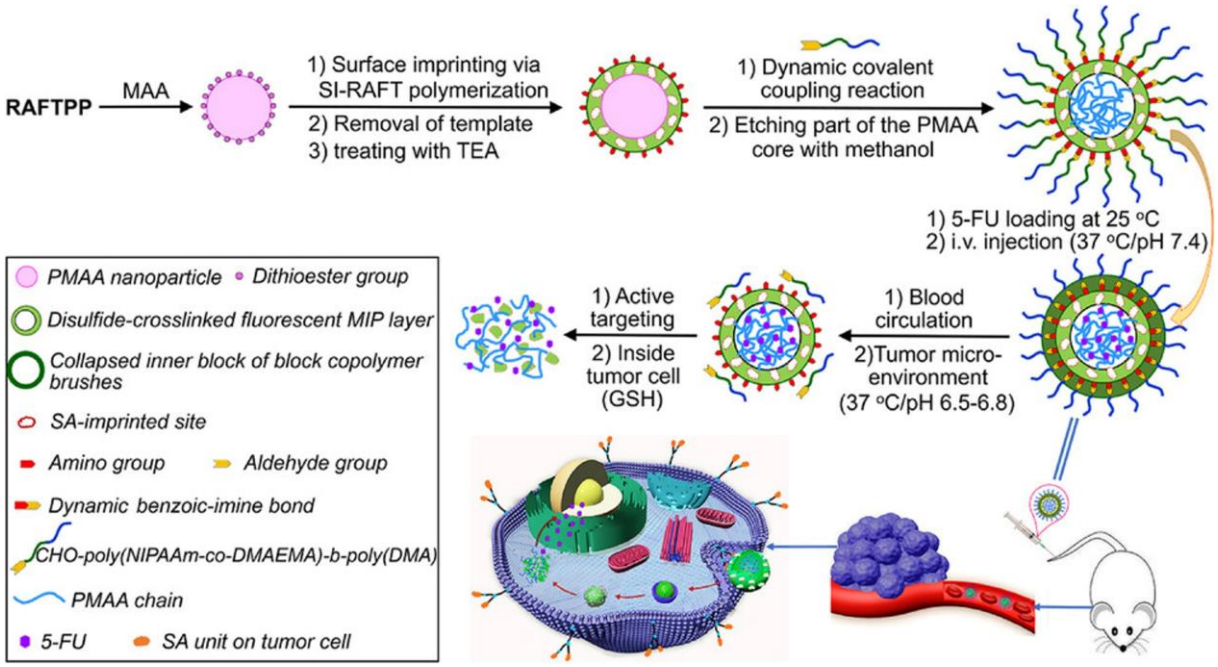

Figure 7. *Schematic representation of the fabrication of multi-responsive hydrophilic fluorescent MIP nanocapsules and their application as bioenvironment-adaptive drug carriers for cancer treatment. Reused with consent.[114] Copyright 2025, Wiley-VCH GmbH.*

innovations are crucial in addressing the challenges of modern drug delivery, especially for biopharmaceuticals and targeted therapies. For example, Zhang *et al*.[114] designed multi-responsive hydrophilic fluorescent molecularly imprinted polymer (MIP) nanocapsules for targeted cancer treatment **(Figure 7)**. These nanocapsules, incorporating disulfide-crosslinked shells with sialic acid-imprinted sites and thermo/pH-responsive polymer brushes, showed excellent stability, biocompatibility, and tumor-specific activity. The MIP nanocapsules demonstrated high drug-loading efficiency, prolonged blood circulation, and rapid intracellular drug release, resulting in effective tumor inhibition. This work presents a versatile "all-in-one" nanoplatform that combines targeting, imaging, and controlled drug delivery for advanced cancer therapy. In a related work from our group, Dolui *et al*.[54] created poly(*N*-isopropylacrylamide)-*block*-poly(methacrylic acid)-umbelliferone ((PNIPAM-*b*-PMAA)$_n$-UMB), a multi-stimuli-responsive multiarm star-shaped block copolymer designed for targeted and regulated drug delivery. In aqueous conditions, this polymer spontaneously self-assembled into nanoscale aggregates that effectively contained DOX inside their hydrophobic cores. These DOX-loaded aggregates enabled controlled, site-specific drug release under physiological settings, particularly at body temperature (~37 °C) and an acidic pH (~5), which resembled the tumour microenvironment. The integration of the fluorescent UMB unit also made it possible to track the distribution process in real time using fluorescence imaging, offering a combination therapeutic and diagnostic benefit.

