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Review

Next-Generation Smart Carbon–Polymer Nanocomposites: Advances in Sensing and Actuation Technologies

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Abstract

The convergence of carbon nanomaterials and functional polymers has led to the emergence of smart carbon–polymer nanocomposites (CPNCs), which possess exceptional potential for next-generation sensing and actuation systems. These hybrid materials exhibit unique combinations of electrical, thermal, and mechanical properties, along with tunable responsiveness to external stimuli such as strain, pressure, temperature, light, and chemical environments. This review provides a comprehensive overview of recent advances in the design and synthesis of CPNCs, focusing on their application in multifunctional sensors and actuator technologies. Key carbon nanomaterials including graphene, carbon nanotubes (CNTs), and MXenes were examined in the context of their integration into polymer matrices to enhance performance parameters such as sensitivity, flexibility, response time, and durability. The review also highlights novel fabrication techniques, such as 3D printing, self-assembly, and in situ polymerization, that are driving innovation in device architectures. Applications in wearable electronics, soft robotics, biomedical diagnostics, and environmental monitoring are discussed to illustrate the transformative impact of CPNCs. Finally, this review addresses current challenges and outlines future research directions toward scalable manufacturing, environmental stability, and multifunctional integration for the real-world deployment of smart sensing and actuation systems.

Keywords: carbon–polymer nanocomposites; carbon nanotube; Mxenes; in situ polymerization; multifunctional sensors; actuators; wearable electronics; soft robotics

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1. Introduction

The continuous drive for advanced methods of interaction, specifically involving wearable electronics and soft robotics, has brought critical flaws in traditional materials to the surface [1], eliciting a pressing demand for the development of future multifunctional composites [2,3]. Wearable electronics are extremely attractive because of their superior

performance in integrating with the human body, and a series of real-time, continuous monitoring for blood pressure, intraocular pressure, heart rate, motion kinetics, wrist pulse waveforms, and biochemistry markers (ions, gases, metabolites) in biofluids can be achieved [4]. In contrast to cumbersome, state-of-the-art monitoring solutions (e.g., clinical blood pressure cuffs), these devices combine technologies in smart and stretchable/flexible sensors, actuators, power, wireless connectivity, and advanced data analytics to create a mobile and user-friendly platform to offer unprecedented access to complex health diagnostics and personalized interaction [5,6]. Of crucial importance is that these core sensors require ultrathin, low-weight, low-modulus substrates and excellent electrical performance, which are simultaneously extremely flexible and stretchable requirements that traditional rigid electronics cannot meet [7].

At the same time, the field of robotics is transitioning from hard, rigidly jointed assemblies driven by motors and gears to soft robotics inspired by natural organisms [8]. These bots employ compliant, deformable structures capable of complex, adaptive behaviors (e.g., bending, twisting, elongation) in unstructured environments [9]. This transition relies on "smart" materials, which are naturally active materials that can directly convert external perturbations (electrical fields, thermal energy, light, magnetic fields, chemical signals) into actually controlled mechanical reactions (actuation) or responses (sensing) [10]. In actuation, innovative materials replace traditional motors to realize intrinsic shape-morphing. In order to sense in such deformable structures, there is a need for new, flexible, or stretchable sensors that are able to convert forces or deformations into an equivalent change of resistance, capacitance, magnetic field, or optical properties [11,12]. But the material properties are crucial for high-performance, durable, and reliable soft robots [13].

These challenging applications are demanding, and there are large, if not insurmountable, shortcomings of conventional classes of materials. Metals are strong, but are rigid and not soft robot or body-worn conforming, prone to corrosion (especially steel in humidity, needing costly protection), thermal bridging (of steel due to high conductivity), and long-term deformation under load (e.g., lead pipes and soldering alloy, enhanced in polymers like gutters at mild temperatures) [14,15]. Natural materials (wood, brick, adobe) are not "malleable" from a design standpoint, deteriorate readily, and have maintenance problems. Typical polymers–rubbers have poor electrical/thermal conductivity as well as UV/oxidative degradation that cause embrittlement or stickiness (e.g., chemical decomposition of rubber, not melting) [15], and gravity is a source of thermal energy and/or motion/service in polymers–rubbers. The anisotropic, difficult-to-repair nature and low recyclability of the composites are usually observed. The integration complexity, scalability, and cost of advanced new materials are challenging. Together, these limitations are a hindrance towards developing truly adaptive, robust, and high-performance systems for sensing and actuation [16,17].

CPNCs present a promising alternative, designed precisely to compensate for these drawbacks [18]. Incorporation of nanoscale carbon-based fillers, known for their excellent intrinsic properties, into tailor-made polymer matrices results in CPNCs' superior structural as well as functional performance properties. Carbon nanomaterials are the fundamental building block. Graphene and its derivatives, like graphene oxide (GO) and reduced graphene oxide (rGO), provide excellent electrical conductivity, mechanical robustness, and enormous surface area with controllable surface chemistry through doping [19]. CNTs, like single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) in particular, feature exceptional mechanical strength and distinctive, chiral-dependent electronic properties [20]. Metallic conductivity, hydrophilicity, and frequent surface chemistry are offered by Mxenes [21]. Additional dimensions arise from other shapes, such as carbon, nanofibers, nanodiamonds, fullerenes, etc. The polymer matrix is just as im-

portant. Thermoplastics can be processible and hard, thermosets (e.g., epoxies) provide structural stability, and elastomers are often required due to flexibility and stretchability for wearables and stretchable robots [22]. These conductive and bio-based polymers further enhance the functionality and sustainability of the material [23]. It is critically important to optimize interfacial adhesion and the dispersion of the nanofiller, e.g., through chemical functionalization and ultrasonication.

In this review, we investigate the recent developments in smart CPNCs in response to the simultaneous needs of the materials in sensing and actuation applications. In addition, particular emphasis is placed on strategies for achieving stable dispersion of carbon nanomaterials within polymer matrices and on tailoring surface wettability and environmental stability, both of which are decisive factors for long-term reliability in sensing and actuation. We demonstrate the essential role of CPNCs in the development of multifunctional, responsive, and adaptive technologies via a critical comparison of the assembly strategies, structure–design principles, and functional frontiers. The review further highlights both the limitations of existing material systems and the research direction required to push toward scalable, sustainable, and intelligent material systems that can revolutionize fields as varied as soft robotics, healthcare, smart infrastructure, and human–machine interfaces.

2. Fabrication Strategies and Performance Optimization of Carbon–Polymer Nanocomposites

2.1. In Situ Polymerization

In situ polymerization has been proven to be an efficient way to prepare graphene/polymer nanocomposites with improved mechanical, electrical, and thermal properties. The mechanism is based on stable chemical bonds that are formed between oxygen-containing functional groups of GO surfaces and various polymers, including polyimide, polyurethane, epoxy resin, polyaniline, and PVA. During the polymerization process, the functionalized graphene plays a dual role as a nanofiller and an active part of the reaction, and the oxygen radicals on the surface of GO can start the polymerization and allow the polymer chains to grow from the graphene layers, shown in Figure 1. This distinctive mode of action via density functional theory forms a stable interfacial bonding between the ionic liquid and the graphene and possesses a desegregation effect on graphene. The polymer chains grown on the surface play double roles: they are covalently linked to graphene and physically separate neighboring layers, and they distribute well in the matrix. This approach has distinct advantages over classical mixing routines, particularly when robust interfacial stress transfer or electrical percolation networks are required. Nevertheless, this implementation success can be achieved when the polymer systems can form a stable bond with the functional group of graphene and optimal reaction conditions is achieved that can maximize the polymerization while capable of maintaining the carbon reinforcement in its nanoscale dispersion [24,25].

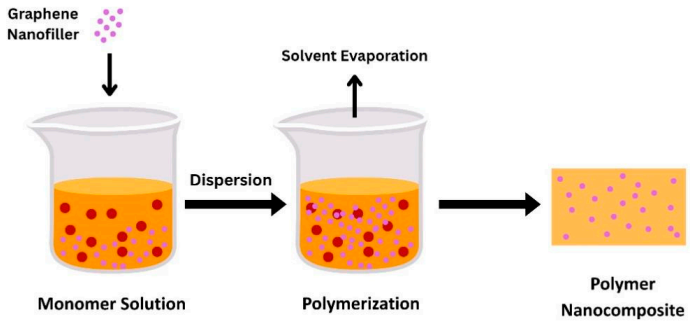


Figure 1. Schematic illustration for the in situ polymerization method.

2.2. Solution Casting and Melt Mixing

The solution casting technique, shown in Figure 2, is a versatile and promising approach to prepare high-performance carbon–polymer nanocomposite membranes, particularly for energy storage and smart material applications. The method includes dissolving polymers such as PVDF and PI in a suitable solvent together with carbon nanomaterials (e.g., graphene, CNTs, carbon dots) to prepare a solution [26]. Controlled evaporation allows the membrane structure to be finely tuned, from molecular interactions to microporosity. In battery separators, adding carbon fillers increased the ionic conductivity (up to 3×), and the samples maintained high thermal stability (>200 °C). Uniformity (100 MPa) and good electrochemical properties have been shown to provide them with a huge promise in flexible energy devices and actuation systems [27].

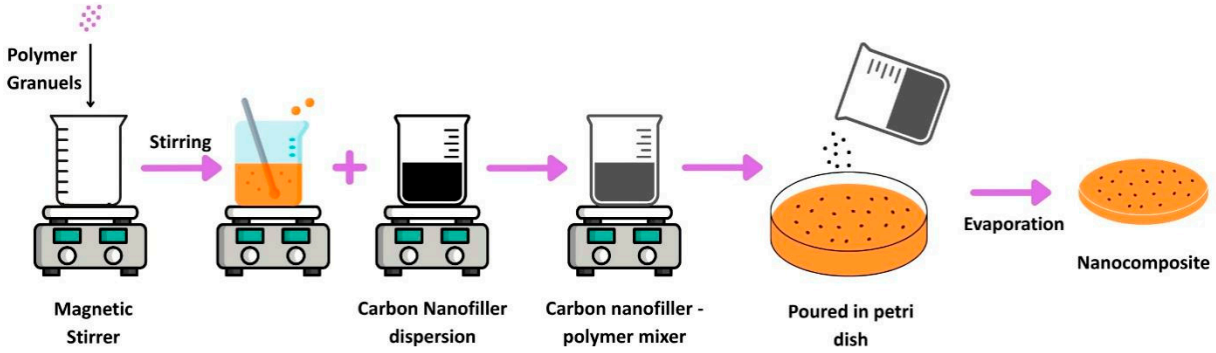


Figure 2. Schematic illustration for the solution casting and melt mixing method.

The excellent electrical and thermal conductivity and mechanical properties (1–1.7 TPa) of CNTs make them some of the most promising candidates for smart materials. The high aspect ratio and piezoresistive behavior of CNTs make them a candidate material for sensing and actuation in polymer nanocomposites [26]. However, there are several difficulties, such as agglomeration and lack of interfacial adhesion, that hinder the homogeneous dispersion. Melt mixing is a cost-efficient, solvent-free process that encounters these problems by shear-induced deagglomeration despite maintaining the intrinsic properties of CNTs. Noncovalent modifications further improve dispersibility while not adversely affecting the performance. Melt-mixed CNT–polymer composites, especially with thermoplastics such as polypropylene (PP), polyethylene (PE), and nylon-6 (PA6), are used for strain sensors, flexible electronics, and self-monitoring systems, etc. Though alternatives such as graphene exist, CNTs remain the most attractive option for constructing conductive percolation networks [28]. Meanwhile, further developments will focus on multifunctional composites for sensing, actuation, and energy-harvesting, as well as improvement of melt-processing for industrial production scale. The present advances place CNT-based nanocomposites at the forefront of future innovative materials.

2.3. Electrospinning and Electropolymerization

Electrospinning and electropolymerization are flexible methodologies used to produce carbon–polymer composites for advanced sensing and actuation applications. During electrospinning, high voltage is applied to the polymer solution to add it to a fine nanofiber, while the nanofiber is gathered on a conductive substrate. By adding carbon-based nanomaterials, such as CNTs or graphene, into the polymer matrix, the electrospun nanofibers have enhanced electrical conductivity, mechanical strength, and surface area [29].

