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Recent advances in biodegradable biosensors for biomedical and environmental applications

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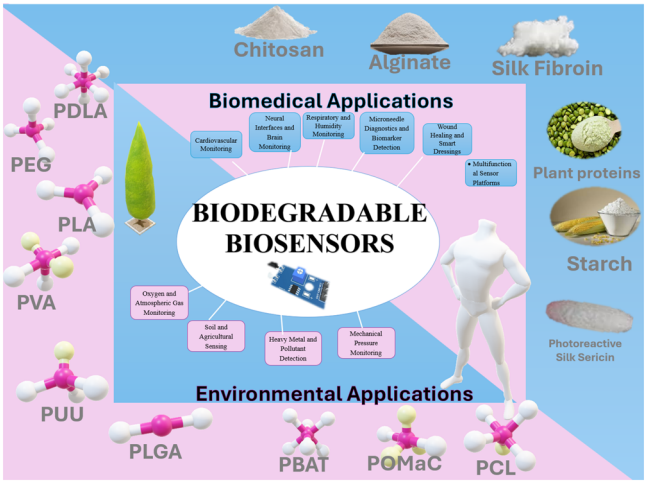
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ABSTRACT

Biodegradable biosensors represent a transformative advancement in sustainable sensing technology, offering an environmentally friendly and biocompatible alternative to traditional sensors. This review examines recent advancements, material innovations, degradation mechanisms, and application areas of biodegradable biosensors within the biomedical and environmental sectors. Natural and synthetic biodegradable polymers, such as chitosan, silk fibroin, alginate, PLA, PLGA, and PVA, are assessed for their functional contributions to sensing platforms. Applications, ranging from implantable cardiovascular and neural sensors to soil nutrient monitors and gas detectors, are detailed with corresponding performance data. Although challenges related to signal stability, integration, and long-term operation persist, future research emphasizes multifunctionality, wireless communication, energy autonomy, and AI-driven diagnostics. This review highlights the potential of biodegradable biosensors to transform health monitoring, environmental assessment, and personalized medicine by aligning technological functionality with principles of sustainability.

GRAPHICAL ABSTRACT



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Introduction

Biosensors are analytical devices that combine biological components (i.e. recognition element) with a transducer to detect and measure specific substances called analyte. From engineering standpoint, biosensors interact with the target substance using a bioreceptor (e.g. enzyme, antibody, or DNA). As a result of this interaction, a signal is generated and converted into a readable output by a transducer [1,2].

Biosensors offer rapid, precise, and cost-effective analyses across diverse disciplines, including medical diagnostics, environmental monitoring, and food safety. They also serve a vital function in detecting disease markers within medical diagnostics, monitoring glucose concentrations in diabetic patients, and identifying infections. In environmental monitoring, biodegradable biosensors are particularly significant as they can detect very low levels of pollutants, which is essential for protecting public health and the environment. Their biodegradability ensures that they do not contribute to electronic waste, further enhancing their environmental impact [3]

With the development of biotechnology, biosensors have become essential tools in health and environmental protection due to their heightened sensitivity and ability to provide timely information. One of the recent advancements in biosensors is biodegradable biosensors [1–3]

The sustainability of biosensors has become a growing concern due to environmental concerns. Recent developments in biotechnology have primarily focused on addressing these ecological challenges. As a result, biodegradable biosensors represent a notable advancement in the field. These devices are manufactured from materials that naturally decompose within days or weeks, thereby reducing the environmental impact associated with conventional biosensors. The adoption of biodegradable biosensors enhances the mitigation of electronic waste and promotes environmental preservation. Moreover, biodegradable biosensors offer an additional advantage: their versatility across diverse application domains. This benefit chiefly stems from the use of biopolymers, natural fibers, and biodegradable metals in their construction. An equally crucial benefit is their cost-effectiveness and sustainability. The production of these biosensors is more economical due to the use of renewable, low-cost materials, which facilitates large-scale manufacturing and enhances access to this technology.

Biodegradable materials used in biosensors

Biodegradable biosensors can provide sustainable alternatives for environmental and biomedical applications by utilizing naturally degradable materials. These materials include natural biopolymers, synthetic biodegradable polymers, and composite or hybrid systems. This section will present information about the properties of these materials.

Natural biopolymers

Natural biopolymers are derived from renewable resources, biodegradable, and possess biocompatibility, making them appealing for biosensor applications.

Chitosan is a readily biodegradable biopolymer derived from the natural polysaccharide chitin. Most chitin is found in the shells of crustaceans (such as shrimp and crabs)

and the cell walls of fungi. Chitosan is prepared by deacetylation of chitin in an alkaline medium, particularly in sodium hydroxide, whereby acetyl groups are removed [4].

In biosensor technology, it efficiently immobilizes biological components such as enzymes, antibodies, and DNA. Additionally, its ability to form thin films makes it especially suitable for various uses and ideal for sensor surfaces. When integrated with conductive polymers, chitosan yields sensor surfaces that are flexible, durable, and biodegradable. Additionally, chitosan has applications in various domains, including wound dressings, drug delivery systems, food packaging, and water treatment. Its solubility in acidic conditions further provides advantages for controlled degradation and targeted applications [5,6].

Cellulose is a naturally occurring polysaccharide, recognized as the most abundant organic polymer in nature and serving as the primary structural component of plant cell walls. Chemically, it consists of D-glucose units linked by β-(1→4)-glycosidic bonds [7,8].

In biosensors, cellulose can be a support material for immobilizing enzymes, antibodies, and other biomolecules. It also possesses moisture-absorbing, gas-permeable, and biodegradable properties, making it an ideal material for environmental monitoring, food safety, medical diagnostics, and wearable sensors. Furthermore, it becomes functional in electronic applications by enhancing its electrical conductivity when integrated with conductive polymers or metal nanoparticles [5–9].

Silk Fibroin is a natural fibrous protein derived from the cocoon of the Bombyx mori silkworm. This protein, which is an essential structural component of silk fibers, has garnered significant attention as a biodegradable biomaterial in recent years [10]. Silk fibroin is often preferred in biosensor design due to its high mechanical strength, biocompatibility, and biodegradability [11,12]. It offers a suitable surface for immobilizing biorecognition elements such as enzymes, aptamers, or antibodies. Furthermore, it is applicable in optical sensors due to its optical transparency and can be utilized in electrochemical sensor platforms by modifying it with conductive polymers or metal nanoparticles. Especially in the case of temporary, implantable sensors, fibroin-based structures offer a significant advantage by gradually dissolving within the biological environment over time, effectively removing the necessity for reoperation [13].

Alginate is a natural polysaccharide derived from brown seaweeds and is widely preferred for developing biodegradable biosensors due to its biocompatibility, biodegradability, and ability to form hydrogels under mild conditions. These properties create an ideal matrix for immobilizing biological agents such as enzymes, antibodies, and living cells [14]. Alginate-based nanomaterials produce pH-sensitive fluorescent nanosensors, enabling the non-invasive detection of intracellular and extracellular pH variations. These sensors are developed using environmentally sustainable materials and solvent-free methodologies, providing a viable option for biomedical diagnostics [14].

Plant proteins, such as Zein, soy, rice, peanut, and wheat gluten, are natural polymers employed in triboelectric nanogenerators. These proteins function as renewable and biodegradable materials that exhibit beneficial mechanical and electrical properties, making them suitable for use in energy harvesting applications [15].

Starch is a natural plant-derived polysaccharide frequently employed in gel electrodes and biodegradable films. Its accessibility, biodegradability, and capacity to form films render it a versatile material for biomedical and sensor applications [16].

Photoreactive Silk Sericin is a derivative of silk protein distinguished by its light-sensitive properties. It is employed in conductive inks and flexible electronic applications, offering biocompatibility and the ability to form photo-crosslinked networks, which are suitable for the development of advanced sensors [17].

The performance of biosensors made from natural polymers like chitosan and alginate heavily depends on source-related variability, such as purity, molecular weight, and levels of deacetylation or crosslinking. For example, higher molecular weight or lower deacetylation in chitosan reduces solubility and impairs uniform film formation, leading to poor reproducibility. Conversely, lower molecular weight improves processability but often decreases sensitivity because of fewer functional groups available for biorecognition. In alginate, variations in the ratio of mannuronic to guluronic acid affect gel strength and ionic conductivity, directly impacting sensor stability and response consistency [18,19]. These aspects directly impact the biosensor's reproducibility, sensitivity, and stability. To address these inconsistencies, researchers typically use standardized characterization techniques, including FTIR for functional groups, GPC for molecular weight, and elemental analysis for purity. Although no specific industry-wide standards for biosensor manufacturing are currently in place, guidelines from bodies like ISO (e.g. ISO 10993 for biocompatibility) and ASTM (e.g. ASTM F2212 for polymer characterization) are increasingly adopted to promote comparability across different studies [20–22]. In Table 1, all the natural polymers mentioned above were summarized.

Suitability of natural polymers for biosensors

Degradation profile and mechanical strength. Cellulose and its derivatives (e.g. nanocellulose) are biopolymers with slow degradation rates and high mechanical strength. This structure is especially preferred in epidermal sensors that require long-term stability [24]Chitosan degrades at a moderate pace and dissolves in slightly acidic environments. It has a strong film-forming ability. Its antimicrobial properties often make it suitable for wound-monitoring sensors. Silk fibroin is notable for its controllable degradability and high mechanical strength. Its protein-based structure also offers excellent compatibility with bio-recognition agents such as antibodies and enzymes [24].

Electrical conductivity and functional modification. Natural polymers such as cellulose and chitosan are intrinsically non-conductive; however, they acquire electrical conductivity when combined with conductive materials such as carbon nanotubes, silver nanoparticles, MXene, and PEDOT:PSS [24]. Silk fibroin is suitable for use in capacitive sensors owing to its dielectric properties and also facilitates energy harvesting applications when combined with piezoelectric additives (e.g. BTO) [24].

Processability and compatibility with micro/nanostructures. Chitosan and cellulose can be easily processed using methods such as electrospinning, casting, and 3D printing. This makes them suitable for both surface sensors and applications requiring volumetric structures. Silk fibroin allows for the creation of high-resolution microstructures through solvent casting, electrospinning, and molding. This is important for microfluidic platforms or thin membrane structures. Chitosan, because it contains amino groups, is

Table 1. A summary of natural polymers used in biodegradable biosensors.

Polymer name	Type	Key properties & applications	References / sources
Chitosan	Natural	Derived from chitin (crustaceans, fungi); biocompatible, biodegradable; used to immobilize enzymes, DNA; forms flexible, conductive sensor films; applied in wound dressings and water treatment	[4–6]
Cellulose	Natural	Abundant plant polysaccharide supports biomolecule immobilization; breathable, moisture-absorbing; used in diagnostics, wearables, and environmental monitoring.	[7–9]
Silk Fibroin	Natural	Protein from silkworm (*Bombyx mori*); high strength, transparent, biodegradable; supports enzyme/antibody immobilization; dissolves *in vivo*—ideal for implantable biosensors	[10–13]
Alginate	Natural	Seaweed-derived polysaccharide; forms hydrogels under mild conditions; used for pH sensors and encapsulating enzymes or bacteria	[14,23]
Plant Proteins	Natural	Includes zein, soy, rice, wheat gluten; used in triboelectric nanogenerators; biodegradable and electroactive materials for energy harvesting	[15]
Starch	Natural	Plant polysaccharides form biodegradable gels and films, which are utilized in gel electrodes and biomedical sensors.	[16]
Silk Sericin	Natural	Light-sensitive silk protein; used in conductive inks; enables photo-crosslinked networks for flexible biosensors	[17]

suitable for covalent binding and can be used for immobilization of biorecognition elements (e.g. cross-linking with glutaraldehyde) [24].

Variability in purity, molecular weight, degree of acetylation, monomer composition, and residual impurities inherent to natural polymers such as chitosan and alginate is source-dependent and can considerably impact the reproducibility and sensitivity of biosensors. This influence manifests through alterations in film formation, analyte diffusion, and biorecognition efficiency [25–28]. Although the development of universal biosensor-specific standards remains pending, existing characterization guidelines issued by ASTM (e.g. F2103 for chitosan) and ISO (e.g. 17871 for alginate) are recommended for adoption to maintain consistency in biosensor fabrication [29,30].