5.2. Cancer Therapy and Diagnostics

Cancer is a complicated and frequently fatal illness that is defined by unchecked cell growth and division that interfere with vital body processes.[115] Surgery, chemotherapy, radiation, immunotherapy, and targeted molecular therapy are examples of current treatments that have therapeutic benefits but also significant drawbacks, such as tumour spread or recurrence, harm to nearby healthy tissues, and extremely harmful side effects.[115] Many smart polymer based sensors developed to monitor glucose in diabetic patients or detect tumor markers in cancer patients can deliver real-time information, facilitating personalized treatment and early medical intervention.[116] For example, Oliveira *et al*.[117] created a MIP-based biosensor to detect the breast cancer biomarker CA 15-3 selectively **(Figure 8)**. They produced high-affinity recognition sites that could differentiate CA 15-3 from other proteins via electro-polymerization on a carbon screen-printed electrode. The sensor has great potential for point-of-care breast cancer detection and provides a quick, sensitive, and affordable substitute for conventional immunoassays.

Polymer based systems can be designed to deliver anticancer drugs in response to the acidic conditions of tumor microenvironments, thereby improving therapeutic effectiveness while reducing adverse side effects.[118] Bai *et al*.[119] designed M-POSS-based molecularly imprinted polymer (MIP) microparticles for paclitaxel (PTX) delivery in cancer therapy. Synthesized via RAFT precipitation polymerization, the spherical microparticles (170–490 nm) showed high drug loading (17.1%) and encapsulation efficiency (85.5%). They exhibited pH-sensitive behavior, releasing PTX faster under acidic conditions similar to tumor environments, indicating strong potential for controlled and targeted cancer drug delivery.

5.3. Tissue Engineering and Regeneration

Tissue integrity can be affected by various factors such as inflammation, tumors, injuries, and surgical procedures.[120] These conditions often result in irregularly shaped defects in tissues like bone, cartilage, and skin, differing in size and depth.[120] Due to the body's limited regenerative ability, biomaterials are often required to support the repair of such complex and extensive tissue damage.[120] Conventional tissue engineering methods usually depend on static scaffolds that cannot dynamically adjust to variations in the tissue environment, restricting their capacity to mimic complex biological conditions.[121] In contrast, smart and functional polymeric materials can sensitively respond to environmental stimuli, creating a dynamically adaptable microenvironment that improves interactions between cells and implants.[122]

