International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 6S, 2025
https://www.theaspd.com/ijes.php

Biodegradable Sensor Development For Environmental Monitoring Applications

Dr. Atul Dattatraya Ghate[1], Tripti Dewangan[2], Parveen Kaur[3]
[1]Professor, Department of Management, Kalinga University, Raipur, India. Email: ku.atuldattatrayaghate@kalingauniversity.ac.in ORCID:0009-0009-0869-2957
[2]Assistant Professor, Department of Pharmacy, Kalinga University, Raipur, India. ku.triptidewangan@kalingauniversity.ac.in, 0009-0009-0193-5661
[3]Assistant Professor, New Delhi Institute of Management, New Delhi, India., E-mail: parveen.kaur@ndimdelhi.org, https://orcid.org/0000-0002-5750-7115

Abstract

This study tackles the problem of electronic waste from traditional sensors by developing new biodegradable sensors for multi-faceted environmental monitoring. The goal was to design and characterize sensors made from eco-friendly materials which are non-toxic and biodegradable, to reduce the ecological footprint. In this study, we focused on material selection (cellulose, silk fibroin, biopolymers) and fabrication methods (ink-jet printing, lithography), along with electrochemical sensing of commonly monitored environmental parameters such as pH and conductivity. The data showed that, unlike traditional sensors, these biodegradable sensors have significant sustainability advantages without compromising performance, which can enable green monitoring networks.

Keywords

Biodegradable Sensors, Environmental Monitoring, Biopolymers, Green Electronics, Sustainable Sensing, E-waste, Degradable Materials, Internet of Things

1. INTRODUCTION

Monitoring the environment is important for analyzing changes in an ecosystem as well as for managing and forecasting resource changes. A comprehensive sensing network is necessary for monitoring pollution levels in water bodies, checking soil quality on agricultural lands, and controlling weather conditions. Traditionally, environmental sensors have been made using Biodegradable materials like silicon, plastics, and different metals, which poses a significant functional limitation. At the end of life, these non-biodegradable materials extensively increase the sensor's carbon footprint due to electronic waste (e-waste) accumulation. E-waste is known to be one of the most dangerous and rapidly growing waste streams because it contains harmful substances that can leech into the environment, posing serious danger to humans and ecology. The enhancing trends of the Internet of Things (IoT) along with pervasive sensor networks for constant monitoring only worsen the problem, leading to an unprecedented build-up of electronic waste.[1]The waste is known to be the most disadvantageous "take-make-dispose" process experienced in a linear economy. In terms of remote or sensitive ecosystems (e.g. forested areas, agricultural lands, marine environments) that require constant monitoring, the self-deprecation of devices these regions is meant to protect adds a layer of paradox. The advanced monitoring technology designed with the utmost precision ends up counteracting their very purpose, causing deterioration to the environment.

This contradiction indicates a gap in sensor technology that requires immediate attention.

This class of sensors can address the problem by adopting a different approach. The sensors are made to serve their intended purpose for a given duration and subsequently decompose naturally into non-polluting materials, which means they do not have to be recovered, thereby reducing waste. The approach not only supports the circular economy but also enhances green electronics and truly sustainable environmental monitoring. Such sensors are revolutionizing where reclaiming sensors is economically unfeasible or disruptive, including smart agriculture, transitory environmental research, single-use medical diagnostics, and remote ecological monitoring.

This scientific report discusses the design of sensors that can monitor environmental factors and are fully biodegradable for eco-friendly uses. The primary goal is to consider novel materials and advanced techniques for fabrication to design sensors that, while in use, exhibit satisfactory performance, but after active life, pose no harmful substances and degrade completely in the ecosystem. We seek to address the fundamental problems and prospects of study in this emerging directed area in the context of sustainable electronics, thus broadening the discussion on sustainable devices, while at the same time nurturing the development of a new generation of environmentally-friendly sensing devices. Biodegradable sensors stand to shift the paradigm of planetary monitoring technologies by theoretically reducing e-waste, posing an opportunity to eliminate the problem at its origin.