Synthetic biodegradable polymers

PLA (Polylactic Acid) is a synthetic biodegradable polymer derived from renewable resources such as corn starch or sugarcane. It is extensively utilized in biomedical applications, including substrates, fibers, stents, and nanocomposites, owing to its

superior biocompatibility and biodegradability. PLA is routinely employed in medical implants, such as bone screws and plates, as well as in packaging and 3D printing. Its capacity to undergo natural degradation renders it an environmentally sustainable alternative to traditional plastic materials [31].

POMaC (Polyoctamethylene Maleate Citrate) is a synthetic, biodegradable elastomer that features dual crosslinking methods, UV and ester bonds. This combination offers both mechanical flexibility and biocompatibility, making it ideal for use in soft tissue engineering scaffolds and flexible sensors [17].

Polycaprolactone (PCL) is a synthetic, semi-crystalline biodegradable polyester characterized by a low melting point and significant flexibility. It is extensively employed in the fabrication of stents, electrospun fibers, wound dressings, and drug delivery systems, owing to its gradual degradation rate and compatibility with bioactive compounds. Additionally, PCL contributes to increased flexibility in biodegradable packaging materials [17].

PEG (Polyethylene Glycol) is a semi-synthetic hydrophilic polymer widely used as a hydrogel base in biomedical applications. It is biocompatible and non-toxic, applied in drug delivery, gene therapy, protein crystallization, and as a dispersant in cosmetics and pharmaceuticals [17,32].

PDLA (Poly(d-lactide)) is a synthetic biodegradable polymer primarily used as a coating for sensors and drug delivery systems. It provides controlled degradation and exhibits biocompatibility and can be copolymerized with PEG to enhance stability and hydrophilicity [17].

PLGA (Poly(lactic-co-glycolic acid)) is a synthetic copolymer composed of lactic and glycolic acid units. It is widely used in biodegradable implants, drug delivery systems, humidity sensors, and membranes. The degradation rate of PLGA can be adjusted by modifying the monomer ratio, enabling precise control over drug release and implant lifespan [17,32].

Polyvinyl Alcohol (PVA) is a synthetic polymer distinguished by its film-forming, emulsifying, and adhesive properties. It is commonly employed in gel electrodes, substrates, and nanofibers, with applications extending across biomedical devices and sensors [17].

PBAT (Poly(butylene adipate-co-terephthalate)) constitutes a flexible, synthetic, and biodegradable polymer. It is utilized in electrochemical sensors and compostable packaging films owing to its mechanical flexibility and environmental compatibility [16].

PUU (Polyurethane) is a synthetic polymer characterized by its electroactive properties, making it suitable for use in gas sensors. Its chemical structure enables a response to electrical stimuli, thereby enhancing sensor sensitivity [17,32]. In Table 2, all the synthetic polymers mentioned above are summarized. Table 3 summarizes the natural and synthetic polymers used in biodegradable biosensors.

Hydrogels and emerging natural/synthetic hybrid systems

Recent advancements in gelatin- and PVA-based hydrogel electronics have broadened the scope of biodegradable biosensors. For instance, a conformal, substrate-free liquid metal electrode has facilitated continuous health monitoring with excellent skin conformability [33] Highly durable and responsive ionic liquid/PVA hydrogels have been

developed for stretchable electronics with enhanced mechanical resilience [34]. Additional studies report skin-printable, anti-freezing, and recyclable ionic hydrogel bioelectrodes for ongoing electrophysiological surveillance [35], paintable and highly adhesive hydrogels for high-fidelity wireless monitoring [36], and ultrathin nanomesh-reinforced, gas-permeable hydrogel skin sensors appropriate for long-term applications [37,38]. Moreover, gelatin-based biodegradable multifunctional platforms have been demonstrated for implantable cardiac monitoring, highlighting the versatility of hydrogel-based systems in both biomedical and environmental domains [39].

Degradation mechanisms

Biological factors affecting degradation

The degradation of biodegradable polymers in biomedical and environmental contexts predominantly transpires *via* three principal mechanisms: hydrolytic, enzymatic, and oxidative degradation. These pathways are affected by both the chemical composition of the polymer and the environmental conditions to which the material is subjected.

Hydrolytic degradation

Hydrolysis constitutes the primary degradation mechanism for synthetic polyesters such as poly(lactic acid) (PLA) and poly(lactic-co-glycolic acid) (PLGA). This process involves the cleavage of ester bonds within the polymer backbone through the action of water molecules *via* second-order nucleophilic substitution reactions. The rate of this reaction is substantially affected by the water content and pH conditions. For example, PLA demonstrates minimal hydrolysis at approximately pH 4, which is attributable to the pKa of lactic acid. In contrast, both acidic and basic environments expedite degradation *via* distinct catalytic pathways. Degradation kinetics for hydrolytically susceptible polymers frequently exhibit a predictable pattern, wherein the reciprocal of the number-average molecular weight increases linearly over time, signifying second-order behavior [40–42].

Biodegradable polymer degradation in biosensors is modeled through kinetic frameworks linking molecular weight loss, mass loss, and time. For hydrolytically labile polymers like PLA, PLGA, and PCL, pseudo-first or second-order hydrolysis kinetics are used, depending on whether water diffusion or ester bond cleavage limits the reaction [40–42]. These systems often show a linear relationship between $1/M_n$ and time, consistent with second-order chain scission [40–42]. Natural polymers such as chitosan, alginate, and silk fibroin are modeled empirically based on Michaelis–Menten-like kinetics or surface erosion rates due to enzymatic specificity [43]. Oxidative degradation follows autocatalytic radical chain kinetics related to reactive oxygen species (ROS)[24]. These models aid in predicting performance, but caution is needed when applying them across different polymers or conditions. Hydrolysis-based linear $1/M_n$–time relationships hold in steady conditions but may not in heterogeneous environments with variable pH, enzymatic activity, or humidity, where surface erosion or multiple mechanisms dominate. *In vitro* parameters often overpredict *in vivo* stability due to combined effects. Models should be tailored to specific polymer chemistry, device shape, and use, with validation under real-world conditions.

Table 2. A summary of synthetic polymers used in biodegradable biosensors.

Polymer name	Type	Key properties & applications	References
PLA (Polylactic Acid)	Synthetic	Derived from renewable resources; biocompatible and biodegradable; used in medical implants, fibers, packaging, and 3D printing	[16]
POMaC	Synthetic	Biodegradable elastomer with dual crosslinking (UV & ester bonds); flexible and biocompatible; used in soft tissue scaffolds and sensors	[17]
PCL (Polycaprolactone)	Synthetic	Semi-crystalline, flexible polyester; gradual degradation; used in stents, wound dressings, drug delivery, and packaging	[17]
PEG (Polyethylene Glycol)	Semi-synthetic	Hydrophilic hydrogel base; biocompatible; used in drug delivery, gene therapy, cosmetics	[17,32]
PDLA (Poly(d-lactide))	Synthetic	Biodegradable coating polymer; controls degradation; biocompatible; copolymerizable with PEG for stability	[16]
PLGA (Poly(lactic-co-glycolic acid))	Synthetic	Copolymer with tunable degradation; used in implants, drug delivery, sensors, membranes	[17,32]
PVA (Polyvinyl Alcohol)	Synthetic	Film-forming, adhesive polymer; used in gel electrodes, substrates, and nanofibers	[17,32]
PBAT	Synthetic	Flexible, biodegradable polymer; used in sensors and compostable packaging films	[16]
PUU (Polyurethane)	Synthetic	Electroactive polymer for gas sensors; responds to electrical stimuli	[17,32]

Enzymatic degradation

Enzymatic degradation provides a high degree of specificity, particularly for natural biopolymers such as chitosan, gelatin, and collagen. Enzymes, including hydrolases, cleave ester or amide bonds, while oxidoreductases (e.g. laccases, peroxidases) can initiate degradation through the oxidation of C–C or C–H bonds. In chitosan-based systems, lysozyme-mediated degradation is significantly influenced by the degree of acetylation (DA). Hydrogels with a higher DA exhibit more rapid degradation due to improved enzyme recognition. For example, chitosan hydrogels with 31.7% DA fully degraded within 65 h, whereas formulations with 28.03% DA required up to 120 h under comparable conditions [43].

Oxidative degradation

Oxidative degradation is particularly relevant within *in vivo* environments, where reactive oxygen species (ROS), including superoxide and hydrogen peroxide, are naturally present. This process involves the formation of polymer radicals through hydrogen abstraction or homolytic bond cleavage, subsequently triggering chain reactions

Table 3. A summary of natural and synthetic polymers used in biodegradable biosensors.

Polymer	Main degradation mechanism	Typical degradation time	Environmental conditions	Sources
PLA	Hydrolysis (ester bond cleavage)	~6–12 months	Aqueous, PBS pH 7.4, 37 °C	[16]
POMaC	Hydrolysis (ester & anhydride bond cleavage)	Weeks to months	Physiological-like (aqueous, 37 °C)	[17]
PCL	Hydrolysis, enzymatic (lipases)	>24 months	Aqueous, PBS pH 7.4, 37 °C	[17]
PDLA	Hydrolysis (stereoisomer of PLA)	Similar to PLA (months)	Physiological (aqueous, 37 °C)	[16]
PLGA	Hydrolysis	1–3 months	PBS pH 7.4, 37 °C	[17,32]
PEG	Oxidation, enzymatic (limited)	Varies, generally slow	Depends on chemical modifications	[17,32]
PVA	Enzymatic, hydrolytic	Varies	Depends on microbes and environment	[17]
PBAT	Enzymatic hydrolysis (of aliphatic parts)	Months	Aqueous, microbial environment	[16]
PUU	Hydrolysis, enzymatic	Varies	Depends on chemical structure and environment	[17,32]
Chitosan	Enzymatic (lysozyme and others)	Weeks to months	Aqueous, pH 7.4, 37 °C	[4–6]
Cellulose	Enzymatic (cellulases)	Weeks to months	Microbial environment	[7–9]
Silk Fibroin	Enzymatic (proteases)	Weeks	Aqueous, pH 7.4, 37 °C	[10–13]
Alginate	Ion exchange, enzymatic	Hours to weeks	Chelating aqueous, pH ~7, 25–37 °C	[14]
Plant Proteins	Enzymatic	Weeks to months	Depends on protein type and environment	[15]
Starch	Enzymatic (amylases)	Weeks	Aqueous, microbial environment	[16]
Silk Sericin	Enzymatic	Faster than fibroin	Aqueous, 37 °C	[17]

that lead to the formation of hydroperoxides and further degradation. Recent advancements in ROS-responsive polymers, such as those capable of selenoxide elimination, enable accelerated and controlled degradation, achieving rates up to seventeen times faster than traditional ROS-sensitive systems [24].

Environmental factors affecting degradation

The degradation rate and mechanisms are profoundly affected by external environmental factors, including temperature, moisture, pH, oxygen levels, molecular weight, and morphology. Elevated temperatures increase molecular mobility and reaction rates; for example, the onset temperatures for thermal degradation vary among polymers: approximately 200 kJ/mol for polystyrene, 150–240 kJ/mol for polyethylene, and polypropylene. Humidity and moisture facilitate hydrolysis by promoting water diffusion into amorphous regions, as observed in PET and PCL systems. pH levels significantly influence the process; acidic environments accelerate hydrolysis through protonation of ester groups, while alkaline conditions favor nucleophilic attack. The concentration of oxygen determines the extent of oxidative degradation. Thermogravimetric analyses demonstrate that polymers such as PE and PP decompose at notably lower temperatures in the presence of oxygen compared to inert nitrogen atmospheres. Molecular weight and crystallinity influence accessibility; higher molecular weight impedes degradation due to reduced chain mobility, and crystalline regions display increased resistance to enzymatic and hydrolytic degradation. Morphological factors such as surface

area and porosity are crucial; porous structures with greater surface areas enhance water ingress and enzyme interaction, thereby hastening degradation. Microbial degradation completes the biodegradation cycle, especially under environmental conditions; microorganisms such as Pseudomonas sp. and Bacillus sp., along with fungi like Aspergillus niger, are capable of degrading polymers, including LDPE and polyurethane by up to 55% and 40%, respectively, within a 30-day period [44–47].