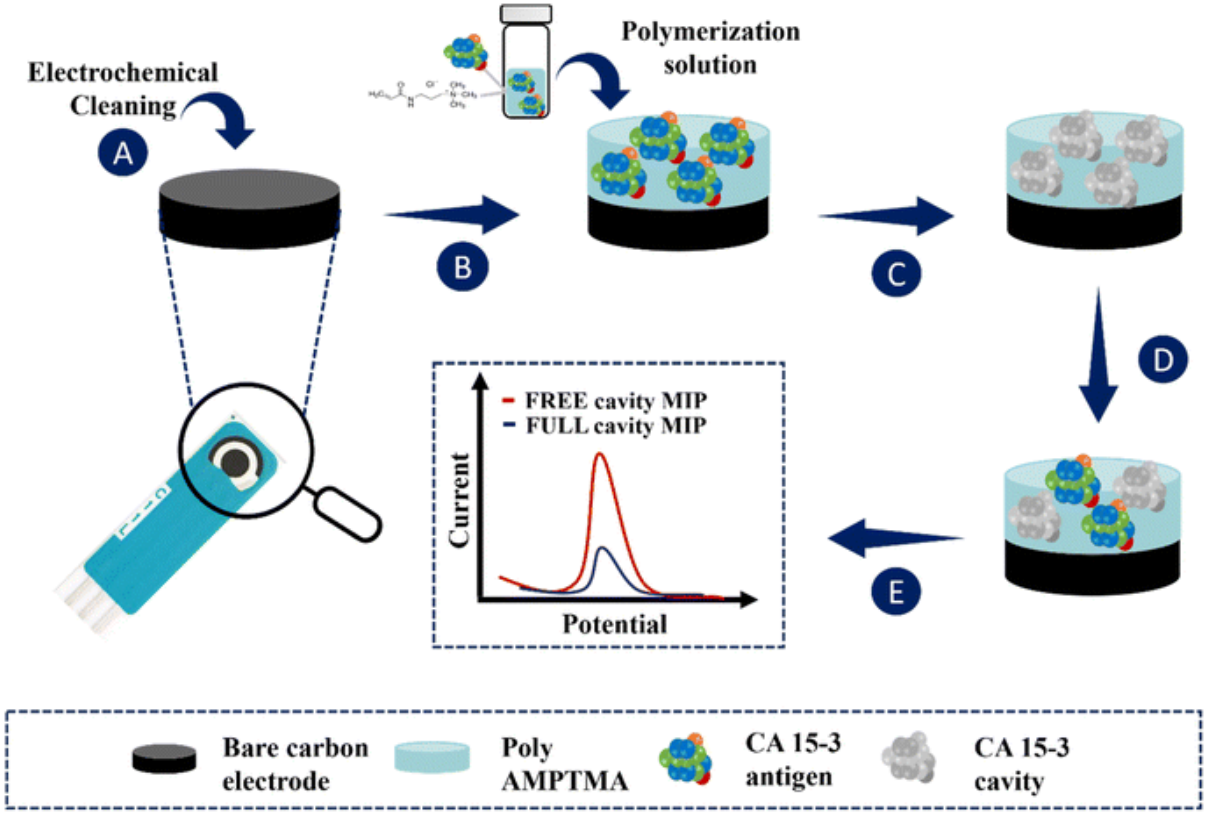

Figure 8. *Schematic illustration of a MIP-based sensor for CA 15-3 protein detection: (A) pretreatment of the working electrode; (B) electropolymerization of a solution containing the CA 15-3 protein and monomer (AMPTMA); (C) removal of the CA 15-3 template from the polymer matrix; (D) rebinding of the target protein to the MIP surface; (E) evaluation of the sensor's analytical performance. Reused with permission.*[117] *Available under a CC-BY license. Copyright 2025 Oliveira et al.*

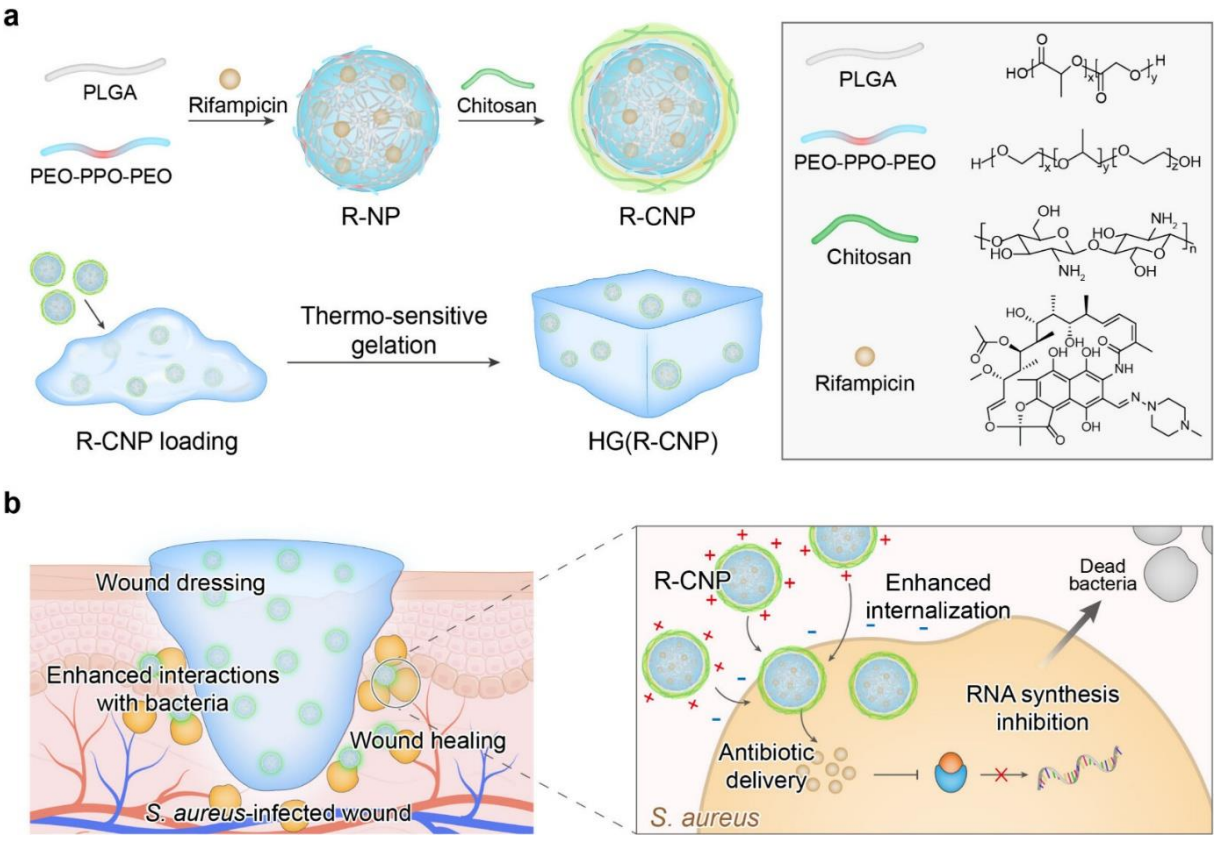

Figure 9. *(a) Schematic representation of the stepwise fabrication of smart nanoparticle–hydrogel systems, including R-CNP, HG, and HG(R-CNP); (b) HG(R-CNP) treats bacteria-infected wounds by enabling effective antibiotic delivery and strong wound protection. Reused with consent.*[128] *Copyright 2025 American Chemical Society.*