Electropolymerization is then used to fabricate a conductive polymer layer, e.g., polypyrrole or a polyaniline layer, on the electrospun fibers. This is done electrochemically by using a potential that initiates the polymerization of monomers directly at the nanofiber

surface to achieve control over the thickness and uniformity of the polymer coating, shown in Figure 3. This hybrid synthesis route allows for nanostructured, flexible, and conducting CPNCs to be formed. These materials are promising candidates for applications in nanofiber-based sensors and actuators that demand high sensitivity, fast response, and mechanical flexibility [30]. An example is a Ppy/PDA-coated fabric sensor that was sensitive to 77.04 kPa^{-1} in the 0.155–2 kPa range, 7.52 kPa^{-1} in the 2–4 kPa range, and 2.07 kPa^{-1} in the 410 kPa range, and that showed their potential in practical sensing applications [31].

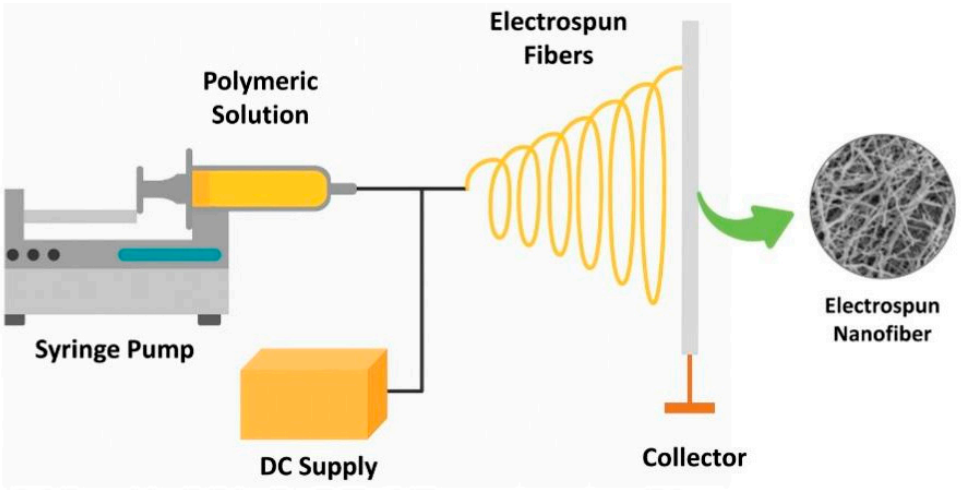


Figure 3. Schematic illustration for the electrospinning method.

2.4. Advanced and Emerging Techniques

Advances in fabrication technologies are now providing an ability to control CPNCs in ways that were not previously possible and which hold promise for future generations of sensors and actuators. Three-dimensional/four-dimensional printing provides the means to generate complex, stimuli-responsive geometries with embedded functionalities, and laser processing offers micron-level precision to pattern conductive networks in flexible structures [32]. High-throughput processes such as nanoimprinting enable mass production of high-resolution sensor arrays with nanoscale features, which are essential for wearable and IoT devices. The emerging category of in-mold electronics puts circuitry within the molded polymer part, making for smooth smart surfaces on automotive and consumer electronics [33]. On the other hand, nature-inspired self-assembly, based on bio-inspired self-assembly, combines molecular interactions to generate well-ordered nanocomposite structures endowed with specific properties. Roll-to-roll processing is a cheap way to produce ordered films of functional nanocomposites for large-area applications at the industrial scale. Together, these advanced methods solve some of the scale, resolution, and multimaterial challenges, propelling the frontier of the smart material system space. With such fabrication techniques combined with melt-processed CPNCs, novel solutions can be engineered for soft robotics, structural health monitoring, and interactive human–machine interaction [34]. Comparison of different fabrication methods for carbon–polymer nanocomposites is shown in Table 1.

Table 1. Critical comparison of fabrication methods for carbon–polymer nanocomposites.

Method	Typical Workflow	Relative Advantages	Challenges	Scalability	Reproducibility	Interfacial Adhesion	Applications	References
In situ polymerization	Disperse nanocarbon in a monomer (or monomer solution), then polymerize so the network forms during cure.	Simple overall workflow; often achieves good, uniform networks because the polymer forms around the filler.	Only applicable to certain monomers/polymers; aggregation can still occur and generally must be mitigated (e.g., ultrasonics/surfactants).	Generally good for batch and scale-up if the target polymer system supports in situ routes.	Moderate–high if mixing/dispersion protocol is controlled; still filler aggregation limited.	Often benefits from chemical/physical compatibilization; functionalization of carbons or matrix can strengthen interfaces. (Examples across systems show property gains when interfacial interactions are improved.)	Structural/functional coatings, sensors, and energy devices where uniform networks are desired.	[1,24,35]
Solution casting (solution method)	Dissolve polymer; disperse nanocarbon in the same solvent; mix/sonicate; cast and evaporate solvent.	Tends to distribute fillers more homogeneously than melt routes (lower viscosity aids dispersion).	Multi-step/solvent-intensive; solvent selection critical; aggregation still possible; cooling/ultrasonics often needed.	Moderate (solvent handling/evaporation can bottleneck scale).	Moderate (sensitive to solvent residue and dispersion history; aggregation is an intrinsic risk).	Interfacial strength can be boosted via filler functionalization or compatibilizers during solution processing, improving dispersion and bonding.	Thin films/coatings; flexible sensor skins; membranes; electrodes.	[35–37]
Melt mixing (melt compounding)	Add nanocarbon to molten polymer (e.g., extrusion, roll-mill); high-shear mixing; shape/cool.	Low cost, simple, industrially ubiquitous; compatible with thermoplastics (extrusion, rheometers, etc.).	High shear promotes dispersion but shortens aspect ratio, degrading properties; difficult to achieve uniform nanoscale dispersion; not suited to thermosets.	High (standard plastics tooling, continuous processing).	Moderate (sensitive to shear history; breakage of high-aspect fillers affects batch-to-batch properties).	Often requires surface treatments/compatibilizers to maintain dispersion and improve matrix–filler bonding.	Bulk structural/EMI parts; conductive/antistatic thermoplastic components.	[35,38]

Table 1. *Cont.*

Method	Typical Workflow	Relative Advantages	Challenges	Scalability	Reproducibility	Interfacial Adhesion	Applications	References
Electrospinning	Spin polymer solutions into nano/microfibers, then (optionally) carbonize to CNF mats; embed or use as freestanding architectures.	Produces porous, interconnected fibrous networks (good ion transport, large surface area); mat/web forms are ideal for electrochemical electrodes and sensors.	Multi-step (spinning + thermal treatment); morphology sensitive to solution/processing parameters.	Moderate (scalable with multi-jet/needleless systems, but slower than melt compounding).	Good when parameters are fixed; fiber morphology is parameter-sensitive (batch variation if controls drift).	Fiber/mat architectures offer large contact area; interfacial effects governed by fiber surface chemistry and post-treatments.	Battery/supercapacitor electrodes; flexible/porous sensors; conductive mats.	[36,39]
Electropolymerization	Electrochemically grow a conducting polymer (e.g., polypyrrole, polyaniline, polythiophene) on a conductive substrate or carbon network.	Conformal coatings and intimate contact at the interface; enhances charge storage and interfacial coupling; can increase adhesion with suitable primers (e.g., PEI).	Requires conductive substrate/path; thickness/uniformity depend on mass transport and potential control.	Good at device scale (wafer/electrode batches) but less suited for bulk parts.	High when deposition parameters are controlled (electrochemical processes are recipe-driven).	Demonstrated adhesion gains for polypyrrole on Au using polyethyleneimine; strong interfacial coupling with carbons improves electrochemical performance.	Supercapacitor/battery electrodes; electrochemical sensors; hybrid CP–carbon energy devices.	[39–41]

2.5. Dispersion of Carbon Nanomaterials in Polymer Matrices

Achieving and maintaining a uniform dispersion of carbon nanomaterials (CNMs) within polymer matrices remains a decisive factor in determining the performance of CPNCs. Dispersion directly influences the percolation threshold, which governs the onset of electrical conductivity, as well as the electromechanical response, hysteresis, and long-term stability of the composites [35]. Poorly dispersed systems often suffer from agglomeration due to the strong van der Waals forces and high surface energies of CNMs, leading to stress localization, premature interfacial debonding, and unreliable sensing behavior [39].

Strategies for Achieving Dispersion: Multiple strategies have been employed to overcome these challenges. Physical methods such as ultrasonication, high-shear mixing, and ball milling can break apart aggregates and aid distribution, though excessive processing may damage nanomaterials or reduce their aspect ratio [36]. Chemical functionalization, either covalent (e.g., oxidation, amination) or non-covalent (e.g., surfactant adsorption, polymer wrapping), improves compatibility with polymer matrices and prevents reagglomeration, while also enhancing interfacial load transfer. For example, surface-treated carbon nanofibers and graphene oxide derivatives have demonstrated significantly improved miscibility in epoxy and polyurethane systems, resulting in higher tensile strength and enhanced thermal [39].

Coupling Dispersion to Sensing Mechanisms: The degree of dispersion is intimately tied to sensing performance. Homogeneous filler distribution lowers the percolation threshold, creating stable conductive networks that yield predictable piezoresistive and thermoresistive responses. Conversely, agglomerates act as stress concentrators, increasing hysteresis during cyclic loading and degrading the repeatability of strain- or pressure-sensing signals. In thermal sensors, dispersion affects the balance between tunneling conduction and polymer expansion, thereby influencing whether the material exhibits positive or negative temperature coefficients of resistance [35].

Maintaining Dispersion in Service: Maintaining dispersion over the service life of CPNCs is as critical as achieving it initially. Polymer relaxation, thermal cycling, and mechanical fatigue can cause nanofillers to migrate or re-cluster, altering conductive pathways and reducing sensor reliability. Emerging solutions include crosslinking strategies, self-healing matrices, and the use of hybrid fillers (e.g., CNT–graphene or CNT–MXene blends) that stabilize percolation networks [39].

2.6. Surface Wettability and Stability to the Environment

Introduction of carbon nanomaterials radically changes the surface wettability of polymer composites [42]. Graphene, CNTs, and carbon black are naturally hydrophobic materials. The scattering in a polymer matrix forms micro- and nano-scale surface roughness [43]. With this architecture, along with low surface energy, it is possible to achieve superhydrophobic properties. Wettability control is a key to real-life performance. Superhydrophobic surfaces are of vital benefit in harsh conditions. They have a high antifouling potential, repellent to water, oils, and biological contaminants. This inhibits the biofilm growth on sensors and actuators.

These surfaces also increase the stability of water. They serve as an obstacle to water infiltration. This inhibits the swelling of the polymer, corrosion, and electrical breakdown [44]. The reliability is enhanced over a long period. The plasticization of the polymer matrix is suppressed by reduced water absorption [45]. This renders mechanical and long-term dimensional stability. Hence, the filler dispersion is critical in the engineering of surface qualities. Composites are humidity and long-lasting applications that are optimized by strategic application of carbon nanomaterials.

3. Sensing Mechanisms and Applications

3.1. Sensing Mechanisms

Polymers are insulating materials with great optical and mechanical properties. Yet, by adding conductive fillers, such as CNTs, graphene, or carbon black, their electrical properties may largely change. In percolation theory, above a critical filler concentration, a tetraglyme gel network is formed, resulting in a significant decrease in resistance. Particles are isolated below this percolation threshold, while above it, conduction is transported by direct contact or quantum tunneling. Notably, the percolation threshold and sensing performance critically depend on the dimensionality of the fillers [46]. An example is one-dimensional (1D) CNTs, which offer long, percolative pathways [46], and two-dimensional (2D) fillers such as graphene sheets or MXenes sheets, which offer large interfacial contact areas, promoting tunneling and capacitive responses [47]. In the meantime, three-dimensional (3D) hybrid structures (e.g., CNT-graphene aerogels) form hierarchical conduction networks, which enhance stability, and multi-modal sensing (strain, pressure, humidity) [48]. Conduction in the polymer depends on the geometry and dispersion of the filler blocks, as well as on the interaction between the polymer and the particles. These mechanisms are fundamental to constructing more advanced nanocomposites that may be used in sensing and actuation devices [49]. Triboelectric nanogenerators (TENGs) can directly convert mechanical stimulation to electrical output without consuming external power and are suitable for active sensing and self-powered electronics. They find applications in tactile, acoustic, motion, and chemical sensors and in advanced human–machine interfaces (HMIs). The recent developments are also not restricted to TENG-based keystroke authentication systems, eye-blink-driven smart homes, and acoustic sensors for voice recognition and hearing aids. TENGs have been designed to get the best surface charge density by incorporating 2D fillers (e.g., graphene oxide) into flexible/stretchable polymers, whereas 1D CNTs increase mechanical durability [50]. Hybrid 3D carbon-based fillers combine these effects and deliver high sensitivity and real-time response in wearable devices. These systems leverage the triboelectric effect in flexible/stretchable nanocomposites to achieve real-time signal sensing, high sensitivity, and hands-free operation. Combining TENGs with carbon-based polymer features is an effective method to improve conductivity, stretchability, and sensitivity, which are crucial for the next generation of wearable and intelligent sensing devices [51].