Applications of biodegradable biosensors: Transforming healthcare and environmental monitoring

Biodegradable biosensors constitute an emerging category of transient, environmentally sustainable diagnostic platforms engineered to function for a predetermined period before degrading safely within biological or environmental systems. Their design addresses critical limitations inherent in permanent electronic devices, such as the necessity for surgical removal and electronic waste management, by facilitating high-performance sensing in conjunction with subsequent bioresorption or decomposition. These sensors are particularly significant in two primary sectors: biomedical and environmental monitoring [48].

Biomedical applications

Biodegradable biosensors offer significant advantages for temporary *in vivo* monitoring due to their biocompatibility, controlled degradation, and wireless integration features. Their ability to operate without the need for retrieval considerably reduces patient risk and healthcare costs, thereby promoting their increasing adoption across diverse clinical settings and disciplines [49,50].

Cardiovascular monitoring

Recent developments encompass fully biodegradable electrocardiogram (ECG) patches constructed from nanocellulose substrates and carbon-based conductors. These devices, exemplified by those developed by the VTT Technical Research Centre, provide modular configurations that facilitate reusable electronics and biodegradable patches capable of decomposing after use. Bioresorbable pressure sensors utilizing POMaC-based dielectrics integrated with chipless wireless systems have exhibited potential for post-operative vascular monitoring, thereby enabling temporary pressure feedback without the need for long-term implantation [49,50].

Neural interfaces and brain monitoring

Biodegradable neural sensors, which frequently integrate two-dimensional TMDC materials and bioresorbable silicon, facilitate the real-time detection of dopamine, pH, temperature, and electrophysiological signals. These platforms afford direct, localized monitoring of neurotransmitters with minimal inflammatory response and complete bioresorption. Furthermore, flexible optoelectronic neural interfaces have been engineered to promote neural regeneration and enable photostimulation, underscoring the potential for closed-loop neuromodulation therapies [51].

Respiratory and humidity monitoring

Sophisticated triboelectric sensors and micro-thermoelectric generators (μTEGs) are engineered to monitor respiratory mechanics and breath biochemistry in real time. These devices demonstrate high sensitivity concerning flow rate (2–8 L/min) and frequency (0.33–0.8 Hz), and are capable of detecting biomarkers such as acetone even in humid conditions. Their rapid response times (<10 ms) and compact design make them suitable for wearable or disposable respiratory health monitoring applications [32].

Microneedle diagnostics and biomarker detection

Biodegradable microneedle-based biosensors offer tether-free, pain-free, continuous glucose monitoring through the integration of glucose-responsive fluorescent monomers. These systems are entirely biodegradable and engineered for compatibility with smartphone platforms. Likewise, nitric oxide (NOx)-responsive biodegradable sensors have demonstrated remarkable selectivity and detection sensitivity, achieving detection thresholds of 0.0005%, rendering them suitable for monitoring disease states associated with oxidative stress [52].

Wound healing and smart dressings

Electrochemical biosensors integrated into advanced wound dressings, such as carbon ultra-microelectrode arrays, facilitate the continuous monitoring of wound biomarkers without necessitating the removal of the dressing. These sensors are particularly beneficial for managing chronic wounds, such as diabetic foot ulcers and pressure ulcers, providing both robustness and real-time feedback to healthcare professionals [52]. For example, Park et al. demonstrated a 3D-printed PCL stent with an integrated sensor exhibiting an initial resonance at 148 MHz and a sensitivity of 60 kHz/mmHg across the range of 0–220 mmHg [53]; Khalid et al. reported a PLGA–PCL nanofibrous pressure sensor with a sensitivity of $0.863 \pm 0.025\,\mathrm{kPa}^{-1}$ (0–1.86 kPa) and approximately 60% mass loss within two weeks (noting only a 19.5% reduction in the low-pressure range after one week)[54], Zheng et al.'s ionic capacitive FPS achieved a sensitivity of $13.7\,\mathrm{kPa}^{-1}$ (0–2 kPa), with 99% cell viability and greater than 95% accuracy in classifying PD severity [11].

Multifunctional sensor platforms

Multicomponent biodegradable platforms incorporate pressure sensors, electrochemical analyte detectors (such as for lactate and pH), and sensors for volatile compounds into a unified wearable device. AI-driven data fusion techniques have been utilized to interpret complex biosignals, thereby facilitating personalized health profiling and generating distinctive 'health barcodes' [55].

Environmental monitoring

The integration of biodegradable materials into environmental sensor design facilitates temporary, non-invasive deployment across diverse ecosystems while mitigating electronic waste accumulation. Representative environmental metrics include: Presley et al. (Pd-porphyrin electrospun fibers) with Stern–Volmer constant KSV = 1.25×10^5

M^{-1} for dissolved oxygen sensing [56]; Gopalakrishnan et al.'s DIRTS soil sensor detecting volumetric water content ranging from 3.7% to 23.5%, with approximately 9.07 MHz per 1% sensitivity and less than 4% sensitivity loss over one year in field tests [57]; and Maciel et al.'s PBAT–CND electrochemical sensor, which achieved a cadmium ion (Cd^{2+}) detection limit of 2.75×10^{-6} M and a sensitivity of 2.06×10^{-6} mA·cm^{-2}·M^{-1} within a linear range of 0.1 to 1.0 mM. [58].

Oxygen and atmospheric gas monitoring

Biodegradable oxygen sensors utilizing OLED/OPD configurations have shown high resolution across oxygen ranges relevant to physiological and environmental conditions (0–418 mmHg). RTIL-based sensors, using double potential amperometry, enable quick oxygen measurements in under 4 s with reliable repeatability. Detection of hydrogen sulfide (H_2S) has been achieved through coconut shell-derived PUU composites and paper-based fluorescent biosensors, offering high selectivity and rapid response times (detection limit of 3 ppb, achieved within 60 s). These platforms are well-suited for industrial and biological monitoring [59,60].

Soil and agricultural sensing

Biodegradable soil sensors produced using screen-printing techniques enable the real-time detection of essential nutrients (NPK), thereby enhancing fertilization strategies within the scope of precision agriculture. The sensors, fabricated from wax-coated nanopaper and tin-based electrodes, are inherently biodegradable, decomposing naturally into organic matter that benefits soil health. Remote wireless activation, combined with thermal imaging, enables non-invasive mapping of soil moisture content and its spatial distribution.

Heavy metal and pollutant detection

Biopolymer-based electrochemical sensors that employ gelatin, collagen, cellulose, chitosan, and polyhydroxyalkanoates facilitate the detection of trace levels of Cd^{2+}, Ni^{2+}, Pb^{2+}, and Cu^{2+}. Biofilm-based systems utilizing Geobacter species have attained high current densities and detection sensitivities (for example, 161.7 μA·μM^{-1}·cm^{-2} for Pb^{2+}), demonstrating potential for sustainable water quality monitoring [61].

Mechanical pressure monitoring

Fully biodegradable RF pressure sensors and polyurethane-based capacitive sensors exhibit high performance in detecting mechanical loads. These sensors incorporate transient materials, such as PVA and PLGA, for dielectric layers, along with bioresorbable conductors, including zinc. Their superior durability, extensive pressure range (up to 62.5 kPa), and recyclability make them highly appropriate for wearable and disposable monitoring systems [35].

Tuning biodegradable biosensors' degradation rate through molecular and morphological parameters

Biodegradable biosensor degradation depends on polymer features like backbone chemistry, crystallinity, crosslinking, and additives. Hydrophilic polymers like PEG and PVA

degrade faster, while hydrophobic ones like PCL and PBAT last longer. Crystallinity slows degradation; PLA degrades slowly due to higher crystallinity. PLGA's degradation rate can be tuned by adjusting the lactic-to-glycolic acid ratio. Crosslinking influences stability; more crosslinking typically slows degradation. Additives like PEG and electroactive polymers enhance tunability for specific applications [62,63]. Rapid diagnostics favor low crystallinity and minimal crosslinking, while environmental sensors require more stability from semicrystalline, crosslinked, and hydrophobic polymers.[62–68]

Biocompatibility and ecological impact of degradation byproducts

The evaluation of biodegradation byproducts is a crucial aspect in ensuring the biosafety and environmental compatibility of biosensors. While numerous studies report the biocompatibility and low cytotoxicity of individual base polymers such as PLA, PLGA, PEG, and PCL, systematic assessments of the cytotoxicity, immunogenicity, and ecological impact of degradation byproducts (especially *in vivo* or under real-world environmental conditions) remain limited and fragmented.

Biocompatibility and immunogenicity of degradation products

PLA, PLGA, and PCL degrade into lactic acid, glycolic acid, and caproic acid, respectively. These degradation products are generally recognized as safe at physiological concentrations and are metabolizable by the human body. Nonetheless, local accumulation may transiently decrease pH levels and could potentially inhibit tissue regeneration or elicit mild inflammatory responses, particularly if degradation occurs rapidly or within a localized area. PEG is extensively utilized owing to its inert characteristics and low toxicity profile. Its degradation byproducts are typically benign; however, comprehensive investigations, especially about long-term immunogenicity or repeated exposure, remain limited. Among PLA, PCL, and PGA, lactic acid (derived from PLA/PLGA) and caproic acid (derived from PCL) are generally considered less toxic at relevant dosages. Although some acute toxicity assessments indicate that lactic acid exhibits marginally greater cytotoxicity compared to caproic acid, all are regarded as safe at standard concentrations. Most *in vivo* studies with PLGA, PLA, and PEG-based materials report minimal acute immune activation. The risk of chronic inflammation is low but not entirely absent, especially if high local byproduct concentrations persist [62–64].

Environmental impact and ecological compatibility

Biodegradable polymers in soil, compost, and freshwater are generally mineralized into CO_2, H_2O, and biomass. Well-established byproducts like lactic acid and caproic acid are not significantly ecotoxic. Life cycle assessments show microplastics from polymers like PLA, PCL, and PBS have lower aquatic ecotoxicity than traditional plastics. However, natural biodegradation may increase greenhouse gases, mainly methane, compared to controlled composting or digestion. While data suggest these polymers are generally safe, there's a lack of standardized long-term research on chronic exposure in medical and environmental contexts. Existing studies show degradation products from

PLA, PLGA, and PCL are mostly non-toxic, though purity and additives can affect safety. Long-term, systematic evaluations are needed, especially for environmental use [31,69,70].

Overview of biodegradable biosensors

Biodegradable biosensors for biomedical applications

M. Boutry et al. reported the design of a pressure sensor composed entirely of biodegradable materials, including polyoctamethylene maleate (anhydride) citrate (POMaC) and PLA. The sensor was developed to measure arterial blood flow in both contact and non-contact modes, utilizing fringe-field capacitor technology. The wireless device, which operates with an inductive coating, exhibits minimal hysteresis, fast response time, superior cyclic stability, and high durability. The sensor does not require removal due to its easy installation, thus reducing the risk of vascular trauma. The performance of the sensor was tested on a specially designed artificial artery model and *in vivo* in rats. This technology may offer significant advantages in real-time monitoring of blood flow after reconstructive surgery [71].

Park and his team have developed a 3D-printed biocompatible and biodegradable polymer stent with an integrated wired pressure sensor designed for advanced health monitoring applications. The polycaprolactone (PCL)-based polymer stent features a drug coating similar to that of herbal drug-eluting stents (DES). It is heated by a wire temperature sensor that provides real-time measurement of pressure in blood vessels. The wireless temperature is made of biocompatible poly(d-lactide) (PDLA) material that can be absorbed and fragmented with the polymer stent as it heats. The sensor's resonance tuning was initially measured at 148 MHz and decreased with changes in blood pressure. The temperature sensors exhibit a linear frequency shift with a sensitivity of 60 kHz/mmHg over the range of 0–220 mmHg [53].

H. Ouyang et al. developed a triboelectric-based, biodegradable, and self-powered sensor capable of converting environmental pressure fluctuations into electrical signals. Additionally, vascular occlusion events in canines were effectively identified utilizing this triboelectric biodegradable sensor. The core component of the fabricated biodegradable pressure sensor comprises two triboelectric layers. A nanostructured polylactic acid (PLA)/4% chitin film was employed as the triboelectric layer, with magnesium functioning as the electrode. The internal components of the sensor are safeguarded from liquid exposure by an external encapsulation layer composed of polylactic acid and chitin. The elastic contact point (POC) functions as the adhesive layer. The sensor demonstrated a service efficiency of 5.95%, a sensitivity of 11 mV $mmHg^{-1}$, and exhibited superior antibacterial properties [72].