These microspheres can accurately control processes like swelling, degradation, and drug release, ensuring timely cellular support and signal communication, which ultimately facilitates effective tissue regeneration.[123]

SRP microspheres have been explored for bone defect repair. Song *et al*.[124] created a dual-responsive microsphere system triggered by ultrasound and the bone injury microenvironment (low pH and high H_2O_2). The system achieved controlled release of Mn^{2+} and bone morphogenetic protein-2 (BMP-2), with ultrasound enhancing release rates. MnO_2 neutralized acidity, removed reactive oxygen species, and promoted osteoblast growth and mineralization. It also facilitated M1-to-M2 macrophage polarization, reduced inflammation, and created an immunoregulatory niche, resulting in nearly 90% bone regeneration after 8 weeks.

5.4. Wound Healing

As the body's largest organ, the skin performs essential physiological functions, including protection and secretion.[125] It acts as a barrier that shields against infections and prevents excessive fluid loss.[125] However, injuries can compromise this barrier, leading to wounds.[126] By adding specific functional groups, polymers can respond to environmental stimuli such as pH, temperature, ionic strength, or biomolecular interactions.[126] Therefore, improving the therapeutic effectiveness of antibiotics at both the bacterial and infected tissue levels is crucial to combat the growing challenge of bacterial infections.[127] Recent progress in biomaterials has highlighted smart and functional polymers as promising candidates for next-generation wound care systems.

For example, Xu and Zou *et al*.[128] created a hydrogel-smart nanoparticle system to heal wounds infected with bacteria **(Figure 9)**. While integration into a thermosensitive hydrogel (HG) allowed for sustained release and wound protection, rifampicin-loaded chitosan nanoparticles (R-CNP) improved antibiotic absorption and bactericidal activity. In a mouse model, this platform reduced bacterial load by 98.5% compared to free rifampicin, demonstrating strong potential for clinical wound infection therapy.

5.5. Biosensing

Polymers have recently become essential in biosensing due to their adjustable chemical structures, mechanical strength, and excellent biocompatibility.[129] Polymers can react to environmental stimuli like pH, temperature, ionic strength, or biomolecular interactions by adding particular functional groups. [130] Additionally, when combined with enzymes, antibodies, nucleic acids, or other biomolecules, they help maintain the activity of these sensing elements, allowing accurate detection and monitoring of target biomarkers.[131]

For instance, Fatkullin *et al*.[132] introduced reduce GO on the surface of a polyethylene terephthalate (PET)/textile sandwich (rGO/PET/textile), a high-performance graphene polymer composite bioelectrodes via laser processing on textile substrates **(Figure 10)**. The incorporation of a PET layer enhanced conductivity (45 Ω sq^{-1}), mechanical stability, and biocompatibility while minimizing polarization effects. These flexible, durable electrodes outperformed commercial ones in biosensing applications, showing excellent skin compatibility and long-term stability for wearable smart clothing devices. The adaptability and responsiveness demonstrated in biomedical systems highlight the broader potential of smart polymers across technologically demanding fields.

6. Smart and Functional Polymers for Energy Applications

Leveraging these same attributes, smart and functional polymers are increasingly being engineered for next-generation energy storage and conversion technologies.

6.1. Energy Storage

In order to address the increasing need for portable and flexible power systems and enable the sustainable and dependable use of renewable energy sources, energy storage is crucial. The search for efficient and environmentally friendly substitutes is prompted by the fact that conventional materials frequently fail to strike a balance between high performance and environmental sustainability. The combination of electrical conductivity, mechanical flexibility, and ease of manufacturing has made conductive polymers (CPs) a potential option. Their attractiveness is further increased by recent developments in bio-derived conductive polymers and polymer electrolytes, which provide environmentally friendly, renewable, and biodegradable alternatives. These materials work together to