An electrochemical biosensor transduces the binding event of a biomolecule with its target into an electric current or potential. Due to their special binding and biocatalytic properties, enzymes represent the most important substrate of the many biorecognition units currently available. Biosensors exploiting electrochemical techniques to sense the biological variations in the solution at a given electrode potential, net charge accumulation, current, conductance, or impedance have been classified in various ways according to the nature of the signal used. The main types of design for electrochemical biosensors have been grouped into amperometric, impedimetric, potentiometric, and conductometric. One-dimensional CNT-based electrodes exhibit better electron transfer kinetics [52] (enhanced amperometric sensitivity), and two-dimensional graphene offers high surface-to-volume ratios (enables enzyme/DNA immobilization). Three-dimensional carbon structures further increase active surface area, allowing multi-analyte detection with a high signal-to-noise ratio [53]. The sensitivity and selectivity of electrochemical biosensors essentially depend on the biorecognition element. The sensitivity is also influenced by the conductivity of the materials. An electrochemical feature of the transducer is linearly related to the feature of the electrode being monitored. An electrochemical property of the transducer is precisely linear with that of the electrode. Due to their sensitivity, simplicity, low cost, and rapid detection, electrochemical biosensors are very suitable for downsizing [54].

3.2. Sensor Types

Sensors are the basis of modern technology, working as the "nervous system" of smart devices and IoT. They sense physical information, such as heat, light, sound, or motion, and convert this information into electrical signals for real-time data processing, automation, and intelligent response in a wide range of applications.

3.2.1. Physical Sensors

A pressure sensor is a device that senses pressure and determines it. The force per unit area measured over an area is called pressure here. Pressure sensors facilitate even more specific maintenance methods, such as predictive maintenance. These devices pull in information about equipment conditions as it is happening [1]. Flexible pressure sensors have become vital components in modern electronics, especially in wearable technologies and artificial electronic skin (E-skin). Their primary function is to detect and respond to mechanical stimuli, converting pressure into readable electrical signals. The design of these sensors relies heavily on materials that offer both electrical conductivity and mechanical flexibility, ensuring reliable performance under various conditions [55]. There are three core transduction mechanisms illustrated in Figure 4 that govern how flexible pressure sensors operate.

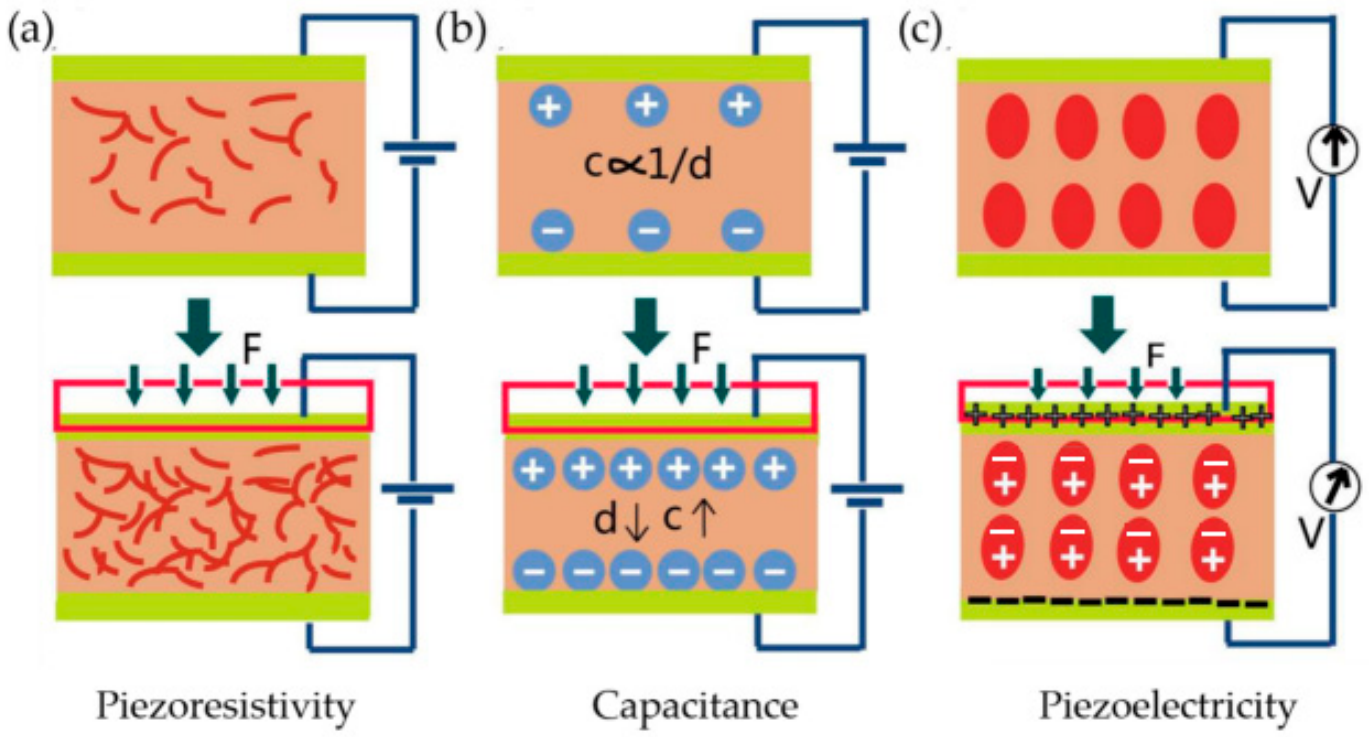


Figure 4. Schematic illustration of three common transduction mechanisms and representative devices: (**a**) piezoresistivity; (**b**) capacitance; and (**c**) piezoelectricity [55].

Piezoresistive Sensors

These types of sensors operate by varying the internal resistance of a material that is experiencing mechanical stress. Pressure changes the shape of the structure and the contact and distribution of conductive fillers in the composite, which changes resistance. This concept makes it possible to realize simple designs with low power consumption and extensive detection capabilities. Piezoresistive sensors are often used in medical diagnostics, fitness, and wearables because they are easy to produce and very sensitive [56].

Capacitive Sensors

Based on the principles of parallel plate capacitors, capacitive sensors measure changes in capacitance caused by external pressure. When force is applied, the distance between conductive plates or the dielectric constant of the material changes, leading to a variation in capacitance. These sensors excel in sensitivity and dynamic range, and they respond quickly to pressure changes. Their sensitivity depends largely on the elasticity of the dielectric material, with softer materials like polydimethylsiloxane (PDMS) improving sensor performance [57].

Piezoelectric Sensors

These sensors utilize materials that generate electrical charges when mechanically stressed. The application of pressure causes polarization within the piezoelectric material, leading to a measurable potential difference across its surfaces. This mechanism is especially effective for detecting rapid pressure changes and is suitable for precision applications. Common piezoelectric materials include PVDF, ZnO, and $BaTiO_3$, with PVDF being particularly favored for its flexibility and ease of processing [58].

The choice of materials is pivotal in sensor performance. Conductive materials like CNTs, graphene, and metallic nanoparticles are frequently used due to their electrical properties and adaptability. For substrates, materials like PET, PDMS, and PI (polyimide) are commonly used to ensure flexibility and durability. Structural designs such as micropatterned surfaces and layered configurations enhance sensitivity and allow sensors to detect minimal pressures, down to the level of a small insect's weight [59].

Emerging fabrication techniques, including 3D printing and soft lithography, are enabling the development of high-resolution sensor arrays and multi-functional designs. These advancements support broader applications in robotics, prosthetics, and real-time health monitoring.

3.2.2. Chemical Sensors

Chemical sensors are compact analytical devices designed to detect and quantify chemical substances by converting chemical information into measurable signals. The systems have two parts: a sensing part that detects the target, and a transducer that transforms the chemical interaction into an electrical or optical signal, shown in Figure 5 [60]. The core function of a chemical sensor is to monitor environmental, biological, or industrial samples for specific targets such as gases, ions, or hazardous chemicals. The interaction between the sensing element and the target leads to a change in physical or chemical properties—such as pH, conductivity, light absorption, or fluorescence—which is then detected and processed by the transducer [61].

Sensors fall into the category of mechanism (optical, electrochemical, thermal, gravimetric) or into the category of material (nanomaterials, carbon-based, biological) [62]. However, with rapid advancements in materials science and nanotechnology, this classification is evolving, and many modern sensors combine elements from multiple domains [63].

Importantly, optical sensors use changes in light properties (like fluorescence or absorbance) to detect analytes, while electrochemical sensors rely on changes in voltage, current, or resistance. Both types are enhanced by the use of nanostructures such as gold nanoparticles, CNTs, and graphene, which significantly improve sensitivity and target specificity [64].

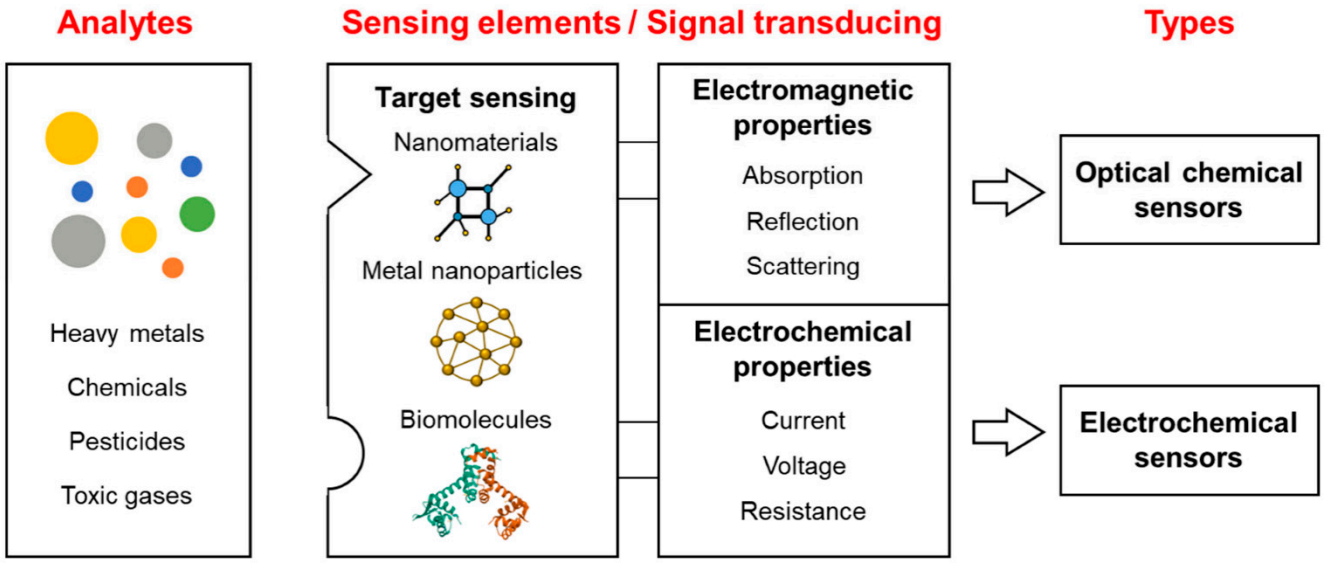


Figure 5. Types of chemical sensors based on sensing and transducing elements [61].

The performance of a chemical sensor relies on the selectivity of its material as well as the sensitivity of its transducer. New methods based on microfluidics, nanofabrication, and bioengineering have enhanced the speed of response, reduced the detection limit, and increased the range of targets [61].

3.2.3. Biosensors

A biosensor is an analytical device that combines a biological sensing element such as an enzyme, antibody, or nucleic acid with a physicochemical detector to produce a quantifiable signal. These devices are designed to identify and monitor biological or chemical changes in the environment. They are highly sensitive, capable of detecting even trace levels of specific substances like pathogens, toxins, or pH variations [65].