Alwraikat et al. successfully synthesized different pH-sensitive alginate nanoparticle models by changing the fluorophore conjugation method. All pH nanosensors exhibited negative zeta potential values due to free carboxylate groups on the nanoparticle surfaces, which supported the colloidal stability of the nanosensors. In addition, the synthesized pH nanosensor models exhibited high pH-sensitivity by showing various correlations between pH measurements and fluorescence signals of the nanosensors. In conclusion, pH-sensitive alginate nanosensors produced using organic, solvent-free, and

environmentally friendly green technology can be used as potential diagnostic tools for intracellular and extracellular pH measurements of various biological systems [23].

Omar et al. have developed a multifunctional, biodegradable, and biocompatible nanosensor platform suitable for implant use in cardiac monitoring. This polylactic acid (PLA)-based system comprises two electrochemical biosensors capable of detecting lactic acid and pH levels, a pressure sensor, and a chemisorptive array with a sensitivity of 38.85 mV/pH designed to identify volatile organic compounds. The biocompatibility of the device with myocytes was validated through *in vitro* testing. Concurrently, the biodegradability and sensing capabilities were validated through *ex vivo* experiments utilizing a three-dimensional (3D) printed heart model and cardiac tissue patches. Additionally, an artificial intelligence-based predictive model was devised to integrate sensor data, thereby improving the precision of health evaluations. In this regard, the sensor platform developed possesses the potential to advance cardiovascular patient monitoring substantially and establish a solid foundation for innovative and potentially life-saving technological developments [55].

Kang et al. presented materials, device architectures, integration strategies, and *in vivo* demonstrations in rats of an implantable device utilizing PLGA and multifunctional silicon sensors designed for the brain. These sensors employ constituent materials that naturally resorb *via* hydrolysis and/or metabolic processes, thereby eliminating the need for extraction. Continuous monitoring of intracranial pressure and temperature exemplifies functionalities essential to the treatment of traumatic brain injury; the measurement performance of these resorbable devices compares favorably with that of non-resorbable clinical standards. In our experiments, insulated percutaneous wires connect to an externally mounted, miniaturized wireless potentiostat for data transmission. In a separate setup, they connect a sensor to an implanted (but only partially resorbable) data communication system, demonstrating the principle that there is no requirement for any percutaneous wiring. The devices can be adapted to sense fluid flow, motion, pH, or thermal characteristics, in formats compatible with the body's abdomen and extremities, as well as the deep brain, thereby suggesting that the sensors may fulfill numerous needs in clinical medicine [73].

Shan et al. have developed an implantable PLA/BTO piezoelectric sensor (PBPS) characterized by high biodegradability and biocompatibility, designed for real-time evaluation of motor function recovery following nerve injury. In this system, PLA fibers with piezoelectric properties are functionalized with barium titanate (BTO) and are capable of converting biomechanical signals generated during movement into electrical signals. The PBPS can be implanted alongside commonly used tissue scaffolds in rat models of sciatic nerve injury. Concurrent with the progression of treatment, the high correlation between signals generated by the PBPS and electromyography (EMG) signals demonstrates that the device is a practical system for assessing motor function. Furthermore, the integration of a wireless module into the PBPS system has addressed temporal and spatial limitations, enabling remote and continuous monitoring of motor functions. This PBPS-based implantable sensor platform offers a novel and promising approach for advancing implantable bioelectronic systems [74].

Zheng et al. developed a biocompatible, biodegradable, and high-performance ionic capacitive fingerprint pressure sensor (FPS). As shown in Figure 1, the sensor comprises starch/PVA gel electrodes coated with conductive silver paste and fingerprint-like microstructures, utilizing an ionic liquid (IL)-doped electrospun dextran nanofiber

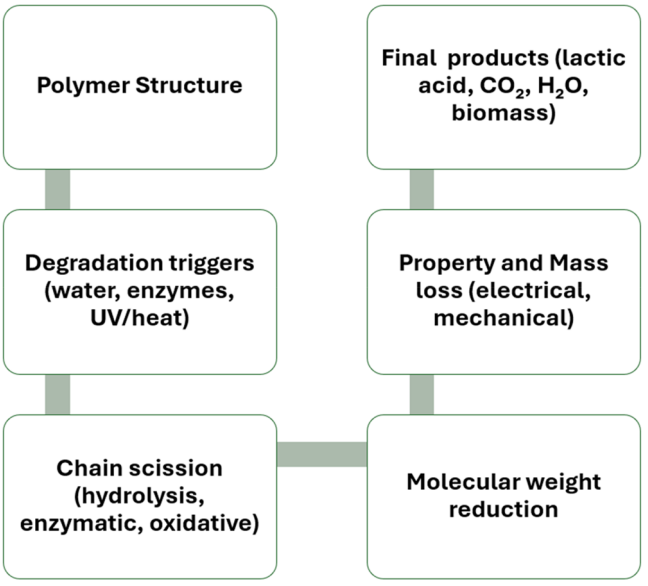


Figure 1. A schematic illustration summarizes the main degradation processes of biodegradable polymers, such as hydrolytic, enzymatic, and environmental pathways, which result in molecular weight loss, property decline, and the formation of harmless final byproducts.

membrane as the dielectric layer. Experimental data indicate that this sensor demonstrates a high sensitivity of 13.7 kPa^{-1} and excellent durability within a pressure range of 0–2 kPa. It also exhibits exceptional biocompatibility and biodegradability, with a cell viability rate of 99%. Through the integration of a convolutional neural network (CNN) algorithm and an embedded system, the sensor has been developed into a system capable of classifying the severity of Parkinson's disease (PD) and assessing rehabilitation, achieving an accuracy rate exceeding 95%. This innovative methodology holds significant potential for providing personalized treatment plans for PD patients and has broad applicability in advanced health monitoring and rehabilitation services for the elderly [75].

Wang et al. developed high-performance, flexible, and bioproteonic devices utilizing chitosan, a biopolymer derived from chitin. This advanced sensor meets all necessary criteria for monitoring human respiratory conditions and is distinguished by its non-contact sensing capability and high humidity sensitivity. The device demonstrates an ultra-high sensitivity of approximately 42.41.7% at 95% relative humidity, coupled with rapid response times and excellent cyclic stability. It is fully biodegradable at the end of its operational life, thereby minimizing potential risks to human health. Cytotoxicity assessments revealed that the device exhibits favorable biocompatibility, as indicated by the viability rates observed in human skin fibroblasts (HSAS1) and human umbilical vein endothelial cells (HUVECs). This confirms the sensor's safety for use in conjunction with human tissues [34].

Xu et al. developed a versatile, all-organic, biodegradable, and label-free impedance-based biosensor for detecting vascular endothelial growth factor (VEGF). In the construction of the sensor, conductive ink containing photoreactive silk sericin conductive polymer was patterned by photolithography. Functional electrodes were printed on flexible fibroin

substrates, whose thickness could be precisely controlled and could conform to both free-standing and soft surfaces. VEGF detection was achieved by using a VEGF-specific antibody immobilized in the conductive matrix. The obtained results showed that this flexible biosensor exhibited high sensitivity and selectivity even in complex biological fluids such as human serum. This inherently biocompatible and biodegradable device offers a simple and label-free method for practical applications such as wound healing, monitoring, and early disease diagnosis [76].

Chi et al. developed a biodegradable microfluidic device that utilizes saliva samples for on-site diagnostic applications. The device comprises sample loading and detection zones, connected by microchannels. A chitosan sponge with high absorption capacity was employed for sample collection; This sponge transferred the absorbed artificial saliva to the detection zone, facilitating its reaction with enzymes within the PEG-based hydrogel module. This enzymatic reaction enabled the colorimetric determination of glucose and creatinine. The device achieved low detection limits of 0.46 mg/dL for glucose and 0.059 mg/dL for creatinine, demonstrating its ability to distinguish between healthy individuals and patients reliably. Furthermore, quantitative measurements were facilitated through spectrophotometric analysis and smartphone-based image processing. The system distinguishes itself as a portable, cost-effective, and highly sensitive diagnostic platform due to its biodegradable structure, biocompatibility, and user-friendly design, thereby offering significant potential, particularly in healthcare applications that require rapid, simple, and label-free analysis [76].

Chao et al. developed a wearable, breathable, biodegradable, and high-sensitivity MXene/protein nanocomposite-based pressure sensor. The fabricated MXene/protein-based pressure sensor was constructed by combining a breathable conductive MXene-coated silk fibroin nanofiber membrane (MXene-SF) with a silk fibroin nanofiber membrane featuring a fingertip electrode pattern printed with MXene ink (MXene ink-SF) as the sensor and electrode layer. The integrated pressure sensor exhibits a wide sensing range (up to 39.3 kPa), high sensitivity (298.4 kPa^{-1} at 1.4–15.7 kPa; 171.9 kPa^{-1} at 15.7–39.3 kPa), rapid response and recovery times, reliable breathability, excellent cyclic stability, favorable biocompatibility, and significant biodegradability. Additionally, it has demonstrated superior sensing performance in monitoring human psychological signals, quantitatively displaying pressure distribution as an artificial skin, and facilitating real-time wireless biomonitoring applications. Given its biodegradable and breathable properties, this sensor is anticipated to have potential applications in fields such as smart electronic skin, human motion detection, disease diagnosis, and human-machine interaction [77].

Khalid et al. proposed a composite material comprising Polylactic-co-glycolic acid (PLGA) and Polycaprolactone (PCL) polymers for the development of biodegradable piezo-capacitive pressure sensors intended for low-pressure measurement. The electrospun PLGA-PCL composite membrane serves as an elastomeric dielectric layer, positioned between biodegradable iron-zinc (Fe-Zn) bilayer electrodes. These electrodes were coated onto a biodegradable polyvinyl alcohol (PVA) substrate *via* electron beam deposition and subsequently encapsulated with PLGA thin films to facilitate device fabrication. The PLGA-PCL nanofibrous dielectric membrane, characterized by high compressibility and porosity, offers adjustable mechanical and dielectric properties and is reported for the first time within the domain of biodegradable pressure sensors. The resulting sensor demonstrated markedly higher sensitivity relative to existing

biodegradable sensors documented in the literature, with a sensitivity of $0.863 \pm 0.025\,kPa^{-1}$ within the range of $0<p\leq 1.86\,kPa$. The device exhibited rapid response and recovery times. *In vitro* degradation assays conducted in PBS solution revealed a 60% reduction in the initial weight of the sensor within two weeks. After one week of incubation, a 19.5% decrease in the low-pressure detection range was observed, while no significant alterations were noted in the upper detection limit [54]. Table 4 provides a summary of studies concerning biodegradable sensors in biomedical applications.

Table 4. A summary of studies concerning biodegradable sensors in biomedical applications.