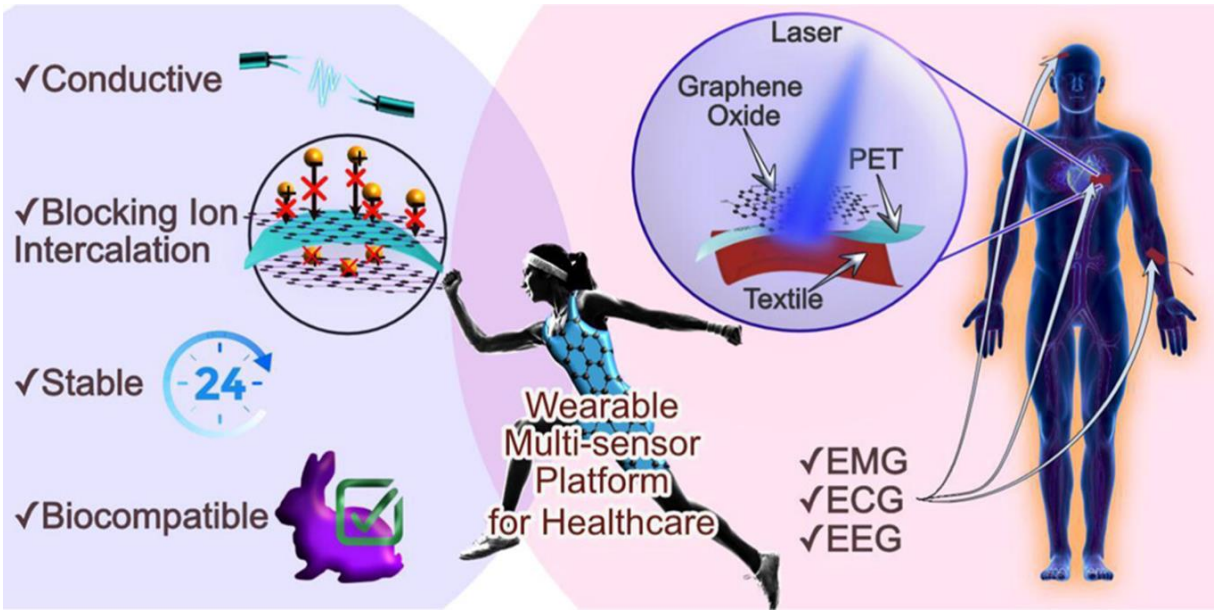

Figure 10. *Schematic illustration of rGO/PET/textile hybrid materisals for biosensing applications in wearable physiological signal monitoring. Reused with consent.*[132] *Copyright 2024 American Chemical Society.*

create lightweight, high-performing, and sustainable batteries and supercapacitors of the future.

6.1.1. Conductive Polymers in Supercapacitors and Batteries

For effective power generation and storage, sustainable energy systems need materials that are lightweight, flexible, and reasonably priced.[133] CPs are one type of developing material, have drawn a lot of interest due to its special capacity to combine the mechanical flexibility and processability of plastics with metal-like conductivity.[134] These conjugated π-electron backbones of intrinsically conductive polymers (ICPs) can be doped to obtain high conductivity.[135] Through quick and reversible redox processes, CPs have exceptional electrochemical behaviour, allowing for high pseudocapacitance and power density in solar cells, batteries, and supercapacitors **(Figure 11)**.[136, 137] Typical instances include PANI, PPy, and PEDOT:PSS's versatility in energy devices is demonstrated by its widespread use as electrode materials, conductive additives, and hole-transport layers.[138, 139]

CPs have found widespread use in energy storage systems, especially in supercapacitors and rechargeable batteries, where their multifunctional qualities enable improved electrochemical performance and device stability. This is due to their special combination of electrical conductivity, flexibility, and tunable chemistry.

Figure 11. *Various applications of conductive polymers. Reproduced with consent.[140] Copyright 2018 American Chemical Society*

6.1.2. Supercapacitors (Electrochemical Capacitors)

CPs serve as effective pseudocapacitive electrode materials, enabling rapid and reversible redox reactions in addition to double-layer charge storage. High-surface-area films of PANI, PPy, and PEDOT exhibit excellent capacitance performance.[141] Hybrid structures combining nanostructured metal oxides with PANI have produced flexible and transparent supercapacitors with enhanced energy storage capability .[142] Notably, PEDOT:PSS thin films can act as both current collectors and active electrodes in all-solid-state transparent devices fabricated via simple spin coating on PET substrates.[143] These electrodes demonstrate high optical transmittance and millifarad-level areal capacitance. The superior conductivity, flexibility, and pseudocapacitive behavior of CPs make them promising materials for next-generation supercapacitors.[144]

6.1.3. Batteries

In rechargeable energy systems such as lithium-ion and sodium-ion batteries, CPs have been explored as sustainable alternatives to conventional electrode materials. The concept of Li-ion batteries, first proposed by *Whittingham (1976)* and commercialized by *Sony in 1990*, inspired the development of polymer-based electrodes that combine flexibility, conductivity, and environmental compatibility.[145] Early efforts by Bridgestone-Seiko and VARTA/BASF led to commercial batteries utilizing PPy and PANI, respectively . When taken as a whole, these advancements position conductive polymers as essential components for the upcoming generation of flexible and environmentally friendly energy storage technologies.