Typically, a biosensor consists of five key elements, shown in Figure 6.

Analyte: The target substance that needs to be detected, such as glucose, ammonia, or alcohol.

Bioreceptor: A biological molecule (e.g., enzymes, antibodies, aptamers, DNA/RNA, or living cells) that specifically interacts with the analyte. This interaction generates a change in measurable properties like heat, light, pH, or charge, a process called biorecognition.

Transducer: The core component that converts the biorecognition signal into a detectable electrical or optical output. This signal generation process is known as signalization. Transducers can be classified as electrochemical, optical, thermal, electronic, or gravimetric depending on their working principle.

Electronics: These components process and amplify the signal for interpretation.

Display: The final output is presented in a readable format, such as digital readouts or graphical data.

Biosensors are produced in various forms and configurations, making them adaptable for applications in medical diagnostics, environmental monitoring, and industrial processes [66].

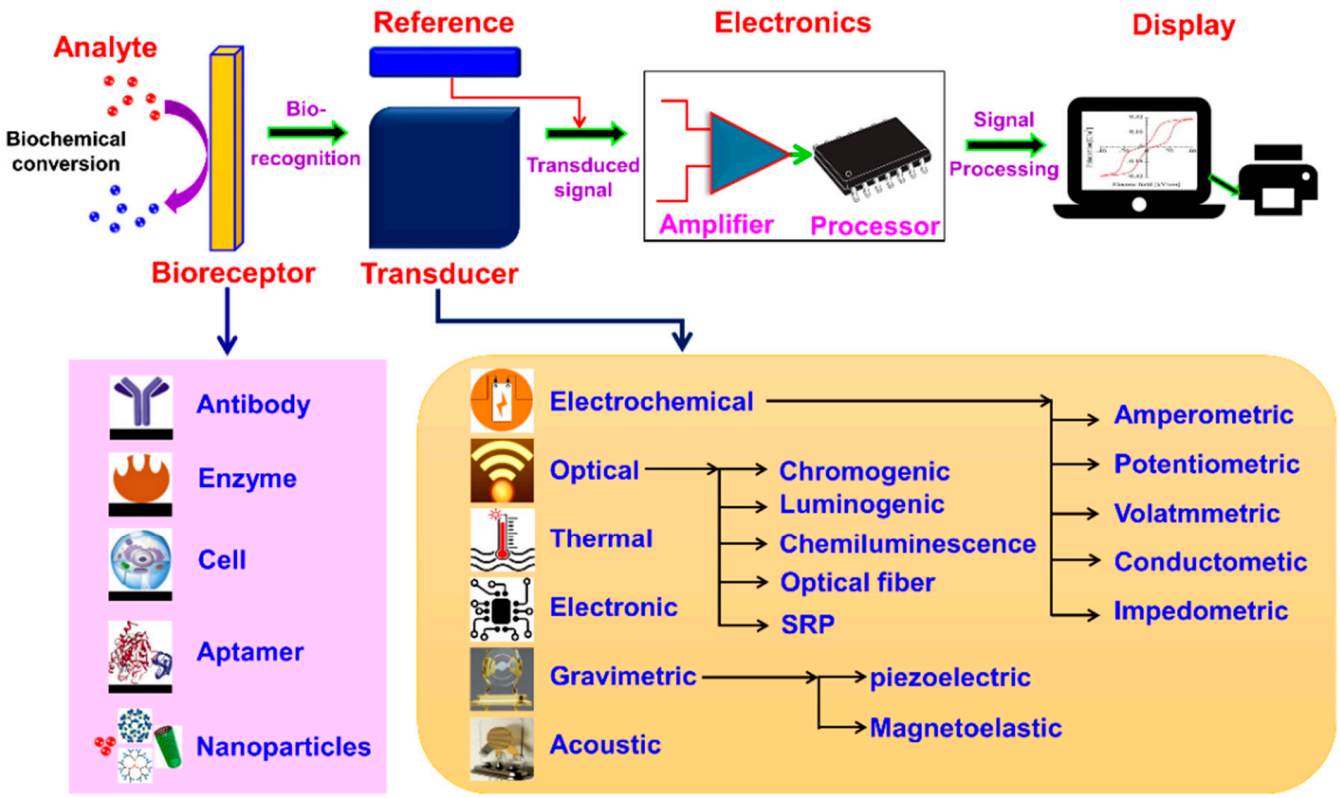


Figure 6. Schematic diagram of a typical biosensor consisting of bioreceptor, transducer, electronic system (amplifier and processor), and display (PC or printer), as well as various types of bioreceptors and transducers used in biosensors [66].

Table 2 provides a representative overview of the detection limits achieved by different categories of smart sensors, including physical, chemical, and biosensors, alongside next-generation CPNC-based devices.

Table 2. Selected detection limits of next-generation smart sensors based on carbon–polymer nanocomposites.

Sensor Category	Target Analytes/Stimuli	Representative Detection Limit	Reference
Physical sensors	Strain, Pressure, Touch, Flex	Strain: <0.1% Pressure: <1 Pa	[57]
	Pressure, Proximity, Touch	Force: ~10 mg	[67]
	Temperature, Heat Flow	Temperature Δ: <0.1 °C	[68]
Chemical sensors	Volatile Organic Compounds (VOCs), NH_3, NO_2, CO, H_3	VOCs/Gases: 0.1–10 ppm NH_3: <1 ppm	[69]
	Heavy Metals (Pb^{2+}, Cd^{2+}, Hg^{2+}), Toxins	Heavy Metals: <1 ppb	[70]
	Humidity, Specific Vapors	Relative Humidity: <1% RH	[71]
Biosensors	Glucose, Cholesterol, Uric Acid, Neurotransmitters (Dopamine)	Glucose: <10 µM Dopamine: <1 nM	[72]
	Proteins, DNA, Viruses, Cancer Biomarkers	Proteins < 1 pg/mL	[73]
	Bacterial Pathogens (*E. coli*, *S. aureus*), Cells	Bacteria: 10–100 CFU/mL	[73]

3.3. Applications in Sensing

In today's information-driven world, sensors play a crucial role in enabling real-time access and automation, as shown in Figure 7. In smart homes, they manage lighting, heating, and fire detection and even guide cleaning robots. Sensors prevent water damage, power autonomous lawnmowers, and improve security with motion detection. Beyond homes, sensors are embedded in mobile devices, vehicles, healthcare, and AI systems. They are everywhere, from optical mice and touchscreen phones to tire pressure monitors and self-driving cars. In healthcare, sensors monitor heart rate, temperature, and muscle activity. As technology evolves, sensors will become even more integral to transportation, medicine, nanotechnology, and immersive digital experiences.

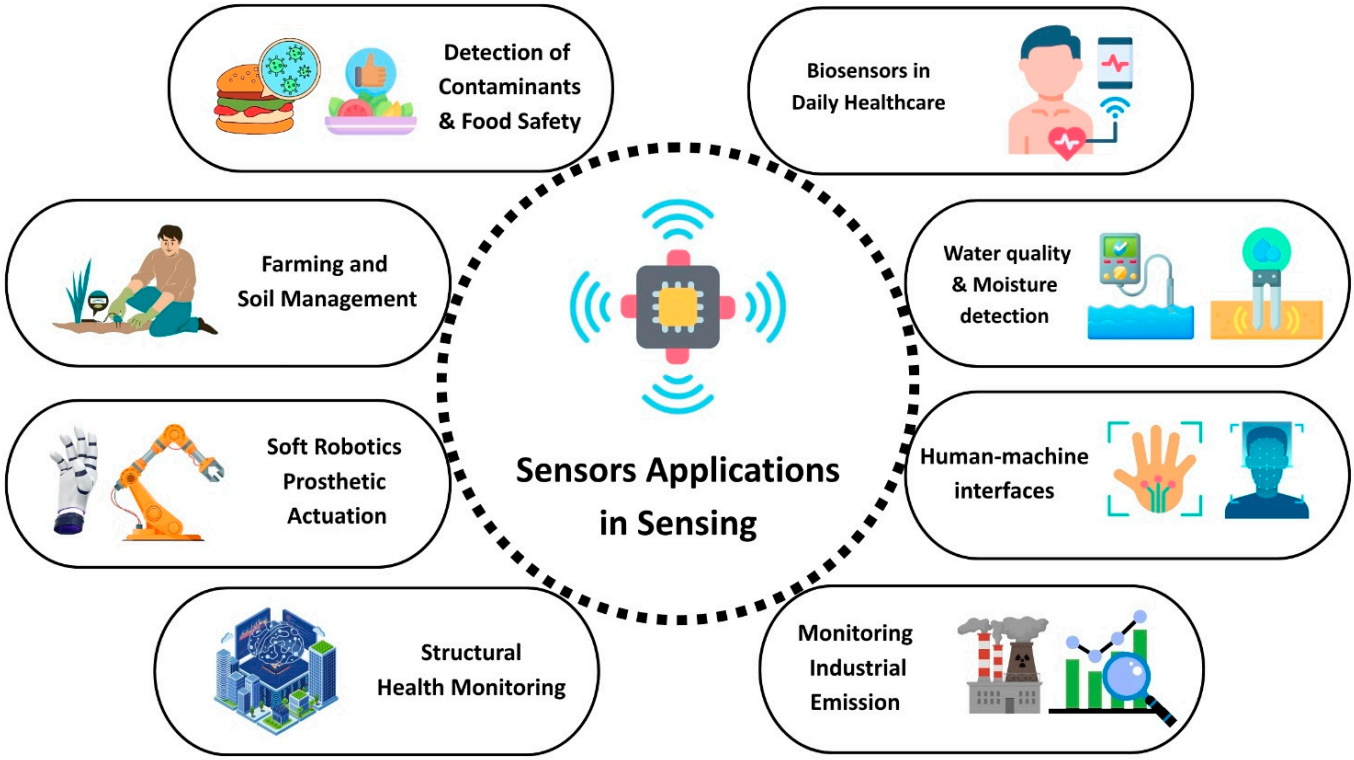


Figure 7. Applications of carbon–polymer nanocomposites in sensing.

3.3.1. Biosensors in Daily Healthcare and Wearable Monitoring

Biosensors are increasingly used in daily healthcare for real-time monitoring of vital signs such as heart rate, brain activity, and stress levels. These devices convert biological signals into quantifiable data using biometric algorithms, enabling wearable technologies to track health metrics like glucose levels, blood pressure, and fatigue. Biosensors are widely adopted in mobile and clinical applications and offer cost-effective, accurate, and user-friendly health monitoring solutions [74]. They are essential for disease screening, diagnosis, and treatment planning. From smart garments to fitness trackers, biosensor-integrated wearables help users understand health triggers and communicate more effectively with healthcare providers [75].

3.3.2. Sensor for Water Quality and Moisture Detection

Water is used practically everywhere. These sensors are essential as they keep an eye on the quality of the water for several purposes. They work in a variety of industries. There are several reasons why water distribution systems utilize water quality monitors. Issues that must be addressed include microbial growth in distribution system pipes, contamination from non-potable water cross-connections, and filthy water entering the

system through leaking pipes in a low-pressure area [76]. Humidity is the amount of water vapor in air or other gases, commonly measured as relative humidity (RH). Humidity sensors are essential in both residential and industrial settings for controlling HVAC (heating, ventilation, and air conditioning) systems and preserving sensitive environments. They are widely used in pharmaceutical storage, museums, greenhouses, automobiles, meteorological stations, paint industries, and hospitals [75].

3.3.3. Human–Machine Interfaces (Gesture Recognition)

A human–machine interface (HMI) displays process information to users and accepts commands to control devices. Modern HMIs aim to enable intuitive, hands-free control with minimal user attention. Hand gesture recognition (HGR) plays a key role by allowing users to operate devices using simple gestures. It removes traditional control limitations and is widely used in areas like smart homes (e.g., changing TV channels) and vehicles (e.g., turning on air conditioning). HGR methods include vision-based (VGR) and sensor-based (SGR) systems. While VGR relies on camera input, its accuracy can suffer under varying lighting conditions [77].