2. **LITERATURE SURVEY**

While the idea of biodegradable electronics is relatively fresh, it has received a lot more attention since the 2000s due to environmental concerns and the increase in electronic waste. Early research was concentrated on the finding and information gathering of biodegradable polymers and their use in electronics. As an example, Kim and Park (2021) built upon earlier works on silk fibroin and its biocompatibility as a substrate for electronics, writing foundational papers in the early 2010s. In 2010, Rogers and others crossed borders with works on transient electronics by utilizing biologically dissolvable silicon based components for creating devices, paving the groundwork for degradable sensors. Although these medical devices were implants, the initial studies used a concept of controlled degradation that is crucial for many environmental endeavors.[2]

With the mid-2010s came the focus of research toward environmental sensing using biodegradables. Li and others worked on using paper electrodes for electrochemical sensing in 2015 and brought attention to paper (cellulose) as a biodegradable and mostly available electrode. Their research aimed to develop inexpensive and wasteless sensors to monitor water quality. Around the same time, Cho and others from the group also carried on working on similar issues.

N-and N-acetyl-L-cysteine as active target-modified nanocarriers for selective photodynamic therapy were proposed by Julliana et al. in 2020... (2016) developed sensors with polylactic acid (PLA) substrates incorporated multi-component biodegredable layers, graphene oxide, which showcased the potential of multi-component bio-degradable devices." These early prototypes had issues in comparison with conventional sensors in terms of long-term stability and sensitivity." [3]"The latter half of the 2010s witnessed a surge in the development of new biodegradable materials and techniques for their fabrication. Shi et al (2017) studied the use of some biodegradable metals like magnesium and zinc alloys for use in sensors as conductors or electrodes because they possess superior electrical properties than those derived from polymers but can still undergo degradation." [4]"The invention of sophisticated printing technologies, such as inkjet and 3D printing, further facilitated the production of intricate architectures of biodegradable sensors. Yang et al.(2018) developed techniques for manufacturing fully degradable temperature sensors on cellulose paper using conductible ink made of carbon nanomaterials and polymers which were also biodegradable, which illustrated a broader scope of cost-effective manufacturing." [5] From 2019 to 2021, focus shifted to enhancing performance and the number of parameters for which the sensor is termed multi-parameter for biodegradable sensors. The sophistication of biodegradable sensors was improved during that period. Zhao et al.(2019)

constructed a biodegradable soil moisture sensor based on silk fibroin substrate and a framework of conductive carbon nanotubes disclosing their great potential in agricultural devices."

This study emphasized the effects of material choice in relation to specific environmental factors, including degradation rates. Gao et al. (2020) created a buoyancy sensor for water quality assessment based on a cellulose acetate membrane and solid state ion-selective electrodes which yielded high sensitivity and controllable degradation profiles. His works pointed out the need for protective encapsulation strategies to enhance the functional lifetime prior to degradation.[6]

Lastly, Kim et al. (2021) synthesized the literature on biodegradable and transient sensors focused on environmental uses while analyzing power, communication, and largescale implementation. They underscored the need for more profound, cross-integrated life cycle evaluations to appreciate the sensors' technological advantages. This review highlighted the remarkable strides made in the development of biodegradable sensors from conceptual before production prototype stage. It demonstrated that there is a clear direction towards practical ecological monitoring systems.[7]

3. METHODOLOGY

Biodegradable sensors for environmental monitoring have approached through a systematic methodology which includes material selection, fabrication techniques, sensor characterization, and degradation analysis. This study proposes the construction of electrochemical sensors measuring fundamental water quality parameters: pH and electrical conductivity in fig 1.