6.1.4. Biopolymer-Based Electrolytes and Separators

The shift to sustainable energy technologies is being propelled by electrochemical energy storage systems, especially supercapacitors and lithium-ion batteries (LIBs).[146] A key component in these systems is the electrolyte, which enables ion migration during electrochemical cycling.[147] Despite having a high ionic conductivity, conventional liquid electrolytes have significant safety issues due to their volatility, flammability, and leaking.[148] To overcome these issues, gel polymer electrolytes (GPEs) have emerged as hybrid systems that combine the high ionic mobility of liquids with the mechanical stability of solids.[149] GPEs consist of a polymer matrix swollen with liquid electrolyte, forming a semi-solid phase that enhances electrode-electrolyte contact, thermal stability, and suppresses lithium dendrite growth. Their tunable electrochemical and mechanical properties make them suitable for diverse energy devices including Li-S, air, Na-ion, Zn-ion, and dual-ion batteries.[150] Overall, GPEs represent a crucial step toward sustainable, high-performance energy storage by coupling green chemistry principles with advanced electrochemical functionality.

6.2. Energy Conversion

Energy conversion technologies are vital for harnessing renewable energy and transforming it into usable electrical power, ensuring long-term sustainability and reduced carbon emissions. Among these, polymer-based systems have gained prominence due to their light weight, flexibility, and tunable electronic properties. CPs and their composites are increasingly employed in solar cells, piezoelectric materials and fuel cells, where they enable efficient photon-to-electric and chemical-to-electric energy conversion, respectively. Their ease of processing, compatibility with flexible substrates, and potential for low-cost, large-scale fabrication make them promising candidates for next-generation clean energy technologies. Additionally, polymer-based piezoelectric materials can convert mechanical vibrations into electrical energy, further broadening their role in sustainable energy harvesting.

6.2.1. Polymer-Based Solar Cells (OPVs, Perovskite Interfaces)

Organic photovoltaic (OPV) and perovskite solar cells (PSCs), two types of polymer-based solar cells, have drawn a lot of interest as flexible and affordable substitutes for traditional silicon photovoltaics. These devices utilize conjugated polymers as active materials for charge transport, light absorption and electrode interfaces, enabling lightweight and mechanically flexible architectures.[151] In order to enable effective exciton dissociation and charge transfer, a common polymer solar cell uses a donor-acceptor bulk heterojunction (BHJ) structure, in which the photoactive polymer donor and fullerene or non-fullerene acceptor materials are closely combined.[152] Moreover, integrating conductive polymer interfaces with perovskite layers enhances interfacial contact, improves hole extraction, and suppresses charge recombination, thereby increasing power conversion efficiencies (PCEs) beyond 12% in flexible all-polymer

devices.[153] Overall, polymer-based solar cells represent a sustainable and adaptable approach toward next-generation clean energy technologies.

6.2.2. Membranes for Fuel Cells and Hydrogen Production

Fuel cells represent an advanced energy conversion technology that directly transforms chemical energy into electricity through electrochemical reactions, offering high efficiency, low emissions, and sustainability. Recent advancements have significantly expanded their application, particularly in electric vehicles and portable power systems.[154] Direct methanol fuel cells (DMFCs) have garnered significant attention among different varieties because of their high energy density, fuel mobility, and environmentally beneficial functioning.[155] The efficiency of DMFCs is largely influenced by the performance of electrocatalysts, whereCPs play a crucial role. CPs, such as PPy, PANI, and PEDOT, often form 1D and 2D nanostructures that enhance proton conductivity, facilitate charge transfer, and improve catalyst dispersion.[156] As a result, conducting polymer-based fuel cells represent a promising pathway toward clean, efficient, and sustainable energy conversion technologies.

6.2.3. Polymer-Based Piezoelectric Materials

Piezoelectric materials have drawn considerable interest because they can be used in advanced energy-storage systems and self-powered devices. Their distinctive property of converting mechanical movement into electrical energy makes them highly effective for harvesting mechanical energy. When mechanical stress such as stretching or compression is applied, these materials become polarized and produce an electric voltage.[157] Compared to conventional approaches, piezoelectric systems offer notable benefits like flexibility, durability, high sensitivity, and increased voltage and power output, making them suitable for battery-free, wireless applications.[158] Their versatile nature also allows seamless incorporation into compact and miniaturized electronic devices.

7. Smart and Functional Polymers for Environmental Applications

Beyond healthcare and energy, smart polymers also play a vital role in environmental protection, offering adaptive solutions for water purification, pollution remediation, and sustainable packaging.