3.3.4. Monitoring Industrial Emission and Toxic Gas Concentrations

Applications of CPNCs are used for real-time detection of air pollutants (NO_2, SO_x, VOCs) in industry. Graphene-polyaniline nanocomposites sensitively detect ppb level NO_2, attributed to the synergistic combination of electrical conductivity and adsorption capacity, and exceed metal oxide sensors on response time (response time < 10 s) and resilience to humidity [78]. The MXene-polyvinylpyrrolidone films modified with Pt nanoparticles exhibit 97% of benzene detection accuracy of petrochemical plants by catalytically amplified charge transfer. These sensors are directly interfaced with IoT infrastructure for automatic regulation of emissions, thereby minimizing the risk of being non-compliant [79].

3.3.5. Structural Health Monitoring for Smart Infrastructure

Self-monitoring CFRP composites with integrated CNT/epoxy networks sense stress, cracking, and corrosion in bridges, aircraft, and pipelines. Functionalized CNTs are beneficial to interfacial adhesion with polymers and can be used to map strains with a 0.1% resolution. The 3DGN grafted porous polymer has 165% enhanced thermal conductivity and a function of temperature/deformation tracking at the same time [80]. Boeing 787 and Airbus A350 adopt CNT-containing SHM for the inspection of wing integrity, reducing manual checking by 40% [81].

3.3.6. Soft Robotics, Prosthetic Actuation

The electroactive CPNC artificial muscles employ CNT-PDMS composites. This low-voltage ($\leq$5 V)-driven reversible joule heating-driven shape memory effect is similar to that of biomimetic motion. These actuators attain 300% actuation strain with 0.1 s response time, providing the manipulation of fragile objects, such as in logistics robots. There are also a few examples in prosthetics where haptic feedback is implemented using graphene-based materials, such as the piezoresistive sensing of strain in a graphene oxide-polyacrylamide hydrogel that is capable of reproducing natural muscle compliance [82].

3.3.7. Precision Farming and Soil Management

MXene-chitosan nanocomposites can function as multifunctional soil sensors. Their swelling upon variations in humidity is responsible for the resistivity shift, while nitrate is detected by ion-selective layers from the impedance spectroscopy. Attached to drones, these wireless sensors create real-time nutrient maps and help save 30% of fertilizers. Moreover, the GO-cellulose nanocrystal films prolong shelf life by sensing ethylene in smart packaging.

3.3.8. Energy Harvesters for Self-Powered Devices

As reported, TENGs based on PVDF-MXene CPNCs can harvest mechanical energy from vibration or human motion to electricity. Increased charge transfer is facilitated by the high electronegativity of the MXene, resulting in power densities of 12.5 Wm^{-2}, enough to power IoT sensors without the use of batteries [83]. The hybrid piezoelectric $BaTiO_3$-carbon nanofiber/polypropylene system permits up to 75–80% mechanical-to-electrical conversion efficiency in industrial machinery [84].

3.3.9. Detection of Contaminants and Food Safety

Graphene-polypyrrole core-branched imprinted polymers identify pathogens and pesticides. The cavities for ochratoxin A in MIPs with the redox activity of PANI facilitate the electrochemical sensing at 0.01 ng/mL. In another study, an AuNP-poly (3,4-ethylenedioxythiophene) (PEDOT) nanocomposite differentiated Salmonella by impedance in 15 min, eliminating the need for lab-centric tests [85].

4. Actuation Mechanisms and Applications

4.1. Actuation Mechanisms

The next generation of actuators and sensors will rely heavily on electroactive polymers (EAPs), a flexible family of smart materials that can transform electrical impulses into mechanical motion and vice versa. They are perfect for use in soft robotics, biomedical devices, aeronautical structures, and energy harvesting systems because of their high strain capacity, flexibility, low density, and mechanical compliance [86]. EAPs are more compliant, biocompatible, and adaptable to soft and dynamic settings than traditional actuators composed of metals, ceramics, or piezoelectric ceramics. These qualities have increased interest in their application in flexible electronics, autonomous robotics, prosthetics, haptic interfaces, artificial muscles, and implantable medical devices. EAPs exhibit deformation under external stimuli not only due to stimulus–response phenomena but also because of well-defined mechanical principles governing stress, strain, and material behavior.

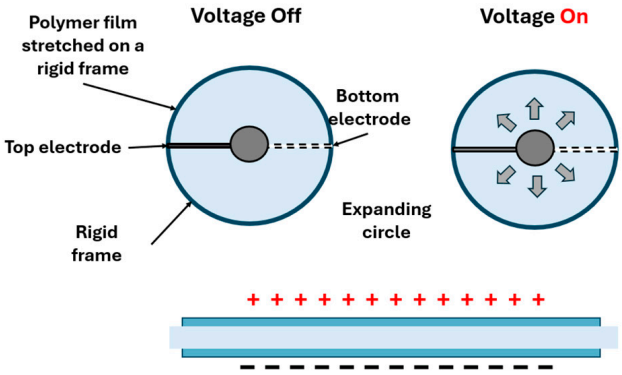
From a mechanical standpoint, dielectric elastomer actuators behave as deformable capacitors. When a voltage is applied across compliant electrodes, opposite charges accumulate on either side of the elastomeric membrane. The resulting compressive pressure in the thickness direction forces the film to expand laterally to conserve volume [85]. For ionic EAPs such as ionic polymer–metal composites (IPMCs), bending deformation is rooted in ion migration and osmotic pressure differentials. When a low voltage (<5 V) is applied, hydrated cations within the polymer migrate toward the cathode, dragging water molecules along. This creates swelling on the cathode side and contraction on the anode side, producing a bending moment. From a mechanical perspective, this is equivalent to a strain gradient across the thickness of the membrane, where ionic flux induces asymmetric expansion and thus curvature of the beam-like structure [86]. In shape memory polymers (SMPs), recovery is governed by thermo-mechanical energy storage in the polymer network. When deformed above the glass transition or melting temperature, polymer chains are stretched and then “frozen” in place upon cooling. Upon reheating, stored entropic

elastic energy drives the chains back toward their equilibrium conformation, releasing macroscopic strain. Mechanically, this is explained by the transition from a glassy, rigid state (where deformation is fixed) to a rubbery state (where elasticity dominates), enabling recovery to the original shape [87]. In all cases, deformation results not only from external stimuli but also from fundamental mechanics, electrostatic pressure overcoming elastic stiffness, ionic migration inducing bending moments, or entropic elasticity driving shape recovery. Considering these mechanics-based explanations enriches the understanding of actuation behavior beyond descriptive stimulus–response narratives.

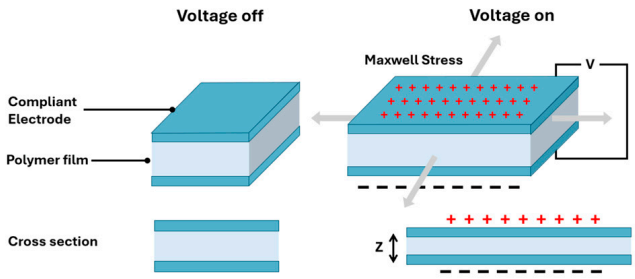
EAPs are generally divided into two main types based on their actuation mechanism: electronic EAPs, such as dielectric elastomers (DEs), and ionic EAPs, such as ionic polymer–metal composites (IPMCs). The following sections provide a detailed overview of each type [85].

4.1.1. Dielectric Elastomers

Dielectric elastomers (DEs) are a class of electroactive polymers that operate based on the principle of electrostatic compression. Structurally, they consist of a thin elastomeric dielectric film sandwiched between two compliant electrodes. When a high voltage is applied across the electrodes, electrostatic forces compress the film's thickness and cause it to expand laterally, generating a mechanical strain. Lateral expansion occurs in dielectric elastomers as a result of compressive stress (Maxwell stress) across the polymer caused by voltage-induced charge buildup on compliant electrodes. Figure 8 illustrates how this process (b) permits considerable deformation, especially with circular geometries (a), where applications involving artificial muscles frequently make use of radial displacement.



(**a**) Radial expansion in a circular DEA.



(**b**) Actuation mechanism due to Maxwell stress.

Figure 8. (**a**) Circular configuration of a dielectric elastomer actuator (DEA), illustrating the radial expansion when voltage is applied. (**b**) Actuation mechanism driven by Maxwell stress where charge accumulation compresses the elastomer axially and expands it laterally [85].

The most widely used dielectric materials in DEs include acrylic elastomers like VHB4905 and VHB4910 (3M), silicone-based elastomers such as PDMS, and thermoplastic polyurethanes (TPU). Acrylics offer a high dielectric constant but are viscoelastic, whereas silicones are highly elastic but require additives to improve dielectric performance. Innovations like interpenetrating polymer networks (IPNs) introduce internal stress during polymerization, enhancing electromechanical response and reducing the need for mechanical pre-strain. Nanocomposites incorporating high-permittivity fillers such as barium titanate ($BaTiO_3$), aluminum oxide (Al_2O_3), or graphene further boost dielectric and mechanical properties [88]. When they are filled with a high-permittivity material and a conductive material in particular, such as graphene, dielectric loss and energy dissipation can increase as heat.

Traditional fabrication techniques include spin coating, molding, and roll-to-roll processing. Emerging additive manufacturing methods such as direct ink writing (DIW) and fused deposition modeling (FDM) now allow precise patterning of elastomer layers and electrodes, especially in TPU-based systems [89,90]. Mechanical pre-strain remains crucial for achieving large actuation strains, with strategies evolving to include patterned or directional straining for anisotropic responses. Compliant electrodes must maintain conductivity under strain. Common materials include carbon grease; graphite; silver nanoparticle inks; conductive polymers like PEDOT: PSS; and metallic films, which are applied via spray coating, inkjet printing, or transfer methods. Advanced designs include stretchable multilayer electrodes and self-healing materials. Diverse actuator configurations such as multilayer stacks, spring-rolls, and bistable electroactive polymer actuators (BSEPs) optimize performance. Control strategies have also advanced, integrating machine learning approaches like convolutional neural networks (CNNs) and deep reinforcement learning (DRL) to compensate for viscoelastic hysteresis and enhance real-time control in wearable and soft robotic applications [85,87].

Dielectric elastomers have a significant dependence of the performance of sensing on the dimensionality of the conductive filler. It defines the conductive network formation, the percolation threshold, and stretchability. Well-connected networks are made of 1D fillers, like CNTs. With 2D fillers such as graphene nanosheets (GNs), percolation is achieved at reduced concentrations [91,92]. High stretchability and good sensing capability are achieved by their large surface area. Percolating networks are also made with 3D fillers, e.g., metal nanoparticles or porous structures [93]. Nevertheless, they might be presented with difficulties in preserving high stretchability in comparison with 1D and 2D fillers.

4.1.2. Ionic Polymer–Metal Composite Actuators

One extensively researched ionic EAP material is the ionic polymer–metal composite (IPMC). The main draw of IPMC actuators, first noted by three research groups almost three decades ago, is their ability to operate at modest voltages. In IPMCs, an electric field is produced through the sample by use of metal electrodes on the surface of an ionomeric polymer backbone. These backbone materials are ionic conductors that enable the high-rate transport of cations via the anionic species fixed in the network. The sulfonic acid ionomeric polymer backbone facilitates the ion transport of hydrated cations to the cathode, as illustrated in Figure 9. A strain is created by the sample's increased cation accumulation on the cathodic side, which results in the sample bending in the direction of the anode. As cation-grafted perfluorinated polymers like poly (vinylidene fluoride-co-hexafluoropropylene) (also known as PVdF–HFP) are developed, anions can be transported, resulting in the opposite bending direction [94].

In ionic polymer–metal composites (IPMCs), the electromechanical properties of conductive fillers are dependent on their dimensionality. They also have an effect on sensing and performance. Carbon nanotubes, i.e., 1D fillers, are well-connected. Two-dimensional fillers such as graphene or MXenes, have larger surface areas [95]. They increase interfacial polarization and augment electrical conductivity. Continuous networks are built as 3D fillers, frequently as agglomerates or 3D structures [96]. These networks enhance conductivity and enhance efficiency, sensitivity, and overall performance of IPMCs in actuation and sensing.