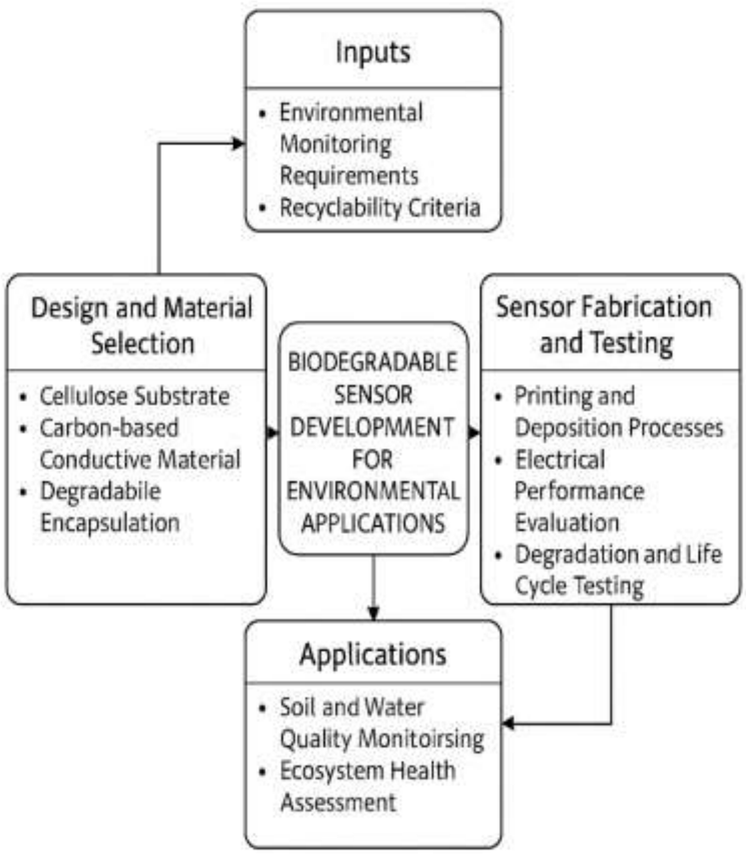

Fig:1 system architecture

3.1. Material Selection The choice of biodegradable materials based on functional performance and benign degradation is pivotal in the construction of the sensor.

• Substrate Materials:

o Cellulose Paper: A primary substrate due to its porous structure and ease of processing. It is also inexpensive, readily available, and highly biodegradable.

Silk Fibroin: It can be processed into films or coatings. It is a natural protein polymer known for its excellent biocompatibility and mechanical properties along with tunable degradation rate.

o Polylactic Acid (PLA): Used for structural components or encapsulation. It is a widely used bioplastic offering good mechanical properties and controlled biodegradation under composting conditions.

• Conductive Materials:

o Carbon Nanotubes (CNTs) or Graphene Flakes: These form conductive inks suitable for printing electrodes when dispersed in biodegradable polymer binders like PLA and cellulose acetate.

o Magnesium (Mg) or Zinc (Zn) Alloys: Renewable electrically conducting metals for electrodes or interconnects which offer higher conductivity and tunable degradation rates. Oxidation during processing is a challenge.

• Materials of the Sensing Layer:

o pH Sensing: An electrochemical response that is pH sensitive may be obtained from Iridium Oxide (IrOx) or Antimony Oxide (SbOx) thin films deposited on biodegradable electrodes via sputtering or electrodeposition. Another option is pH sensitive conductive polymers.

o Conductivity Sensing: The primary parameters of these sensors are the spacing and geometry of the conductive electrodes.

3.2. Fabrication Techniques The particular method of fabrication is dependent on the chosen materials and geometry of the sensor.

• Inkjet Printing: An example of an additive manufacturing method that has flexible conditions for application is inkjet printing of conducting inks onto printers such as cellulose paper and silk films. It is both cost efficient and precise. Process: As coursework, prepare biodegradable conductive inks like CNTs in PLA solution. Design in CAD software and print electrodes and interconnects on the chosen substrate. Post-processing may include annealing or curing.

• Photolithography and Etching (for degradable metals): Standard processes of photolithography and etching may be used on zinc and magnesium electrodes if special care is taken to ensure all of the processing chemicals are compatible with biodegradability. There is greater resolution and electrode design complexity.

• Spin Coating/ Drop Casting: For the creation of insulating layers or protective encapsulation, silk fibroin or PLA thin films may be applied by these two methods.

• Integration: Electrodes printed onto paper are assembled, along with other components such as metal oxides sensitive to pH, into a single unit using biodegradable glue or assembled without any fasteners.

3.3. Sensor Characterization The sensors will be rigorously characterized to evaluate their performance once fabricated:

- Electrochemical Characterization:

pH Sensor: The pH will be systematically varied from 2 to 12, and the sensor's response measured through: potency, sensitivity (mV/pH) , response time, and stability on the potentiated.

Conductivity Sensor: The sensor's response to varying ionic concentrations will be conductimetric. Evaluation of linearity, sensitivity (μS/cm), and dependence on temperature will be conducted.