7.1 Water Purification and Treatment

The integration of nanostructured adsorbents and membranes for the efficient removal of heavy metals, dyes, and newly emerging pollutants including microplastics has been the focus of recent developments in water purification technologies.[159] High surface area nanomaterials, like covalent organic frameworks (COFs), metal-organic frameworks (MOFs), and electrospun nanofibrous membranes (ENMs), show higher adsorption capability and tunable pore topologies. In addition to prove high flux and antifouling resistance, hybrid ENMs embedded with metal oxides, carbon nanotubes, or chitosan matrices work exceptionally well in capturing Pb^{2+}, Cd^{2+}, and Cr^{2+} ions. Additionally, membrane functionalization with hydrophilic and zwitterionic groups enhances regeneration, stability, and selectivity, making them more suitable for wastewater treatment in the real world.[160] At the same time integration of degradable backbones, bio-based monomers, and controlled polymerization strategies that enable chemical recycling will be essential to limit microplastic formation and ensure that the development of functional polymers remains environmentally safe.

Smart hydrogels have become dynamic materials that can trap pollutants and release them under regulated conditions, going beyond adsorption.[161] Through electrostatic and hydrogen bonding interactions, these stimuli-responsive gels can bind dyes and heavy metals, releasing them in response to temperature or pH triggers for regeneration.[21] The synergy between these hydrogels and membrane systems is highlighted by Randhawa *et al*.[162] with their function in next-generation hybrid purification platforms. When combined, membrane-assisted and adsorbent-based methods offer a sustainable route for effective wastewater treatment.[163]

7.2 Pollution Remediation

7.2.1. Oil-Water Separation Membranes

Membrane based oil-water separation has become a viable and effective substitute for traditional purification techniques because of its high selectivity, low energy consumption, and scalability. To selectively penetrate one liquid phase while rejecting the other, the fundamental idea is to manipulate surface wettability and create superhydrophobic–superoleophilic or superhydrophilic-superoleophobic interfaces. Recent research emphasises how additive manufacturing, fluorine-free coatings, and hierarchical micro/nano structures can enhance membrane durability and anti-fouling effectiveness. Furthermore, tunable separation under external triggers like pH, temperature, or light is made possible by Janus membranes with asymmetric wettability and stimuli-responsive materials.[164] Pollutant degradation and self-cleaning capacities are further improved by using conductive

Table 3. *Representative smart polymer applications and their key performance indicators.*

Application Domain	Representative Function	Key Performance Metrics	Example Materials (with Citations)
Drug Delivery	Stimuli-triggered drug release; tumor-specific targeting	Drug loading efficiency; release kinetics at physiological pH; cytocompatibility	PNIPAM-based nanogels; pH-responsive PAA copolymers.[110,114,115]
Tissue Engineering	Adaptive scaffolds supporting cell growth	Cell adhesion/proliferation; ECM remodeling; modulus & degradation rate	PEG-DA hydrogels; PDMAEMA copolymers; bio-based elastomers.[122,124,175]
Wound Healing	Antibacterial hydrogels for moisture balance	Antibacterial inhibition zone; fluid retention; healing time	Chitosan-PAA hydrogels; Ag-loaded networks.[128,176]
Biosensing & Wearables	Conductive, flexible electrodes for sensing	Sensitivity; detection limit (LOD); signal stability	PEDOT:PSS hydrogel patches; MIP sensors.[141,177]
Energy Storage	Supercapacitor electrodes; battery interfaces	Capacitance; cycling stability; ionic/electronic conductivity	PANi electrodes; PEDOT:PSS-CNT composites.[145,178]
Energy Conversion	OPVs, perovskite interlayers, PEM membranes	Power conversion efficiency (PCE); mobility; durability	Dopant-engineered CPs; Nafion-type copolymers.[151,179]
Water Purification	Ion-selective adsorption; dye removal	Adsorption capacity; selectivity; regeneration cycles	PAA/PVA hydrogels; MOF-polymer membranes.[163,180]
Pollution Remediation	Oil–water separation; antifouling surfaces	Separation efficiency; fouling resistance; recyclability	Janus membranes; amphiphilic graft copolymers.[166,181]

and photocatalytic nanoparticles. The necessity for environmentally benign, multipurpose, and regenerable membranes for next-generation oil-water separation systems is highlighted by the difficulties in large-scale fabrication, fouling resistance, and long-term stability that persist despite notable advancements.[165, 166]

7.2.2. Smart and Functional Polymers for Carbon Capture and Gas Separation

Smart and functional polymers have created new opportunities for gas separation and carbon capture due to their strong CO_2 affinity, adjustable selectivity, and recyclable nature. Advanced materials such as amine-functionalized polymers, porous organic polymers, and polymeric membranes that exhibit dynamic responsiveness to stimuli such as temperature, pressure, or humidity enable efficient CO_2 adsorption and controlled desorption.[167] Incorporating nanomaterials such as graphene, MOFs, or ionic liquids into polymer matrices improves permeability and CO_2/N_2 selectivity beyond Robeson's upper bound.[168,169] Furthermore, flexible polymeric topologies can be incorporated into scalable membrane modules for post-combustion capture and industrial gas purification. Because they provide environmentally benign, regenerable, and energy-efficient alternatives to conventional sorbents, these intelligent polymer systems are crucial enablers of next-generation carbon management solutions.[170]