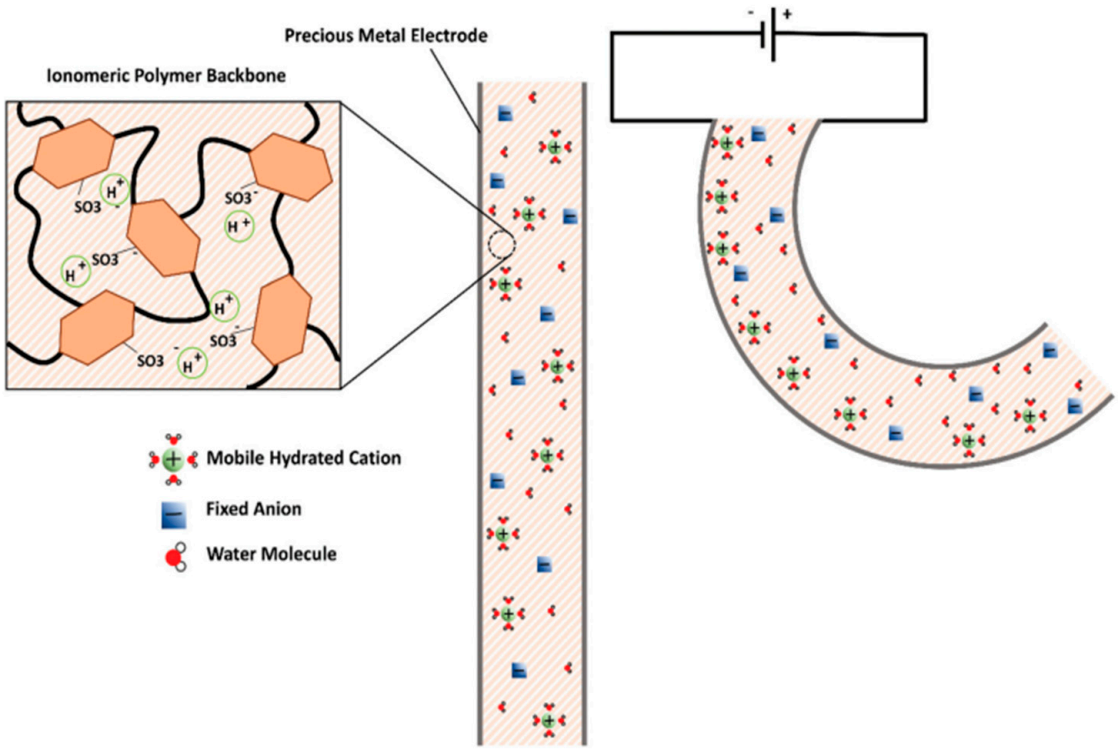


Figure 9. Ionic polymer–metal composite actuator with a single electrolyte solution. Reproduced with permission from Engel et al., Polymer Chemistry; published by Royal Society of Chemistry, 2022 [94].

4.1.3. Thermal Actuators

Shape memory polymers (SMPs) are smart materials exhibiting the ability to dynamically change geometry (dimensions, shape, stiffness) upon an external trigger; for biomedical applications, there is a critical emphasis on thermal activation. Their performance relies on bifunctional molecular architecture: the stimuli-responsive switching segments (e.g., crystalline/amorphous domains) induce in a reversible manner a temporary deformation, while the net-points (chemical crosslinks or crystallites) maintain the permanent shape [97]. Three major shape memory effects of SMPs are one-way shape memory effects (OWSMEs), two-way shape memory effects (TWSMEs), and multiple-SMEs [98]. Figure 10 illustrates the different SMPs.

OWSMEs: The form of materials cannot reversibly shape-change, and an additional step is necessary to re-induce the shape after the SMP recovers to its original one [98].

TWSMEs: Materials that can return to their original and original-like shapes many times, but without the need for any re-shaping. Another name for a TWSME is the reversible shape-memory effect (reversible SME), and a reversible SMP is a polymer possessing reversible SME.

Multiple-SMEs: Those that exhibit two or more temporary shapes, plus the original shape, are called multi-SMEs. External triggers promote the descent of the polymer from the first to the second temporary shape, and finally, a stimulus that drives the polymer back to its initial state.

Thermally induced SMPs are the most studied SMPs. Investigations have shown that the reversible response of SMPs can be induced through direct heating, and a transient shape can be programmed when the temperature application exceeds the polymer transition temperature (T_{trans}). The thermally induced SM performance in the above SMPs arises from two thermal transitions, the glass transition temperature (T_g-based) and the melting temperature (T_m-based) [99].

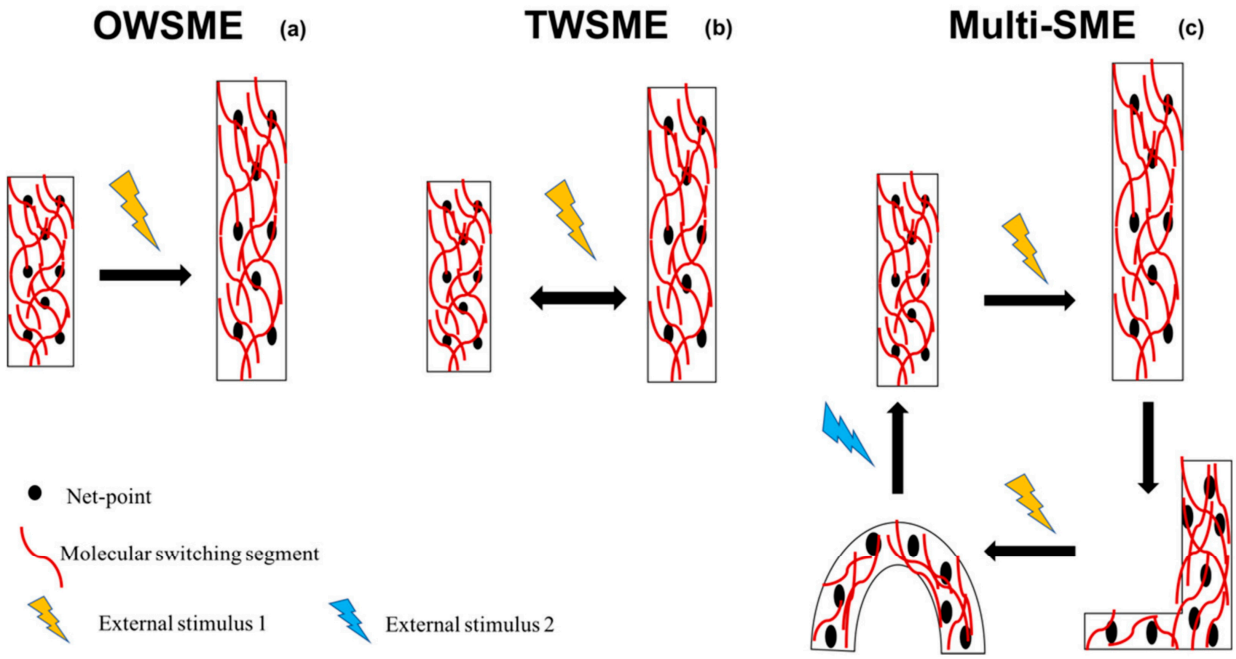


Figure 10. SMPs with different shape memory effects (SME): (**a**) one-way (OWSME), (**b**) two-way reversible (TWSME), and (**c**) multiple-SME [98].

The T_m-based thermal-induced SMP mechanism is universal for the chemically and physically crosslinked polymers. This class of SMPs is based on a multiblock copolymer containing a low-melting-temperature phase segment, which is used as the switchable segment, whereas the higher-melting-temperature phases are the permanent network. T_m-based SMPs are predominantly made of polyolefins, polyethers, and polyesters, and they have a soft phase at a low melting temperature and a crystalline hard phase that is insensitive to temperature. The branching level and cross-linking density provide the switching temperature of these materials [98].

The glass transition temperature (T_g) is where the SMPs become rubbery and can be deformed from an original shape to a temporary shape by a force; thermal T_g-based SMPs are sensitive to temperature changes. After the distorted shape is formed, the polymer can be cooled to a temperature lower than its T_g to freeze the induced distorted shape and then heated to a temperature higher than its T_g to return to the original shape [100].

SMPs can be remotely activated in the presence of special nanofillers (Fe_3O_4, Au NPs, or carbon nanotubes CNTs) [101]. Examples of remote triggering are magnetic field, UV light, or near-infrared radiation. Molecular vibration transforms the energy into heat, and the fillers absorb it. The shape recovery of the SMP is propelled by this heat [102]. The concentration and size of nanofillers have a direct influence on the heat generation. They also affect actuation efficiency. In addition to conductivity, carbon nanomaterials like CNTs or graphene exhibit special characteristics. They are highly photothermal converting [103]. They are very powerful in mechanical reinforcement. The high aspect ratios enable a more uniform energy transfer, compared to metallic or oxide fillers [104].

Multifunctionality is also added by carbon nanomaterials. They combine electrical, thermal, and mechanical reactions into a single system. But there are trade-offs. Filler content is high, and flexibility is compromised. It can increase brittleness. Agglomerates can be created and lower performance. Carbon fillers also have transparency that may be decreased, and this is critical in optical applications. Carbon nanomaterials can therefore not simply be considered as conductive fillers. They have distinct, and even incomparable, functions in SMP actuation. There should be a careful optimization of performance and limitations.

Thermally responsive SMPs can be triggered by direct or indirect heat. Remote temperature control by magnetic and electric fields, microwaves, UV (ultraviolet), and NIR (near infrared) irradiations is also achievable when SMPs are combined with other stimuli-responsive materials (nanofillers) such as Fe_3O_4, gold nanoparticles (AuNPs) and silver nanoparticles (AgNPs), CNTs, GO, and cellulose nanocrystals. In such systems, heating due to molecular vibration takes place, and the energy level is linearly proportional to the concentration and grain size of the nanofillers [79].

Another medical device in clinical trial is the TrelliX Embolic Coil System (NCT03988062) manufactured by Shape Memory Medical Inc., Santa Clara, California, USA, a thermoresponsive device composed of SMPs and used for embolization treatment of medium-to-large unruptured or ruptured cerebral aneurysms [105]. A self-expanding porous SMP is accommodated to the non-stretched platinum–tungsten alloy coil (TrelliX Embolic Coil). The porous SMP will slowly self-expand when placed in the target lesion and heated by body temperature in an aqueous environment. The TrelliX Embolic Coil devices were covered by the following granted patents (US8133256 and US10010327) [106].

Based on the stimulus to be applied to trigger the shape-memory effect, chemically induced and physically induced SMPs can be distinguished. More advanced SMPs can respond to two or more stimuli (i.e., multistimuli-responsive SMPs). Various stimulus-triggered SMPs are diagrammed in Table 3.

Table 3. Classification of stimuli-responsive shape memory polymers: activation mechanisms and core materials.

Stimuli-Responsive Behavior	Types	Activation Mechanism	Core Materials	Reference
Chemically induced SMPs	Thermally induced SMPs	Induced by direct heating and hardware-based one if the applied temperature goes over the polymer transition temperature (T_{trans}).	Integrating SMPs with other stimuli-responsive materials (nanofillers) including Fe_3O_4, AuNPs and AgNPs, CNTs, GO, and cellulose nanocrystals.	[98]
	Light-induced SMPs	Laminating under external tension with short-wavelength UV light fixes the temporary shape, while longer-wavelength exposure restores the polymer shape.	Typical fillers for thermal conductivity are carbon-based, metallic, or organic compounds.	[107]
	Electric/magnetic-induced SMPs	SMPs recover shape via Joule heating, where applied voltage generates heat above the transition temperature.	SMPs incorporate conductive fillers like CNTs, graphene, or silver nanoparticles for Joule heating under electric fields, as well as magnetic particles (Fe_3O_4, $CoFe_2O_4$) for alternating magnetic field activation.	[108]

Table 3. *Cont.*

Stimuli-Responsive Behavior	Types	Activation Mechanism	Core Materials	Reference
Physically induced SMPs	pH-induced SMPs	pH-sensitive SMPs are designed based on reversible bonds (e.g., β-cyclodextrin—alginate inclusion complex or protonatable groups like pyridine) that disintegrate or are formed at different pH.	The pH-responsive SMP, made of poly (ethylene glycol)–poly(-caprolactone)-based polyurethane with pyridine-functionalized CNCs (CNC–$C_6H_4NO_2$), used the functional groups as switching units to enable effective shape-memory behavior.	[109]
	Water-induced SMPs	Water-responsive SMPs absorb moisture, leading to plasticization, hydrogen bond cleavage, and lowered glass transition temperature (T_g), enabling shape recovery at body temperature (such as 37 °C). Hydrophilic fillers like cellulose nanowhiskers (CNWs) enhance this sensitivity.	Hydro-responsive SMPs use hydrophilic polymers (PVA, PVAc) and cellulose-related derivatives (CNWs) that either expand or break H-bonds upon wetting.	[110]
	Enzymatically triggered SMPs	Enzyme-responsive SMPs recover their shape through enzymatic degradation, enabling controlled activation in biological environments.	By choosing PCL (enzyme degradable), Pellethane (stable matrix), and natural/synthetic biopolymers (polysaccharides, polyamino acids), the enzymatic shape-memory activation under physiological conditions can be allowed.	[111]
Multi-stimuli responsive SMPs	Multifunctional SMPs	Multi-stimuli SMPs are activated under stress conditions, which may include heat, light, chemicals, etc. Metal–ligand bonds cleave upon stimuli, while thiol-ene photocrosslinking can fix a permanent shape allowing for precise and reversible transformations.	Soft poly(butadiene), soft metal–ligand moieties, and PVA-graft-polyurethane-based multi-stimulus responsive networks for multi-step shape recovery using UV/heat/water triggers.	[112]

Light-Responsive Actuators (Photo-Thermal Effects)

In light-responsive actuators, energy-changing mechanisms that result in actuation are divided into classes such as photo-thermal, photo-chemical, or photo-electric. Photo thermal action is particularly notable within polymer systems incorporating advanced nanomaterials. This type of actuation uses the photothermal effect, where light converting to heat, for its operational energy. The materials most effective for such devices need to absorb light and conduct heat strongly. Such materials fulfill necessities with distinct benefits: (1) no photochemical fatigue damage; (2) responsiveness across the entire solar spectrum; and (3) the ability of heat to diffuse beyond photon penetration depths, facilitating uniform activation [113].