Author(s) & year	Material / technology	Application area	Key performance features	Reference
M. Boutry et al.	POMaC, PLA	Arterial blood flow pressure sensor	Wireless, minimal hysteresis, fast response, durable, *in vivo* tested	[71]
Park et al.	PCL-based polymer stent, PDLA	Blood vessel pressure and temperature monitoring	Resonance at 148 MHz, 60 kHz/mmHg sensitivity, biocompatible	[53]
H. Ouyang et al.	PLA/Chitin nanostructured film, magnesium electrode, triboelectric	Pressure sensor, vascular occlusion detection	5.95% efficiency, 11 mV/mmHg sensitivity, antibacterial properties	[72]
Alwraikat et al.	Alginate nanoparticles	Intracellular and extracellular pH measurement	Negative zeta potential, high pH sensitivity, green synthesis	[23]
Omar et al.	PLA-based nanosensor platform	Cardiac monitoring (lactate, pH, pressure)	Multifunctional, biocompatible, AI-assisted data analysis	[55]
Kang et al.	PLGA, silicon sensors	Intracranial pressure and temperature monitoring	Biodegradable by hydrolysis, wireless data transmission	[73]
Shan et al.	PLA/BTO piezoelectric fibers	Motor function recovery after nerve injury	Wireless, biocompatible, correlates with EMG signals	[74]
Zheng et al.	Starch/PVA gel electrodes, silver coating, ionic liquid-doped electrospun membrane	Fingerprint pressure sensor, Parkinson's disease monitoring	High sensitivity ($13.7\,kPa^{-1}$), 99% cell viability, >95% classification accuracy	[75]
Wang et al.	Chitosan-based sensor	Human respiratory monitoring	Ultra-high sensitivity (~42.4%), fast response, biocompatible	[34]
Xu et al.	Photoreactive silk sericin conductive ink, fibroin substrate	VEGF detection, wound healing, and early diagnosis	High sensitivity/selectivity, label-free, biocompatible, biodegradable	[76]
Chi et al.	Chitosan sponge, PEG-based hydrogel, microfluidic device	Saliva-based glucose and creatinine diagnostics	Low detection limits, portable, cost-effective, and biodegradable	[76]
Chao et al.	MXene/silk fibroin nanocomposite	Wearable pressure sensor, artificial skin	High sensitivity ($298.4\,kPa^{-1}$), breathable, biodegradable	[77]
Khalid et al.	PLGA-PCL nanofibers, Fe-Zn electrodes, PVA substrate	Low-pressure measurement sensor	Sensitivity $0.863\,kPa^{-1}$, fast response, 60% weight loss in 2 weeks	[54]

Biodegradable biosensors for environmental applications

As shown in Figure 2, Presley et al. developed biodegradable sensors containing Pd(II) benzoporphyrin through the electrospinning process. These sensors demonstrated high sensitivity with a constant (K_{SV}) of 1.25×10^5 M^{-1}, facilitating the monitoring of dissolved oxygen under physiological conditions. PCL-based single-component fibers exhibited high sensitivity characterized by monoexpansive quenching behavior, indicating a homogeneous distribution of the chromophore. This property was maintained in both PCL:gelozin and PCL:gelozin-PCL systems. Conversely, PCL: PLGA blends displayed lower sensitivity and exhibited biexponential quenching profiles. In all examined systems, a linear Stern–Volmer relationship was observed within the physiological oxygen range (Figure 3) [56].

She and Allen reported the development of a biodegradable and self-powered sensor designed to measure dissolved oxygen levels within biosystems. The operational principle of this sensor relies on the competition between the oxygen reduction reaction and the more predominant hydrogen reduction reaction. Given that the relative contribution of these two electrochemical processes varies following the environmental oxygen level, the resulting output voltage of the sensor exhibits sensitivity to the local oxygen concentration. The sensor was constructed by laminating biodegradable metals, specifically magnesium and molybdenum, onto a poly(lactic acid) (PLA)-based biodegradable substrate. An external physiological solution functions as the electrolyte within the system. In the study, the output voltage of the sensor was evaluated in relation to concentrations corresponding to typical oxygen levels observed under physiological conditions [78].

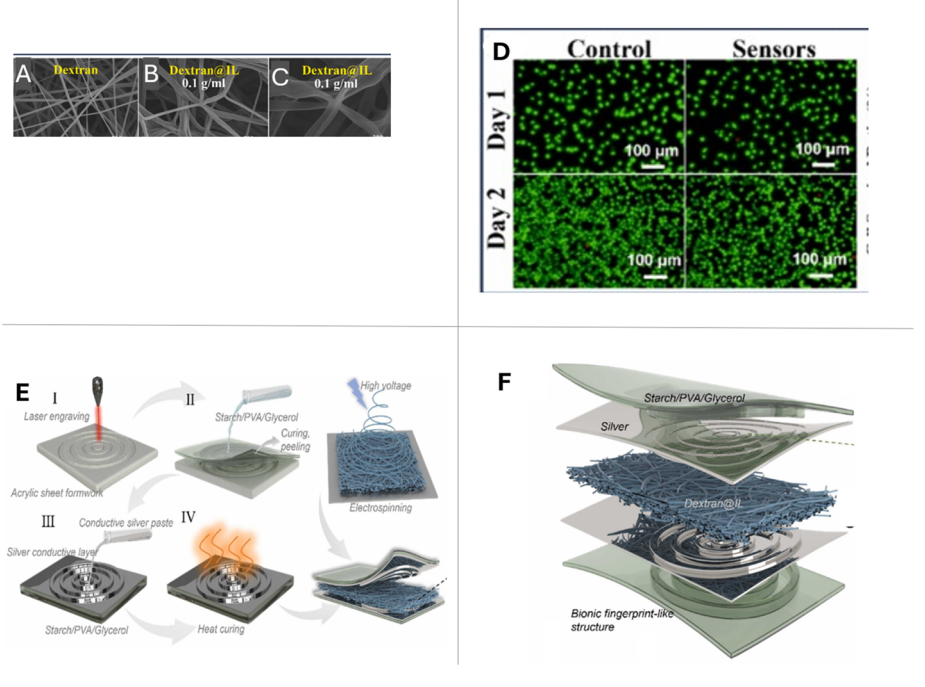


Figure 2. (A) SEM image of dextran nanofibers. (B) Low-magnification and (C) high-magnification SEM images of nanofibers. (D) Fluorescent live/dead staining image of fibroblasts (L929) cultured on the (E) Fabrication process of the FPS. (F) Schematic diagram of the FPS structure.

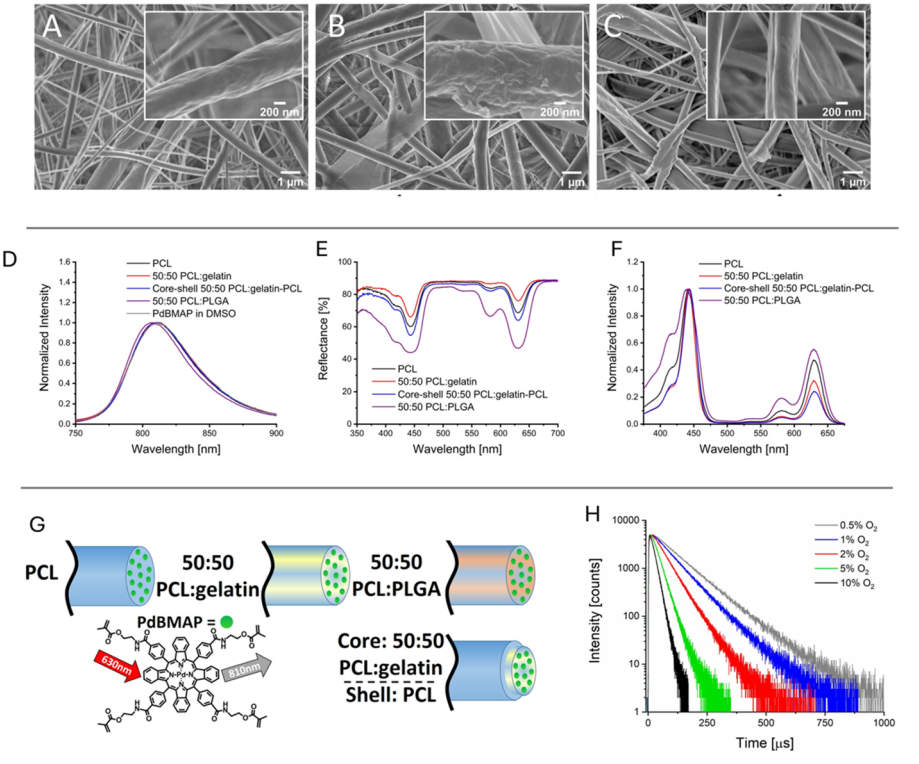


Figure 3. A) SEM images of PCL + PdBMAP electrospun fibers, B)SEM images of 50:50 PCL: gelatin + PdBMAP electrospun fibers, (C)SEM images of 50:50 PCL: PLGA + PdBMAP electrospun fibers. (D) Normalized phosphorescence emission spectra, E) UV/Vis reflectance spectra, and (F) normalized excitation scans (Emission: 810 nm) of PdBMAP-containing electrospun fiber samples in PBS. Emission spectrum of PdBMAP in DMSO included for comparison. (G) Schematic of each composition and chromophore structure. H) DO sensing behavior of PCL + PdBMAP tested in 37 °C PBS.

Gopalakrishnan et al. have developed a fully biodegradable and intelligent radio transmission sensor (DIRTS) system that enables the remote monitoring of subsoil volumetric water content. The system comprises a miniaturized resonant antenna mounted on 3D printed PLA sheets and coated with a biodegradable polymer material. The straightforward design of DIRTS enables ease of manufacturing using low-cost, biodegradable materials in compact sizes, and through scalable additive manufacturing techniques, thereby facilitating their automatic placement within the soil. Laboratory and field trials conducted for conceptual validation demonstrate that the sensors can detect soil volumetric water content within the range of 3.7% to 23.5%, with a minimum frequency sensitivity of 9.07 MHz per 1% water content. Remote sensing of DIRTS systems can be accomplished using drones from a height of 40 cm, yielding results comparable to those obtained in laboratory measurements. Systematic biodegradation studies have indicated that the sensors can operate stably with less than 4% sensitivity change over one year. DIRTS provides an innovative sensor platform that has the potential to enhance precision agriculture applications while contributing to environmental sustainability impacts [57].

C. Jiang et al. examined the triboelectric charging behavior of diverse plant proteins, including zein, soy protein isolate, rice protein, peanut protein isolate, and wheat

gluten, on PEDOT: PSS-coated PLA films. The study further described a system capable of generating electric fields and enhancing plant growth, designed for agricultural applications through a novel structural integration of polylactic acid film within biodegradable triboelectric nanogenerators derived from plant proteins. This system presents an innovative methodology that advances a sustainable recycling cycle [79].

Soomra et al. pioneered the development of the first biocompatible, rapid, linear, and wide-range humidity sensor utilizing polylactic glycolic acid (PLGA). The device was entirely fabricated employing printing methodologies. A high-resolution interdigitated electrode (IDE) structure was printed on a flexible PET substrate using silver ink through an inverse offset printing technique. In contrast, the PLGA ink was applied *via* spin coating. The IDE designs were produced in two distinct sizes, with three samples fabricated for each. The impedance, serving as the sensor's output signal, decreased in response to increasing relative humidity (%RH) within a controlled environment. The results demonstrated excellent stability and notable humidity responsiveness, with a rapid response time of 3 s and a recovery time of 6 s across the 0% to 100% RH range. The biocompatibility of the sensor's active layer was examined and confirmed through the cultivation of human small airway epithelial cells over seven days. Leveraging this biocompatibility attribute, the sensor was employed to monitor human respiration, positioning it as a robust candidate for wearable electronics and health monitoring applications [80].

Rivadeneyra et al. documented the development of transparent and biodegradable humidity sensors founded on cellulose nanofibers (CNF). Four distinct sensor variants were fabricated through the combination of CNF films with grammages of 21 g/m^2 and 10 g/m^2, utilizing silver and PEDOT: PSS pastes as conductive electrodes, and employing a screen printing technique for their production. Of these, the sensor with a grammage of 21 g/m^2 and a silver electrode demonstrated superior performance, characterized by a sensitivity of −0.10 (Ω/% RH). This sensor exhibited exponential resistance behavior across the humidity range of 20% to 85% RH at a frequency of 100 Hz. Furthermore, this sensor type emerges as a promising candidate for hybrid temperature-humidity sensing applications, given its operational capacity within a temperature range of 20 °C to 65 °C at 55% RH [81].

Luan et al. developed a dual-response pressure sensor (DRPS) employing both piezoresistive and capacitive mechanisms, utilizing biodegradable polylactic acid (PLA) nonwoven fabrics. Instead of utilizing a traditional compressible dielectric layer, the design incorporates PLA-based piezoresistive fabric (CPPF) embedded with multi-walled carbon nanotubes (MWCNTs) alongside a capacitive pressure sensor. The dual resistance-capacitance configuration of the DRPS introduces a distinctive response mechanism driven by porosity effects, thereby setting it apart from sensors that depend solely on capacitance. This configuration enhances the sensor's sensitivity across a wide pressure spectrum, enabling the measurement of pressures ranging from gentle leaf loads to substantial human steps and joint movements [82].