7.3. Sustainable Packaging and Waste Management

7.3.1. Biodegradable and Recyclable Polymer Systems

Biodegradability and biocompatibility are crucial for SRPs used in environmental and biomedical sectors. Biocompatible SRPs are appropriate for medication administration, biosensing, and tissue engineering because they shouldn't cause toxicity or immunological reactions. Using natural polymers like hyaluronic acid or chitosan, adding PEG chains, or altering surfaces to lessen immunological recognition and protein adsorption can all improve their compatibility.[171] Biodegradability is essential for temporary implants, wound healing, and environmental remediation because it guarantees that polymers break down into innocuous byproducts, limiting long-term buildup in the body or environment. Degradable backbones are often designed using hydrolysable, redox-labile, or enzyme-sensitive connections. The development of sustainable and ecologically friendly SRPs is being aided by the increasing usage of renewable monomers and green synthesis methods.[172]

7.3.2. Self-Healing or Long-Life Materials to Reduce Waste

The creation of long-lasting and self-healing materials presents a revolutionary way to reduce waste and increase the longevity of useful equipment. Advances in polymeric, supramolecular, and dynamic covalent systems have made it possible for mechanical and electrical damage to be repaired autonomously, restoring performance without the need for outside assistance.[173] These materials become more versatile and recyclable when reversible bonds like hydrogen bonding, disulphide, and Diels-Alder adducts are incorporated. Research by Chandrasekar *et al*. shows that advanced composites with incorporated healing agents show improved durability in severe conditions, while self-healing energy devices maintain efficiency under repeated stress. These materials encourage sustainable, circular design in next-generation technologies by prolonging product life and drastically reducing electronic and polymer waste.[174]

The broad utility of smart and functional polymers across environmental, biomedical, and energy sectors reflects their unmatched versatility and transformative potential **(Table 3)**.

8 Future Perspectives

Advancements in smart and functional polymers will depend on the integration of cutting-edge molecular design with sustainable and scalable production methods. New strategies such as sequence-controlled polymerization, eco-friendly synthesis methods, and bio-derived monomers will facilitate the creation of materials that can be finely adjusted and that have less impact on the environment. In order to realize translation in the real world, forthcoming systems need to provide long-term stability, dependable responsiveness, and suitability for large-scale production. The advancement of adaptive, reconfigurable polymers will be expedited by technologies like 4D printing, material discovery guided by machine learning, and self-assembling architectures. It is of equal importance to incorporate aspects of recyclability, repairability, and end-of-life management into the design of materials. By integrating performance with lifecycle considerations, we can ensure that next-generation smart polymers are designed not only for advanced functionality but also for full environmental compatibility.

9 Conclusion

Smart and functional polymers are rapidly evolving as adaptable materials capable of responding to diverse physical, chemical, and biological triggers while supporting sustainable technological development. This review summarized how advanced polymerization methods including ATRP, RAFT, RDRP, and other controlled or green synthetic approaches, enable precise tuning of polymer structure, responsiveness, and long-term stability. The adoption of renewable monomers, environmentally benign catalysts, and recyclable or degradable designs further enhances their ecological relevance. Their wide-ranging applications from targeted drug delivery, cancer therapy, tissue regeneration, and biosensing to energy storage, energy conversion, water purification, pollution control, and sustainable packaging, demonstrate their impact across multiple sectors. The development of dynamic, recyclable polymers that adhere to the principles of the circular economy and tackle global issues in energy, environmental protection, and healthcare will depend on the use of technologies such as 4D printing, nanofabrication, and AI-driven molecular design. It is essential to combine molecular design with lifecycle thinking, and this review highlights the necessity of designing future smart polymer systems for not just advanced functionality but also full environmental compatibility over their entire lifespan. Together, these directions will guide the creation of next-generation, high-performance materials that are both intelligent and environmentally responsible.

Author Contribution Declaration & Information

Contribution

Koushik Mahata writing - original draft, writing - review & editing; Sudipta Paul writing - original draft, writing - review & editing; Ankit Kumar Kaushik writing - original draft, writing - review & editing; Sanjib Banerjee conceptualization, funding acquisition, project administration, resources, supervision, writing - original draft, writing - review & editing.

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Data Availability Declaration

No new data were created hence data sharing is not applicable.

Declaration of Conflict of Interest

The authors have no conflict of financial interest.

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