GO and other carbon-based substances serve very well as photothermal converters owing to their high efficiencies [114]. However, traditional carbon actuators do not respond selectively by wavelength, which hampers elaborate control in soft robotics. To resolve this challenge, SMPs which recover programmed shapes upon heating are coupled with photothermal nanomaterials. As an example, graphene-TPU composites use the versatility of graphene that acts both as a light absorber and a mechanical enhancer, enabling the directed microweaving of constructed patterns. This integrated approach permits substantial deformations while retaining precision during delicate controlled motion routines.

Different azo compounds photothermal methods use polymer systems that are photothermally activated via external heating (4.6 ms). The structure has a major impact on the exertion of shape: non-woven microfibers exhibit more intense temperature gradients because of stress when compared to films due to scattering effects. This architecture, which is beneficial in biomedicine and micro-robotics, enables large geometric changes with low stress [115].

Magneto-Responsive Actuators (Magnetic Nanoparticle-Doped CPNCs)

CPNC magneto-responsive actuators involving magnetic-nanoparticle-doped polymeric nanocomposites are a new advanced category of smart materials. These systems usually have a soft polymeric network (e.g., elastomers, hydrogels, or liquid crystalline elastomers) where magnetic material nanoparticles (e.g., iron oxides, ferrites, or metallic alloys) are embedded. The use of magnetic nanoparticles allows directing actuation remotely, untethered, and in a concise manner under external magnetic flows, which is very useful in comparison with other stimulus-based approaches [116].

The magneto-responsive actuators of particular interest are the liquid crystalline elastomers (LCEs) because they represent a material with intrinsic characteristics of large reversible deformations in response to stimuli. Doping LCEs with magnetic nanoparticles enables researchers to take advantage of the versatile characteristics of fields using magnetic fields, such as the ability to penetrate deep into the tissue, quick response, and the inability to make contact. This has provided the potential of new applications of soft robotics, biomedical applications, and adaptive systems [117].

The selection of the polymer matrix and the magnetic filler is crucial in determining the performance of the magneto-responsive CPNCs. In general, softer matrices (e.g., silicone-based elastomer) obtain larger deformations in the presence of a magnetic field, whereas stiffer matrices (e.g., acrylate-based polymers) provide better mechanical stability. In the meantime, the sensitivity and response time of the actuator are determined by the size, concentration, and distribution of magnetic nanoparticles. Advanced recent developments in nanoparticles manufacturing and composite material construction have made these materials even more capable of customizing answers to various applications [118].

4.2. Role of Carbon-Based Polymer Nanocomposites in Actuation

Exceptional properties of carbon nanomaterials, such as CNTs, graphene derivatives, and fullerenes, have made CPNCs a critical component of high-tech actuation systems. They have a large surface area, superb electrical/thermal conductivity, and great mechanical strength, and thus they can be integrated with polymer matrices such as thermoplastics and biopolymers [119]. Their distinct nanostructure improves nanocomposite qualities that are important to high-performance actuators. CPNCs have impressive versatility in potential applications that range from thermal management to energy storage. In actuation systems, they react very accurately to electrical, thermal, or magnetic stimuli. Such carbon materials as CNTs and graphene allow efficient storage of energy in supercapacitors due to their high rate of ion adsorption. Although pure carbon materials have poor energy density in EDLCs, merging them with electrochemically active materials (such as metal oxides and conducting polymers) increases performance through Faradaic reactions, although at the cost of durability [1]. These composites utilize synergetic effects, e.g., high aspect ratios and conductivity to develop actuators of the next generation. CPNC-based systems have specific potential in the field of soft robotics and medical equipment when accuracy and responsiveness play an essential role. The advancement of such functions is still under development, and the actuation technology will be revolutionized to be multifunctional.

4.3. Applications in Actuation

CPNCs have emerged as transformative materials in a range of advanced applications due to their exceptional flexibility, conductivity, and responsiveness. Figure 11 shows different applications of sensors in actuation technologies. In soft robotics, CPNCs such as carbon nanotubes (CNTs) enable biomimetic motions like gripping, crawling, and swimming through adaptive actuators. CNT-based artificial muscles exhibit high power output, flexibility, and biocompatibility, making them ideal for prosthetics, exoskeletons, and medical devices. Conductive nanocomposites also power smart textiles with sensing, actuation, and energy-harvesting functions for wearable electronics. Additionally, CPNC-based micro-actuators offer precise control in microfluidics and MEMS, supporting innovations in diagnostics and miniature robotics.

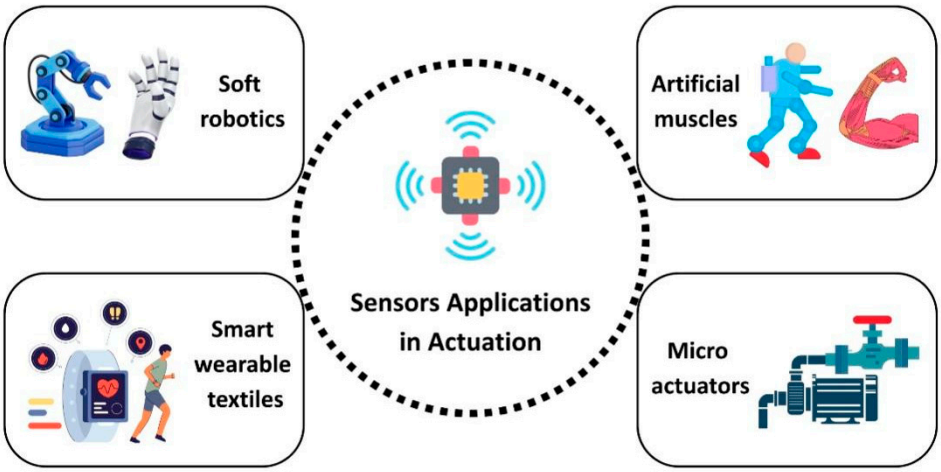


Figure 11. Integration of sensors in actuation applications.

4.3.1. Soft Robotics

CPNCs are transforming soft robotics, facilitating adaptive and compliant actuation, as well as sensors like those seen in biology. DEAs made using CNT-based electrodes have considerable deformation (>100%) under electric fields. Maxwell stress-induced motions are possible in the form of gripping, crawling, and swimming, as well as biomimetic motions

of elastomers (e.g., silicones, acrylics) placed between CNT electrodes. Their conductivity is increased using CNT electrodes, and they can be flexible, which allows them to be used as grippers that can be used to pick up fragile objects (e.g., fruits, biological tissues) with pressure-adjusted gripping. New developments center on the unstructured environment locomotion systems. Others include CNT-reinforced liquid crystal elastomers (LCEs) that allow light-driven robotic crawlers that can respond to thermal gradients with displacements 2500 times their weight. In a similar manner, undulatory swimming is enabled in aquatic robots by controlled flexural stiffness using layered graphene/polyurethane composites [120].

4.3.2. Artificial Muscles for Prosthetics and Exoskeletons

CPNCs use electricity to imitate the movement of natural muscles in artificial muscles. Yarns made of CNT are able to generate powerful movements, and the work capacity is 40 W/kg greater than that of natural muscles. They are flexible to 15 percent and can withstand stress as high as 34 MPa, being applicable in prosthetic fingers and exoskeletons. Recently, developments such as low-voltage use (13 V) have been made, and as a consequence, they can be used in battery-operated equipment. Moreover, they are also biocompatible, among which CNT hydrogels can be applied safely in medicinal devices such as artificial hearts and eye muscles. Others are able to detect the movement so that they can enable smart control in wearable robotics [121].

4.3.3. Smart Textiles for Adaptive Clothing and Wearables

Conductive nanocomposites provide sensing, energy harvesting, and actuation capabilities to realize smart textiles as wearable electronic devices. For example, graphene and polyaniline-based fabrics have the possibility to monitor health by using sensors that detect gases such as sulfur compounds in the breath. Actively invisible coatings allow temperature control through modified insulation and can use the energy of motion to supply power to sensors. Virtual reality also has some textiles that provide touch. New materials are offering a solution to challenges such as wear and tear and breathability [122].

4.3.4. Micro-Actuators for Microfluidics and MEMS

Micro-actuators are the main applications of microfluidics and MEMS in that precise control of fluids and mechanical motion (at the micro scale) can take place. Such actuators are usually manufactured with smart materials (eg, CPNCs) to drive micro-pumps, valves, and switches. They are highly scalable, low-power, and quick in response, and they are suitable for lab-on-chip diagnostics, biomedical devices, and miniature robotics applications [122].

5. Sustainability

The sustainability of biosensors must be evaluated from a full lifecycle perspective, as single-use devices contribute significantly to the growing problem of electronic waste. This challenge can be addressed through sustainable design strategies, such as the incorporation of bio-based polymers, polylactic acid (PLA) or cellulose [123], into new SMPC studies, since these materials enable the substrate of the sensor to be biodegradable. Equally important is the integration of recycled materials, which not only reduces the consumption of virgin resources but also aligns with the principles of the circular economy [124]. Designing devices that can be easily disassembled facilitates component recycling, while simultaneously enhancing energy efficiency, and further progress depends on the development of low-energy manufacturing processes. Self-powered systems, employing either piezoelectric materials or biofuel cells, offer an additional solution by eliminating the need for conventional batteries and thereby minimizing battery waste. A particularly effective

approach is the use of a reusable reader paired with a disposable sensor tip, as this model significantly reduces the overall generation of electronic waste [125].

The regulatory pathway for biosensors is equally demanding, particularly in the medical field, where agencies such as the FDA and the EU MDR classify devices according to risk categories and mandate comprehensive clinical validation to ensure safety, accuracy, and reliability. Increasingly, biosensors incorporate complex software, and when such systems fall under the designation of Software as a Medical Device (SaMD) [126]. They require additional layers of verification and authentication. Moreover, as connected devices, biosensors must be secure-by-design, featuring robust cybersecurity safeguards, frequent security updates, and compliance with privacy regulations such as GDPR and HIPAA. At the same time, regulators impose strict scrutiny on environmental claims: terms like "biodegradable" must be substantiated with empirical evidence, particularly through lifecycle assessment (LCA), which is becoming a recognized standard for substantiating sustainability claims and preventing greenwashing. Collectively, these sustainability and regulatory considerations form the foundation for the successful and responsible development of next-generation biosensors.