In the study conducted by Bibi et al. a high-performance hydrogen sulfide (H_2S) sensor operable at ambient temperature (RT) was successfully developed. Biodegradable electroactive polyurethane-urea (PUU) and PUU-activated carbon (AC) composites served as the sensing materials. These composites were fabricated through a physical mixing methodology and designated as PUU-AC0, PUU-AC1, and PUU-AC3. While the sensitivity of the PUU sensor to H_2S was measured at 0.1269 ppm^{-1}, the sensitivity of the PUU-AC1

composite was found to be 1.66 times greater than that of PUU-AC0 and 2.42 times greater than that of PUU-AC3. This enhancement is ascribed to the accelerated processes of gas diffusion, adsorption, and electron transfer, which are facilitated by the high specific surface area of 1620 m^2/g and the abundance of reactive sites present on the activated carbon [83].

Maciel et al. proposed the fabrication and optimization of a flexible electrochemical sensor incorporating low-cost, flexible, biodegradable, and easily disposable polymer poly(butylene adipate-co-terephthalate) (PBAT) and Carbon Nitride Dots (CNDs). Characterization of the sensor was conducted using Cyclic Voltammetry (CV), Electrochemical Impedance Spectroscopy (EIS), contact angle measurement, Raman spectroscopy, Fourier Transform Infrared Spectroscopy (FTIR), and Transmission Electron Microscopy (TEM). The sensor was applied for the simultaneous detection of emerging pollutants such as cadmium and copper through Square Wave Anodic Stripping Voltammetry (SWASV). The results demonstrated that cadmium and copper exhibited a linear response within the concentration range of 0.1 to 1.0 mM; for cadmium, the correlation coefficient (R^2) was 0.988 and sensitivity was 2.06×10^{-6} (mA cm^{-2} M^{-1}). For copper, R^2 was 0.975 and sensitivity was 1.38×10^{-6} (mA cm^{-2} M^{-1}). The detection limit (LD) for cadmium was 2.75×10^{-6} M, and the quantification limit (LQ) was 9.16×10^{-6} M. For copper, LD was 7.09×10^{-6} M, and LQ was 2.36×10^{-5} M. The sensors developed in this study provide advantages for the simultaneous detection of emerging pollutants like cadmium and copper in real tap water samples [58]. Table 5 provides a summary of studies concerning biodegradable sensors in environmental applications.

Challenges and limitations of biodegradable biosensors

The challenges of using biodegradable biosensors in biomedical settings

Biodegradable sensor technologies, particularly in the realms of medical implants and health monitoring, possess significant potential; however, they encounter various challenges and limitations. Primarily, the mechanical strength and long-term stability of the biodegradable polymers utilized are essential considerations that directly impact sensor performance. For example, rapid degradation of polymers within biological environments may result in diminished measurement accuracy and a reduced operational lifespan of the device [54]. Moreover, securing the stability of sensor signals amidst environmental variations and preserving high sensitivity continue to pose significant technical challenges. This complicates the continuous and reliable monitoring of vascular pressure, temperature, or biochemical parameters [74]. Regarding energy sources, the reliance on external energy for most biodegradable sensors confines their application scope. Although advancements in energy harvesting and self-powered systems have been made, the efficiency and long-term operational capacity of these technologies still need to meet the desired standards [43]. Integration issues constitute another significant limitation; the development of wireless data transmission and tissue compatibility remains an ongoing process. Although some studies have attempted to address these challenges through wired connections, further innovation is necessary to achieve fully wireless, convenient, and reliable usage [53]. Regarding biocompatibility,

Table 5. A summary of studies concerning biodegradable sensors in environmental applications.

Author(s) & year	Material / technology	Application area	Key performance features	Reference
Presley et al.	PCL: PLGA electrospinning	Dissolved oxygen monitoring under physiological conditions	High sensitivity, KSV = 1.25×10^5 M^{-1}, linear Stern–Volmer behavior	[56]
She & Allen (2020)	Mg and Mo biodegradable metals on PLA substrate	Self-powered dissolved oxygen microsensor	Voltage output sensitive to oxygen levels, biodegradable	[78]
Gopalakrishnan et al.	Miniaturized resonant antenna on 3D printed PLA sheets, biodegradable polymer coating	Remote soil moisture sensing	Detects 3.7%–23.5% soil water content, stable over 1 year with <4% sensitivity loss	[57]
C. Jiang et al.	Plant protein-based triboelectric nanogenerators on PEDOT: PSS-coated PLA films	Agricultural electric field generation for plant growth	Sustainable recycling cycle, triboelectric charging behavior	[79]
Soomra et al.	PLGA-based printed humidity sensor on flexible PET substrate	Wearable human respiration monitoring	Rapid response (3 s), recovery (6 s), wide RH range (0–100%), biocompatible	[80]
Rivadeneyra et al.	Cellulose nanofiber films with silver or PEDOT: PSS electrodes	Transparent, biodegradable humidity sensors	Sensitivity −0.10 (Ω/% RH), operates 20–85% RH and 20–65 °C	[81]
Luan et al.	PLA nonwoven fabric with MWCNTs; piezoresistive	Wide-range pressure sensing (e.g. leaf to joint load)	Enhanced sensitivity *via* porosity effects, dual sensing mechanism	[82]
Bibi et al.	Electroactive polyurethane-urea (PUU) and PUU-activated carbon composites	Hydrogen sulfide (H_2S) gas sensing at room temperature	Sensitivity enhanced by activated carbon surface area, operable at RT	[83]
Ferrerira M et al.	PBAT polymer and Carbon Nitride Dots (CNDs)	Electrochemical detection of heavy metals (Cd, Cu) in water	Low detection limits, linear response, flexible, biodegradable sensor	[58]

while short-term compatibility has been proven in most sensor studies, the risks of immunological reactions, inflammation, and tissue irritation associated with long-term implants have not been fully eliminated [55]. Additionally, most existing sensors operate within limited pressure or biomarker ranges, rendering them difficult to adapt for broad clinical applications. Extensive testing and validation processes are essential for transitioning to human clinical use, which consequently delays the widespread adoption of these technologies.

The challenges of using biodegradable biosensors in environmental applications

The fundamental challenges and limitations encountered in biodegradable sensor technologies emerge as common themes among the reviewed studies. Although high sensitivity and homogeneous chromophore distribution were achieved in Pd(II) benzoporphyrin-containing oxygen sensors developed by Presley et al. [56], low

sensitivity and bio-exponential quenching behavior observed in PCL:PLGA blends indicate that material blends can adversely affect sensor performance. In self-powered oxygen sensors developed by She et al. [78], it was noted that environmental factors, such as competition of electrochemical reactions, influence the sensor output voltage and pose difficulties in maintaining signal stability and accuracy. In the domain of humidity sensors, Rivadeneyra et al. [81]. and Soomra et al. [80]. have demonstrated that cellulose nanofiber (CNF) and PLGA-based sensors deliver high sensitivity and rapid response times; however, the variability of sensor responses, dependent on operating frequency and film thickness, limits their application flexibility. Furthermore, the long-term stability and biodegradation timelines of these sensors pose significant challenges regarding sensor lifespan and reliability in practical applications. Regarding the radio transmission sensors developed by Gopalakrishnan et al. for measuring soil water content, although the sensor performance in field applications approaches that of laboratory conditions, a sensitivity variation of up to 4% was observed during the extended biodegradation period, underscoring the need to balance biodegradability with sensor performance. While Bibi et al. [83] the standardization of sensor sensitivity. In dual-mode pressure sensors developed by Luan et al. [82], Although combining piezoresistive and capacitive measurements offers benefits across a broad pressure spectrum, integrating this dual mechanism and ensuring the mechanical robustness of the sensor involves complex design considerations. Lastly, in the realm of flexible electrochemical sensors devised by Ferreira et al. [58], while the application of cost-effective polymers and nanodots has yielded promising results, issues related to sensor selectivity against various pollutants and the complex matrix effects in ambient water samples require further mitigation.

The clinical and commercial translation of biodegradable biosensors is impeded by regulatory obstacles, including the delineation of classification pathways, thorough safety assessment of degradation products, and manufacturing consistency requirements. Although no specific harmonized guidance currently exists, established standards such as ISO 10993, ASTM F1904, FDA biocompatibility guidance, and EMA environmental risk assessment frameworks can be utilized to facilitate regulatory approval [84].

Performance maintenance in biodegradable biosensors: material, structure, and system integration

Material Selection for Controlled Degradation: Biopolymers like PLA, PLGA, and PCL allow customization of degradation based on structure and ratios. Khalid et al. developed a sensor with PLGA-PCL membranes showing high flexibility and sensitivity before degradation [54]. Shan et al. created BTO-doped PLA fibers that convert biomechanical signals into electrical signals, correlating well with EMG signals [74]. Layered Device Architectures and Encapsulation: Multilayer and biocompatible coatings protect devices from liquids and environmental effects. Ouyang et al. coated a PLA/chitin triboelectric sensor with a capsule to enhance signal reliability [72]. Zheng et al. made a fingerprint pressure sensor with ionic liquid-doped nanofibers and gel electrodes for stability and longevity [75]. Wireless and Self-Powered Systems: Wireless setups prevent connectivity issues. Boutry et al. designed a sensor for arterial blood flow using inductive coating for stable, wireless data [71]. Park et al. integrated a

wireless temperature sensor in a PCL stent, measuring pressure variations at 148 MHz with 60 kHz/mmHg sensitivity [53]. Use of Functional Nanocomposites: Nanomaterials like MXene, BTO, and MWCNTs boost strength and conductivity. Chao et al. achieved high sensitivity, stability, and breathability in an MXene/silk fiber sensor for health monitoring and human-machine interface [77]. Luan et al.'s MWCNT-PLA fabric sensor maintained operation over a broad pressure range with a dual piezoresistive-capacitive setup [82]. Functional Validation with Systematic Tests: Omar et al. tested their sensor for heart monitoring, confirming biocompatibility and degradability *in vitro* and *ex vivo*, with AI-enhanced analysis [55]. Kang et al. made sensors for intracerebral pressure and temperature, transmitting data non-invasively *via* PLGA and silicon, maintaining signal quality without degradation [73].

Comparative performance and design limitations

Comparative studies in the existing literature suggest that biodegradable and transient sensors can attain comparable sensitivity and selectivity to traditional devices throughout their designated lifespan [1,85–88]. Nonetheless, these devices generally demonstrate elevated baseline drift and limited long-term stability, which can only be addressed through specialized design strategies such as conducting nanocomposites, encapsulation, and multilayered architectures [65,86,88]. Major trade-offs encompass the lifetime-biodegradability balance, conductivity-biocompatibility considerations, environmental sensitivity, batch-to-batch variability, and the mechanical strength-degradation rate relationship. These factors underscore the importance of selecting appropriate materials and design considerations tailored to the specific application of the device.

Future perspectives and emerging trends of biodegradable biosensors

Biodegradable biosensors for biomedical applications

The future path of biodegradable sensor technologies focuses on creating fully integrated, wireless, and completely biodegradable systems. The natural dissolution of these sensors within the body, obviating the need for removal post-implantation, will enhance patient comfort and offer substantial benefits in clinical applications [55,71]. Multifunctional sensor platforms enable more comprehensive and real-time monitoring of patients' health by simultaneously measuring various parameters, including pressure, biochemical markers, and temperature [55]. The use of artificial intelligence in data analysis, as seen in Omar et al.'s study, facilitates the interpretation of large datasets collected from sensors, enabling early diagnosis and personalized treatment strategies. These advancements are particularly promising in managing neurological disorders, including Parkinson's disease [11,72,77]. In materials science, the incorporation of next-generation components such as nanocomposites, piezoelectric, and triboelectric materials enhances the sensitivity, biodegradability, and energy efficiency of sensors. Energy-autonomous sensors, which can generate their own power from environmental motion or pressure, will support the long-term and uninterrupted operation of implants. This development is especially crucial in critical applications, such as cardiac and neurological monitoring [72]. Additionally, microfluidic biosensors and

portable diagnostic devices enhance access to healthcare by offering affordable and easy-to-use solutions. Overall, the widespread use of biodegradable sensors in clinical and healthcare monitoring fields is expected to accelerate thanks to innovations in materials science, energy efficiency, wireless communication, and the integration of artificial intelligence. These advances have the potential to significantly improve patient comfort and transform personalized healthcare management.