6. Challenges and Limitations

One of the main issues facing the development of CPNCs is having control over inherent property trade-offs. Electrical conductivity is high, which demands high filler loadings, yet this can decrease elasticity and lead to embrittlement because of limiting polymer chain mobility. Maximizing performance requires strategic practices. Hybrid fillers (e.g., CNTs containing graphene) form useful networks with reduced loadings and maintain flexibility [127,128]. Dispersion is improved by precision functionalization without crippling filler conductivity. Conductive fillers are more accommodated by the choice of polymer matrices that are inherently elastic (e.g., TPU, PDMS). Lastly, more sophisticated dispersion methods, such as in situ polymerization [129] and 3D printing, attains better dispersion or strategic position of fillers to have a good balance between electrical and mechanical properties [130].

The challenge of emerging smart CPNCs is substantial in a wide range of fields, as summarized in Figure 12. The problems of materials are mainly associated with the specifics of carbon nanomaterials (CNMs), such as CNTs and graphene. Unfortunately, obtaining complete dispersion and avoiding agglomerates in the polymer matrix is very challenging because strong van der Waals forces and high surface energies result in local stress buildup. Moreover, poor load transfer and interfacial debonding under stress, which are caused by interfacial bonding and compatibility problems between the generally hydrophobic CNMs and various polymer matrices, largely hinders the ability of reinforcing and functional performance of the CNMs [2]. Surface chemistry of the CNM is important to tailor, but it complicates this idea by functionalizing the CNM either covalently or non-covalently [28].

There are significant manufacturing issues that revolve around how to translate the good results in the laboratory into actually being able to make the production viable. Scaling up of advanced methods of fabrication, e.g., in situ polymerization, layer-by-layer assembly, accuracy 3D printing, or electrospinning, is usually economically unstable or technologically taxing to scale up to high production volumes [131]. Going hand in hand with quality control is the problem of reproducibility. Small changes in dispersion protocol, mixing conditions, or curing conditions, or variability in the source/batch of CNMs, result in profound discrepancies in the nanostructures (e.g., orientation, network structures) and thus electrical, mechanical, and sensing/actuation characteristics of the final composites, which complicates standardization.

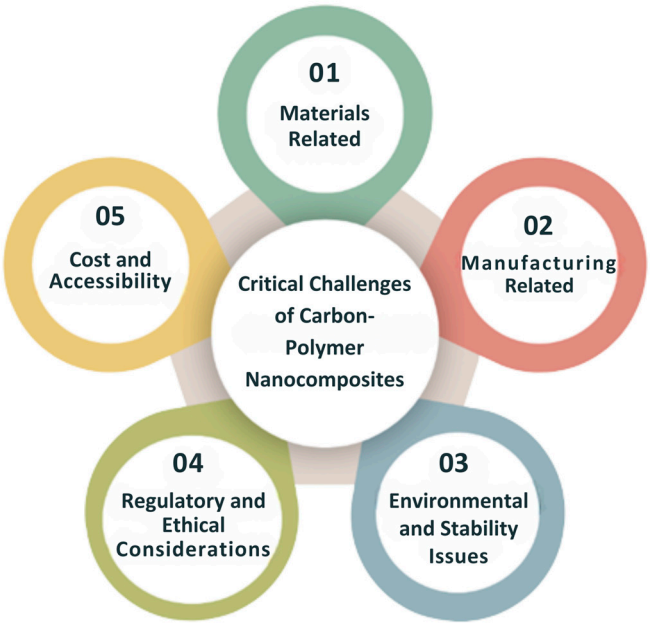


Figure 12. Critical challenges of carbon–polymer nanocomposites.

The real-world deployment issue becomes critical towards environmental and stability. Thermal and chemical stability in severe conditions (e.g., high temperature, humidity, corrosive chemicals, UV exposure) is a necessity. The accuracy of sensing and actuation performances may be permanently lost due to the deterioration or rupture of the CNM network or even the polymer itself [132]. Long-term durability and fatigue resistance are equally important, particularly of significance in actuators subject to repeated mechanical cycling. Precise modeling of the degradation processes, such as interfacial failure, pull-out by CNM, or chain scission of polymers under sustained loading, is essential for confident lifespan prediction.

There is another dimension of regulatory and ethical considerations. In biomedical applications (i.e., biosensors, implantable actuators), the biocompatibility and non-toxicity of the CNMs and their possible degradation are essential, and non-toxicity must be rigorously demonstrated and demand extensive testing. Nanomaterials in the environment and their disposal (product lifecycle, production, use, and end-of-life) have concerns regarding their toxic and persistent nature to water ecosystems [133]. The critical issue is to come up with safe recycling or degradation routes. The current regulatory landscape on the commercialization of nanomaterials has been shifting and evolving, but it is considerably different in various parts of the world. It rarely gives specific directions on nanocomposites that pose serious uncertainty to manufacturers [134].

At last, affordability and accessibility are major impediments. The material makeup of good-quality nanomaterials (e.g., defect-free graphene, certain CNTs) is expensive, and advanced processing methods to achieve optimal dispersion and structure are also expensive, with considerable consequences on the economics of the final product. The implementation of cost reduction strategies, i.e., the use of sustainable precursors (e.g., lignin-derived carbon, biochar), or even the scalable or energy-efficient manufacturing process, is the key to wider adoption in the market and sustainability [135].

Recent studies have proposed several constructive approaches to overcome the existing challenges of dispersion, interfacial bonding, and scalability in CPNCs. For dispersion, advanced processing routes such as controlled ultrasonication combined with surfactants or polymer wrapping have been shown to individualize CNTs while minimizing damage, thereby enhancing uniformity and stability in the matrix [28]. At the materials level,

graphene platelets (GPLs) have emerged as a superior alternative to CNTs, offering greater surface area, wrinkled morphology for mechanical interlocking, and two-dimensional geometry that enables more efficient load transfer at even lower filler contents [132]. Hybridizing CNTs with GPLs could simultaneously improve dispersion and interfacial adhesion.

In terms of stability and toxicity, the use of surface functionalization strategies (covalent and non-covalent) has been highlighted as a means to not only improve compatibility with diverse polymer matrices but also to tailor biocompatibility and reduce cytotoxicity for biomedical uses. Moreover, predictive models such as nano-QSAR (quantitative structure–activity relationships) are being developed to anticipate nanomaterial toxicity early in the design cycle [133]. In the economic area, promising cost-reduction strategies include sustainable carbon precursors sourcing, such as biochar or lignin-derived carbons, and employing scalable low-energy processes, such as calendaring or three-roll milling for industrial production [28].

Together, these insights demonstrate that the future of CPNCs lies not only in addressing technical bottlenecks but also in integrating sustainable materials, predictive modeling, and multifunctional hybrid fillers to ensure reproducibility, safety, and commercial viability [136].

7. Future Prospects and Research Directions

The field of CPNCs stands at the precipice of a technological revolution, with emerging advances poised to transform these materials from passive components into intelligent, adaptive systems. As we look toward the future, several critical research directions and technological integrations will shape the development of next-generation CPNCs for sensing and actuation applications. These advancements will be driven by the convergence of materials science with cutting-edge digital technologies, sustainable engineering principles, and innovative energy solutions, ultimately creating a new paradigm for smart material systems.

At the forefront of this evolution is the integration of artificial intelligence and edge computing with CPNC-based sensor networks. The marriage of these technologies will enable the development of truly intelligent material systems capable of real-time data processing and autonomous decision making at the material level. Imagine infrastructure components that not only detect structural fatigue but also predict failure points and initiate self-repair mechanisms, or medical implants that continuously monitor patient health indicators and automatically adjust therapeutic responses. This transition from "smart" to "intelligent" materials will be facilitated by the unique properties of CPNCs, particularly their ability to serve as both sensors and actuators while maintaining mechanical flexibility and environmental resilience [137]. The development of multifunctional CPNC architectures represents another crucial research direction. Future materials will need to combine sensing, actuation, energy harvesting, and even energy storage capabilities within single, integrated systems. Researchers are already making progress in this area through innovative material combinations, such as graphene-MXene heterostructures embedded in shape-memory polymers, which can exhibit simultaneous piezoresistive sensing and electroactive actuation while generating power from mechanical deformations. Three-dimensional printing techniques are enabling the creation of these complex material architectures with precise control over nanomaterial distribution and alignment, opening new possibilities for customized, application-specific material designs.

Sustainability considerations will play an increasingly central role in CPNC development, driving research into eco-friendly material solutions across the entire product lifecycle. On the materials front, this includes the development of bio-based polymers and the use of renewable or recycled carbon nanomaterials. Exciting work is being done

with cellulose-derived nanocarbons and biodegradable polymer matrices that maintain high performance while offering reduced environmental impact. Equally important are advances in material longevity and recyclability, such as self-healing nanocomposites that can autonomously repair microdamage, significantly extending product lifetimes. Closed-loop material systems are also emerging, where advanced separation and purification techniques allow for the efficient recovery and reuse of high-value nanomaterials from end-of-life products [138].

Energy autonomy represents another critical frontier for CPNC research. The next generation of smart materials will need to operate independently of external power sources, driving innovation in energy harvesting and storage technologies integrated directly into material systems. Triboelectric and piezoelectric CPNCs are particularly promising in this regard, capable of converting ambient mechanical energy from vibrations, human motion, or even blood flow into usable electrical power. When combined with flexible energy storage solutions like micro-supercapacitors based on laser-scribed graphene–polymer composites, these systems could enable entirely self-powered sensor networks and electronic devices. Recent breakthroughs in photo-thermoelectric CPNCs also suggest potential for solar energy harvesting directly at the material interface [138,139].

A particularly promising direction for future research is the integration of CPNCs with quantum computing technologies. Carbon nanomaterials such as graphene and graphene quantum dots (GQDs) inherently display quantum confinement effects, tunable electronic band gaps, and excellent charge transport properties, all of which make them attractive for quantum information applications [140,141]. When these materials are embedded within polymer matrices, they not only gain mechanical flexibility and environmental stability but also open opportunities for scalable and defect-tolerant quantum devices. For instance, GQDs dispersed in polymers have shown potential as stable single-photon emitters and qubits, which are essential building blocks for quantum communication and sensing [141]. Advances in additive manufacturing and self-assembly techniques are further enabling precise spatial control of nanomaterial distribution, allowing researchers to envision large-area, flexible quantum circuits integrated directly into polymer substrates [140].

The fabrication of CPNCs and the commercialization of them are subject to major challenges in the scalability of synthesis, material reproducibility, and interdisciplinary efforts. Properties: roll-to-roll processing, 3D printing, and self-assembly for fabricating high-performance composites with uniform nanomaterial dispersion [141]. A consensus of methods is needed for industry adoption. Interdisciplinary works will increasingly fuel innovation as electronic skins based on CPNC, implantable biosensors, and drug release systems responding to the local changes are forming. Potential integrations with quantum computing and neuromorphic engineering may come together to provide ultra-sensitive sensors and adaptive, brain-like interfaces. Issues of safety, the environment, and ethics also have to be considered. These include assessing the long-term effects of nanomaterials, safe disposal, and responsible regulations, especially for biomedical and surveillance applications. In medicine, CPNCs introduce stretchable and biocompatible devices for diagnostics and therapy [140]. In industry applications, they provide long-lasting protection for industrial areas and warehouses. For consumer electronics and the IoT, stretchable, energy-efficient CPNCs will enable next-generation devices in homes, cities, and infrastructure.

8. Conclusions

Smart CPNCs represent a transformative material platform at the intersection of nanotechnology, polymer science, and intelligent systems. This review has comprehensively explored their dual roles in sensing and actuation, emphasizing how the integration of

carbon nanomaterials with functional polymers unlocks unprecedented combinations of flexibility, conductivity, and responsiveness. Through a systematic analysis of fabrication techniques, including in situ polymerization, electrospinning, and 3D/4D printing, we have highlighted how tailored interfaces and nanoscale architectures are enabling next-generation device performance. Our review further illustrates the broad applicability of CPNCs across emerging fields such as soft robotics, wearable health monitoring, smart textiles, and environmentally responsive systems.

Importantly, we identify critical limitations that must be addressed such as nanofiller dispersion, long-term stability, and scalable production while also outlining realistic pathways toward overcoming them via interdisciplinary strategies and sustainable design principles. Our synthesis of current advancements, challenges, and future prospects aims to serve as a foundational roadmap for researchers and technologists working toward multifunctional, autonomous, and intelligent material systems.

Ultimately, this work underscores the pivotal role of CPNCs in enabling the future of adaptive electronics and smart devices and positions them as a keystone in the evolution of next-generation HMI interfaces and energy-autonomous systems.

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