Recent advancements in additive manufacturing, particularly high-resolution 3D printing, have considerably broadened the prospects for patient-specific and pathology-targeted biodegradable biosensors. Techniques such as direct ink writing, stereolithography, and fused deposition modeling now facilitate the creation of intricate architectures tailored to individual anatomical geometries, thereby enhancing device–tissue integration and functional performance [53]. The integration of tunable nanomaterials, such as MXenes [77], graphene derivatives, piezoelectric nanoparticles [74], and pH-responsive biocomposites [72]—further enables the modulation of sensor sensitivity, selectivity, and degradation kinetics in accordance with the pathological microenvironment. For example, 3D-printed PLA or PCL scaffolds functionalized with responsive nanocomposites have been examined for localized tumor or cardiovascular monitoring [53,55], while gradient porosity designs support controlled biodegradation rates in implantable devices. Nevertheless, several challenges impede widespread customization: (i) the high cost and limited scalability of multi-material 3D printing systems with medical-grade resolution; (ii) the necessity for standardized bioinks and printable biodegradable composites with reproducible mechanical and electrical characteristics; (iii) regulatory and biosafety validation for patient-specific devices, particularly in acute clinical contexts; and (iv) the integration of wireless communication and power systems without compromising biodegradability [53,55,77]. Overcoming these obstacles will be essential for transitioning from proof-of-concept devices to broadly accessible, customized biodegradable biosensor platforms.

Biodegradable biosensors for environmental applications

The future directions of biodegradable sensor technology are indeed promising. As Presley et al. [56] emphasize, various polymer blends significantly influence sensor performance; therefore, researchers will continue to investigate methods to develop more sensitive, durable sensors composed of more uniform biodegradable materials. The advent of self-powered sensors, introduced by She and Allen [54], signifies a move towards fully autonomous systems that do not rely on external energy sources. Another noteworthy trend is the advancement of multifunctional and hybrid sensors, exemplified by the dual-mode pressure sensors developed by Luan et al. [82], which integrates multiple sensing mechanisms to enhance accuracy and coverage, particularly in fields such as medicine, environmental monitoring, and agriculture. Printing and additive manufacturing techniques, as explored by Rivadeneyra et al. [81] and Soomra et al. [80], are making sensor production more cost-effective and versatile, thereby making them suitable for large-scale manufacturing and diverse applications. In environmental and health domains, biodegradable soil moisture sensors, as developed by Gopalakrishnan et al. [57], and pollutant detectors by Maciel et al. [58] are proving invaluable for sustainable farming practices and water quality assessment. These sensors are contributing to the broader adoption and reliability

of smart agriculture and environmental health monitoring. Furthermore, the use of nanomaterials, such as activated carbon and polyurethane-urea composites, as discussed by Bibi et al. [83], enhances sensor reactivity, making them more selective, faster, and durable. On the health side, biocompatible sensors developed by Soomra et al. [80] are advancing wearable health technologies, with a growing focus on developing comfortable and long-lasting sensors that utilize cutting-edge biomaterials. The prospects for biodegradable sensors are indeed bright, with considerable potential to improve various aspects of daily life and environmental stewardship.

Conclusion

Biodegradable biosensors have emerged as a crucial innovation for addressing the dual requirements of technological efficacy and environmental sustainability. Their applications in both medical and environmental spheres have demonstrated significant potential, particularly in short-term implants, non-invasive diagnostics, pollutant detection, and precision agriculture. Despite challenges such as limited mechanical durability, control over degradation rates, and data transmission issues, the field is advancing rapidly through progress in material science and interdisciplinary integration. As research efforts continue to surmount these limitations, biodegradable biosensors are expected to become indispensable tools for real-time, sustainable, and patient-centered monitoring systems. The integration of biodegradable materials with wireless systems, artificial intelligence analysis, and energy-harvesting techniques is anticipated to define the next generation of biosensor technology.

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References

[1] Hosseini ES, Dervin S, Ganguly P, et al. Biodegradable materials for sustainable health monitoring devices. ACS Appl Bio Mater. 2021;4(1):163–194. doi:10.1021/acsabm.0c01139.

[2] Alam F, Ashfaq Ahmed M, Jalal AH, et al. Recent progress and challenges of implantable biodegradable biosensors. Micromachines. 2024;15(4):475. doi:10.3390/mi15040475.

[3] Prabowo BA, Purwidyantri A. Environmentally friendly and biodegradable components for biosensors. IEEE Nanotechnology Mag. 2022;16(5):13–19. doi:10.1109/MNANO.2022.3195107.
[4] Rinaudo M. Chitin and chitosan: properties and applications. Prog Polym Sci. 2006;31(7):603–632. doi:10.1016/j.progpolymsci.2006.06.001.
[5] Nath N, Chakroborty S, Vishwakarma DP, et al. Recent advances in sustainable nature-based functional materials for biomedical sensor technologies. Environ Sci Pollut Res Int. 2024;31(46):57289–57313. doi:10.1007/s11356-023-26135-w.
[6] Chauhan S, Thakur A. Chitosan-based biosensors – a comprehensive review. Mater Today Proc. 2023. doi:10.1016/j.matpr.2023.01.123.
[7] Chang M, Song T, Liu X, et al. Cellulose-based biosensor for bio-molecules detection in medical diagnosis: a mini-review. Curr Med Chem. 2020;27(28):4593–4612. doi:10.2174/0929867327666200221145543.
[8] Baharifar H, Honarvarfard E, Malek-Kheili MH, et al. The potentials and applications of cellulose acetate in biosensor technology. Nanomed Res J. 2017;2:216–223. doi:10.22034/NMRJ.2017.04.002.
[9] Kamel S, A, Khattab T. Recent advances in cellulose-based biosensors for medical diagnosis. Biosensors. 2020;10(6):67. doi:10.3390/bios10060067.
[10] Meng G, Long F, Zeng Z, et al. Silk fibroin based wearable electrochemical sensors with biomimetic enzyme-like activity constructed for durable and on-site health monitoring. Biosens Bioelectron. 2023;228:115198. doi:10.1016/j.bios.2023.115198.
[11] Zheng H, Zuo B. Functional silk fibroin hydrogels: preparation, properties and applications. J Mater Chem B. 2021;9(5):1238–1258. doi:10.1039/D0TB02099K.
[12] Cao Y, Wang B. Biodegradation of silk biomaterials. Int J Mol Sci. 2009;10(4):1514–1524. doi:10.3390/ijms10041514.
[13] Xu M, Jiang Y, Pradhan S, et al. Use of silk proteins to form organic, flexible, degradable biosensors for metabolite monitoring. Front Mater. 2019;6:331. doi:10.3389/fmats.2019.00331.
[14] Vigués N, Pujol-Vila F, Marquez-Maqueda A, et al. Electro-addressable conductive alginate hydrogel for bacterial trapping and general toxicity determination. Anal Chim Acta. 2018;1036:115–120. doi:10.1016/j.aca.2018.06.062.
[15] Alaswad SO, Mahmoud AS, Arunachalam P. Recent advances in biodegradable polymers and their biological applications: a brief review. Polymers. 2022;14(22):4924. doi:10.3390/polym14224924.
[16] Tom D. Biodegradable polymers: a sustainable approach towards environmental conservation. 2023; 7(5): 1000171. doi:10.4172/bsh.1000171.
[17] Wei XW, Guo G, Gong CY, et al. Biodegradable polymers: research and applications. In Sharma SK, Mudhoo A, editors. A Handbook of Applied Biopolymer Technology: synthesis, Degradation and Applications. Cambridge, UK: The Royal Society of Chemistry; 2011. doi:10.1039/BK9781849731515-00365.
[18] Fu Y, Zhao S, Zhang B, et al. Multifunctional cross-sensitive magnetic alginate-chitosan-polyethylene oxide nanofiber sensor for human-machine interaction. Int J Biol Macromol. 2024;264(Pt 1):130482. doi:10.1016/j.ijbiomac.2024.130482.
[19] Bocchetta P, Othman A, Gupta M, et al. Chitosan in electrochemical (bio)sensors: nanostructuring and methods of synthesis. Eur Polym J. 2024;213:113092. doi:10.1016/j.eurpolymj.2024.113092.
[20] Wathoni N, Suhandi C, Ghassani Purnama MF, et al. Alginate and Chitosan-based hydrogel enhance antibacterial agent activity on topical application. Infect Drug Resist. 2024;17:791–805. doi:10.2147/IDR.S456403.
[21] Singh A, Verma N, Kumar K. Fabrication of chitosan alginate nanoparticle based fibre optic biosensor. Int J Pharm Sci Res. 2021;12:559. doi:10.13040/IJPSR.0975-8232.12(1).559-68.
[22] Nowacki K, Galiński M, Stępniak I. Synthesis and characterization of chitosan/sodium alginate blend membrane for application in an electrochemical capacitor. PCACD. 2020;XXV:174–191. doi:10.15259/PCACD.25.014.
[23] Alwraikat A, Jaradat A, Marji SM, et al. Development of a Novel, ecologically friendly generation of pH-responsive alginate nanosensors: synthesis, calibration, and characterisation. Sensors. 2023;23(20):8453. doi:10.3390/s23208453.

[24] Wang L, Zhu K, Cao W, et al. ROS-triggered degradation of selenide-containing polymers based on selenoxide elimination. Polym Chem. 2019;10(16):2039–2046. doi:10.1039/C9PY00171A.
[25] Rumi SS, Liyanage S, Abidi N. Soil burial-induced degradation of cellulose films in a moisture-controlled environment. Sci Rep. 2024;14(1):36. doi:10.1038/s41598-024-57436-w.
[26] Lu Q, Zhang B, Li M, et al. Degradation mechanism and control of silk fibroin. Biomacromolecules. 2011;12(4):1080–1086. doi:10.1021/bm101422j.
[27] Barceló X, Eichholz KF, Garcia O, et al. Tuning the degradation rate of alginate-based bioinks for bioprinting functional cartilage tissue. Biomedicines. 2022;10(7):1621. doi:10.3390/biomedicines10071621.
[28] Nagasawa N, Mitomo H, Yoshii F, et al. Radiation-induced degradation of sodium alginate. Polym Degrad Stab. 2000;69(3):279–285. doi:10.1016/S0141-3910(00)00070-7.
[29] Ishihara H, Obata T, Sulpice R, et al. Quantifying protein synthesis and degradation in arabidopsis by dynamic $^{13}CO_2$ labeling and analysis of enrichment in individual amino acids in their free pools and in protein. Plant Physiol. 2015;168(1):74–93. doi:10.1104/pp.15.00209.
[30] Evci Ş, Karsli M. Evaluating nutrient degradation and degradation kinetics of some starch-rich cereal and legume grains in sheep consuming a starch-rich diet. Cent Eur Agrijc. 2025;26(1):45–55. doi:10.5513/JCEA01/26.1.4295.
[31] Samir A, Ashour FH, Hakim AAA, et al. Recent advances in biodegradable polymers for sustainable applications. Npj Mater Degrad. 2022;6(1):68. doi:10.1038/s41529-022-00277-7.
[32] Salazar M. d R, Solanilla Duque JF, Saenz-Galindo A, et al. Biodegradable Polymers. Boca Raton: CRC Press; 2023. doi:10.1201/9781003230533.
[33] Zhang YZ, Venugopal J, Huang Z-M, et al. Crosslinking of the electrospun gelatin nanofibers. Polymer. 2006;47(8):2911–2917. doi:10.1016/j.polymer.2006.02.046.
[34] Wang L, Lou Z, Wang K, et al. Biocompatible and biodegradable functional polysaccharides for flexible humidity sensors. Research. 2020;2020:8716847. doi:10.34133/2020/8716847.
[35] Liu X, Wang S, Liu Y, et al. Synthesis of Poly(ether carbonate)-Based Polyurethane for Biodegradable–Recyclable Pressure Sensors. ACS Sustainable Chem Eng. 2023;11(10):4258–4268. doi:10.1021/acssuschemeng.2c07516.
[36] Kim JS, Kim J, Lee SM, et al. Development of guar gum-based dual-layer wound dressing containing Lactobacillus plantarum: rapid recovery and mechanically flexibility. Int J Biol Macromol. 2022;221:1572–1579. doi:10.1016/j.ijbiomac.2022.09.049.
[37] Lee CH, Singla A, Lee Y. Biomedical applications of collagen. Int J Pharm. 2001;221(1-2):1–22. doi:10.1016/S0378-5173(01)00691-3.
[38] Lee KY, Mooney DJ. Alginate: properties and biomedical applications. Prog Polym Sci. 2012;37(1):106–126. doi:10.1016/j.progpolymsci.2011.06.003.
[39] Lee Y, Yim S-G, Lee GW, et al. Self-adherent biodegradable gelatin-based hydrogel electrodes for electrocardiography monitoring. Sensors. 2020;20(20):5737. doi:10.3390/s20205737.
[40] Kim G, Gavande V, Shaikh V, et al. Degradation behavior of Poly(Lactide-Co-Glycolide) monolayers investigated by langmuir technique: accelerating effect. Molecules. 2023;28(12):4810. doi:10.3390/molecules28124810.
[41] Lyu S, Untereker D. Degradability of polymers for implantable biomedical devices. Int J Mol Sci. 2009;10(9):4033–4065. doi:10.3390/ijms10094033.
[42] Silva RRA, Marques CS, Arruda TR, et al. Biodegradation of polymers: stages, measurement, standards and prospects. Macromol. 2023;3(2):371–399. doi:10.3390/macromol3020023.
[43] Gohil SV, Padmanabhan A, Kan H-M, et al. Degradation-dependent protein release from enzyme sensitive injectable glycol chitosan hydrogel. Tissue Eng Part A. 2021;27(13-14):867–880. doi:10.1089/ten.tea.2020.0124.
[44] Tsuji H, Hayashi T. Hydrolytic degradation and crystallization behavior of linear 2-armed and star-shaped 4-armed poly (<scp>l</scp> -lactide)s: effects of branching architecture and crystallinity. J Appl Polym Sci. 2015;132:983. doi:10.1002/app.41983.
[45] Li X, Cui J, Liu Y, et al. The effect of molecular weight on the physical properties and *In Vitro* enzymatic degradation behavior of poly (ε -caprolactone). Sci Adv Mater. 2019;11(10):1369–1375. doi:10.1166/sam.2019.3419.

[46] Zhang X, Yin Z, Xiang S, et al. Degradation of polymer materials in the environment and its impact on the health of experimental animals: a review. Polymers. 2024;16(19):2807. doi:10.3390/polym16192807.
[47] Sreejith S, Leo Joseph LMI, Kollem S, et al. Biodegradable sensors: a comprehensive review. Measurement. 2023;219:113261. doi:10.1016/j.measurement.2023.113261.
[48] Dutta A, Cheng H. Pathway of transient electronics towards connected biomedical applications. Nanoscale. 2023;15(9):4236–4249. doi:10.1039/D2NR06068J.
[49] Shin Y-K, Shin Y, Lee JW, et al. Micro-/Nano-structured biodegradable pressure sensors for biomedical applications. Biosensors. 2022;12(11):52. doi:10.3390/bios12110952.
[50] Sun P, Li C, Yang C, et al. A biodegradable and flexible neural interface for transdermal optoelectronic modulation and regeneration of peripheral nerves. Nat Commun. 2024;15(1):4721. doi:10.1038/s41467-024-49166-4.
[51] Liu B, Libanori A, Zhou Y, et al. Simultaneous biomechanical and biochemical monitoring for self-powered breath analysis. ACS Appl Mater Interfaces. 2022;14(5):7301–7310. doi:10.1021/acsami.1c22457.
[52] Simoska O, Duay J, Stevenson KJ. Electrochemical detection of multianalyte biomarkers in wound healing efficacy. ACS Sens. 2020;5(11):3547–3557. doi:10.1021/acssensors.0c01697.
[53] Park J, Kim J-K, Park SA, et al. Biodegradable polymer material based smart stent: wireless pressure sensor and 3D printed stent. Microelectron Eng. 2019;206:1–5. doi:10.1016/j.mee.2018.12.007.
[54] Khalid MAU, Ali M, Soomro AM, et al. A highly sensitive biodegradable pressure sensor based on nanofibrous dielectric. Sens Actuators A Phys. 2019;294:140–147. doi:10.1016/j.sna.2019.05.021.
[55] Omar R, Saliba W, Khatib M, et al. Biodegradable, biocompatible, and implantable multifunctional sensing platform for cardiac monitoring. ACS Sens. 2024;9(1):126–138. doi:10.1021/acssensors.3c01755.
[56] Presley KF, Reinsch BM, Cybyk DB, et al. Oxygen sensing performance of biodegradable electrospun nanofibers: influence of fiber composition and core-shell geometry. Sens Actuators B Chem. 2021;329:129191. doi:10.1016/j.snb.2020.129191.
[57] Gopalakrishnan S, Waimin J, Zareei A, et al. A biodegradable chipless sensor for wireless subsoil health monitoring. Sci Rep. 2022;12(1):8011. doi:10.1038/s41598-022-12162-z.
[58] Ferreira M, Maciel CC, Barros A, et al. Development of a miniaturized photoelectrochemical sensor based on biodegradable polymer Pbat and Carbon Nitrite Dots (Cnds) for the detection of emerging pollutants in water supply samples. 2023. doi:10.2139/ssrn.4354739.
[59] Lim C-J, Lee S, Kim J-H, et al. Wearable, luminescent oxygen sensor for transcutaneous oxygen monitoring. ACS Appl Mater Interfaces. 2018;10(48):41026–41034. doi:10.1021/acsami.8b13276.
[60] Costanzo I, Sen D, Adegite J, et al. A noninvasive miniaturized transcutaneous oxygen monitor. IEEE Trans Biomed Circuits Syst. 2021;15(3):474–485. doi:10.1109/TBCAS.2021.3094931.
[61] Helim R, Zazoua A, Korri-Youssoufi H. Sustainable biopolymer-based electrochemical sensors for trace heavy metal determination in water: a comprehensive review. Chemosensors. 2024;12(12):267. doi:10.3390/chemosensors12120267.
[62] Calzoni E, Cesaretti A, Polchi A, et al. Biocompatible polymer nanoparticles for drug delivery applications in cancer and neurodegenerative disorder therapies. J Funct Biomater. 2019;10(1):4. doi:10.3390/jfb10010004.
[63] Makadia HK, Siegel SJ. Poly Lactic-co-Glycolic Acid (PLGA) as biodegradable controlled drug delivery carrier. Polymers. 2011;3(3):1377–1397. doi:10.3390/polym3031377.
[64] Çiftçi F, Özarslan AC. Preparation of PLGA-PEG/Hydroxyapatite composites via simple methodology of film formation and assessment of their structural, thermal, and biological features. J Turkish Chem Soc, Section A: Chem. 2023;10(4):1123–1132. doi:10.18596/jotcsa.1313562.
[65] Karamzadeh V, Shen ML, Ravanbakhsh H, et al. High-resolution additive manufacturing of a biodegradable elastomer with a low-cost LCD 3D Printer. Advanced Healthcare Materials 2023;13(9):2303708. 10.1002/adhm.202303708

[66] Turner BL, Twiddy J, Wilkins MD, et al. Biodegradable elastomeric circuit boards from citric acid-based polyesters. Npj Flex Electron. 2023;7(1):58. doi:10.1038/s41528-023-00258-z.
[67] Demirel Üniversitesi S, Mühendisliği Bölümü G, Geliş T. Biyobazlı nanokompozitler ve gıda ambalajlamadaki uygulamaları. Gida. 2017;47:821–833. doi:10.15237/gida.GD17084.
[68] Üner İ, Dilara E. Poli(laktik asit)'in kullanim alanlari ve nano lif üretimdeki uygulamalari. n.d.
[69] Andorko JI, Hess KL, Pineault KG, et al. Intrinsic immunogenicity of rapidly-degradable polymers evolves during degradation. Acta Biomater. 2016;32:24–34. doi:10.1016/j.actbio.2015.12.026.
[70] Piao Z, Agyei Boakye AA, Yao Y. Environmental impacts of biodegradable microplastics. Nat Chem Eng. 2024;1(10):661–669. doi:10.1038/s44286-024-00127-0.
[71] Boutry CM, Beker L, Kaizawa Y, et al. Biodegradable and flexible arterial-pulse sensor for the wireless monitoring of blood flow. Nat Biomed Eng. 2019;3(1):47–57. doi:10.1038/s41551-018-0336-5.
[72] Ouyang H, Li Z, Gu M, et al. A bioresorbable dynamic pressure sensor for cardiovascular postoperative care. Adv Mater. 2021;33(39):e2102302. doi:10.1002/adma.202102302.
[73] Kang S-K, Murphy RKJ, Hwang S-W, et al. Bioresorbable silicon electronic sensors for the brain. Nature. 2016;530(7588):71–76. doi:10.1038/nature16492.
[74] Shan Y, Wang E, Cui X, et al. A biodegradable piezoelectric sensor for real-time evaluation of the motor function recovery after nerve injury. Adv Funct Materials. 2024;34(33):295. doi:10.1002/adfm.202400295.
[75] Zheng X, Li Y, Zhou Q, et al. Biocompatible, biodegradable, and high-performance flexible pressure sensors for severity grading and rehabilitation assessment in Parkinson's disease management. Nano Energy. 2025;140:111030. doi:10.1016/j.nanoen.2025.111030.
[76] Xu M, Yadavalli VK. Flexible biosensors for the impedimetric detection of protein targets using silk-conductive polymer biocomposites. ACS Sens. 2019;4(4):1040–1047. doi:10.1021/acssensors.9b00230.
[77] Chao M, He L, Gong M, et al. Breathable $Ti_3C_2T_x$ MXene/protein nanocomposites for ultrasensitive medical pressure sensor with degradability in solvents. ACS Nano. 2021;15(6):9746–9758. doi:10.1021/acsnano.1c00472.
[78] She D, Allen MG. A self-powered, biodegradable dissolved oxygen microsensor. J Microelectromech Syst. 2020;29(5):1074–1078. doi:10.1109/JMEMS.2020.3013208.
[79] Jiang C, Zhang Q, He C, et al. Plant-protein-enabled biodegradable triboelectric nanogenerator for sustainable agriculture. Fundam Res. 2022;2(6):974–984. doi:10.1016/j.fmre.2021.09.010.
[80] Soomro AM, Jabbar F, Ali M, et al. All-range flexible and biocompatible humidity sensor based on poly lactic glycolic acid (PLGA) and its application in human breathing for wearable health monitoring. J Mater Sci: Mater Electron. 2019;30(10):9455–9465. doi:10.1007/s10854-019-01277-1.
[81] Rivadeneyra A, Marín-Sánchez A, Wicklein B, et al. Cellulose nanofibers as substrate for flexible and biodegradable moisture sensors. Compos Sci Technol. 2021;208:108738. doi:10.1016/j.compscitech.2021.108738.
[82] Luan X, Zhu Y, Chen Y, et al. Biodegradable pressure sensors with high sensitivity and wide detection range *via* a piezoresistive/capacitive dual response. Polym Chem. 2024;15(48):4972–4981. doi:10.1039/D4PY00675E.
[83] Bibi A, Santiago K, Yeh J-M, et al. Valorization of agricultural waste as a chemiresistor H2S-gas sensor: a composite of biodegradable-electroactive polyurethane-urea and activated-carbon composite derived from coconut-shell waste. Polymers. 2023;15(3):685. doi:10.3390/polym15030685.
[84] Williams A, Aguilar MR, Pattiya Arachchillage KGG, et al. Biosensors for public health and environmental monitoring: the case for sustainable biosensing. ACS Sustain Chem Eng. 2024;12(28):10296–10312. doi:10.1021/acssuschemeng.3c06112.

[85] Guo D, Li Y, Zhou Q, et al. Degradable, biocompatible, and flexible capacitive pressure sensor for intelligent gait recognition and rehabilitation training. Nano Energy. 2024;127:109750. doi:10.1016/j.nanoen.2024.109750.
[86] Janićijević Ž, Huang T, Bojórquez DIS, et al. Design and development of transient sensing devices for healthcare applications. Adv Sci. 2024;11(20):e2307232. doi:10.1002/advs.202307232.
[87] Wawrzynek E, Baumbauer C, Arias AC. Characterization and comparison of biodegradable printed capacitive humidity sensors. Sensors. 2021;21(19):6557. doi:10.3390/s21196557.
[88] Han WB, Lee JH, Shin J, et al. Advanced materials and systems for biodegradable, transient electronics. Adv Mater. 2020;32(51):e2002211. doi:10.1002/adma.202002211.