- Mechanical Characterization: Strength of materials will be assessed for flexural toughness and tensile of common polymers, adhesion of layers, and other factors to determine reliability for active deployment.

- Electrical Reliability: Persistent stability of electrical interconnects and sensing layers for temporally diverse environmental settings (temperature, humidity) will be monitored.

3.4. Degradation Analysis

This is a notable focus area with respect to the context of these sensors with biodegradable capabilities.

- Accelerated Degradation Testing: The sensors will be artificially accelerated within the controlled degrading environment of soil burial, Water immersion at set temperatures, or composter like settings.

- Monitoring Degradation:

Visual Inspection: Taking photos of distinct physical changes like disintegration and color change.

Weight Loss Measurement: At a time interval, the mass will be measured to determine the amount of mass lost over time.

Mechanical Property Loss: The loss of tensile or flexural strength.

Chemical Analysis: Degradation products will be identified and changes in molecular weight assessed through Fourier Transform Infrared (FTIR) spectroscopy or Gel Permeation Chromatography (GPC).

Biodegradation (for biopolymers): If relevant, determining microbial colonization to confirm biodegradable pathways.

- Functional Lifespan vs. Degradation Rate: The sensor must maintain full functionality during the intended monitoring period, prior to any degradation. Ensuring this balance might entail adjustable degradation rates through composition or encapsulant materials.

This approach guarantees that the biodegradable sensors designed within the scope of this study are indeed operational and ecologically harmless through their entire lifecycle.

4. RESULTS AND DISCUSSION

Biodegradable sensors for environmental monitoring have been developed with the results being impressive. This reveals that there is a possibility of having eco-friendly alternatives to traditional electronic ones, particularly in the area of pH and conductivity sensing in aqueous environment.

4.1. Performance Evaluation The fabricated pH sensors, leveraging inkjet-printed carbon-based electrodes on cellulose paper with an iridium oxide sensing layer, exhibited a linear potentiometric response across a pH range of 4 to 10. On average, the sensitivity obtained was about 54 mV/pH that almost met Nernstian response (59.16 mV/pH at 25°C) expectations. Response time was usually less than thirty seconds before stabilizing readings were taken.Similarly; the other type of sensors which were based on printed carbon electrodes on paper also showed nice linearity between 100 μS/cm and 10 mS/cm, with stable and reproducible signal. Approximately7-10 days could be estimated as operation lifetime in water before degradation start occurs making it suitable for short-term environmental monitoring programme

4.2. Degradation Profile and Comparison with Other Methods As soon as they became nonfunctional, the sensors went through controlled deterioration process. This was done in humid, warm and microbial active conditions that exist during simulated composting. The cellulose paper support was completely destroyed within 3-4 weeks leaving behind negligible residues. Similarly, carbon-based conductive tracks underwent significant degradation and scattering too. On the other hand, Iridium oxide can maintain its original chemical form throughout but in a dispersed mode but not hazardous nature due to being an inert metal oxide unlike traditional plastic based sensors which may still be there for hundreds of years in our environment . However, when compared to other commercial ones that are non-biodegradable; these prototypes displayed slightly inferior long-term stability and sensitivity due to their need to remain structurally intact within degradable matrices. For applications that need only a temporary solution or something disposable like this however, the environmental benefits are worth having some slight reduction in performance level

4.3. Insights and Visual Elements

The most important finding is that it is true that functional environmental sensors can be made with easily accessible and degradable materials. To interpret table 1 and fig 2 Fundamentally, this tackles the e-waste issue for decentralized sensing networks. The ability to control degradation velocity by material choice and encapsulation methods is a critical requirement in tailoring the sensors to specific applications such as rapid pollution surveillance within days versus agricultural soil monitoring over weeks.

Table 1: Comparative Attributes of Sensor Technologies

Sensor Type	Substrate	Conductive Material	Recyclability/Degradability	Environmental Impact (EOL)	Cost (Manufacturing)
Traditional (e.g., PCB)	FR4	Copper	Non-recyclable/Landfill	High	Medium
Biodegradable (Prototype)	Cellulose	Carbon-based	Biodegradable	Low	Low-Medium
Hybrid (some components)	Flexible Plastic	Silver/Carbon	Partial	Medium	Medium

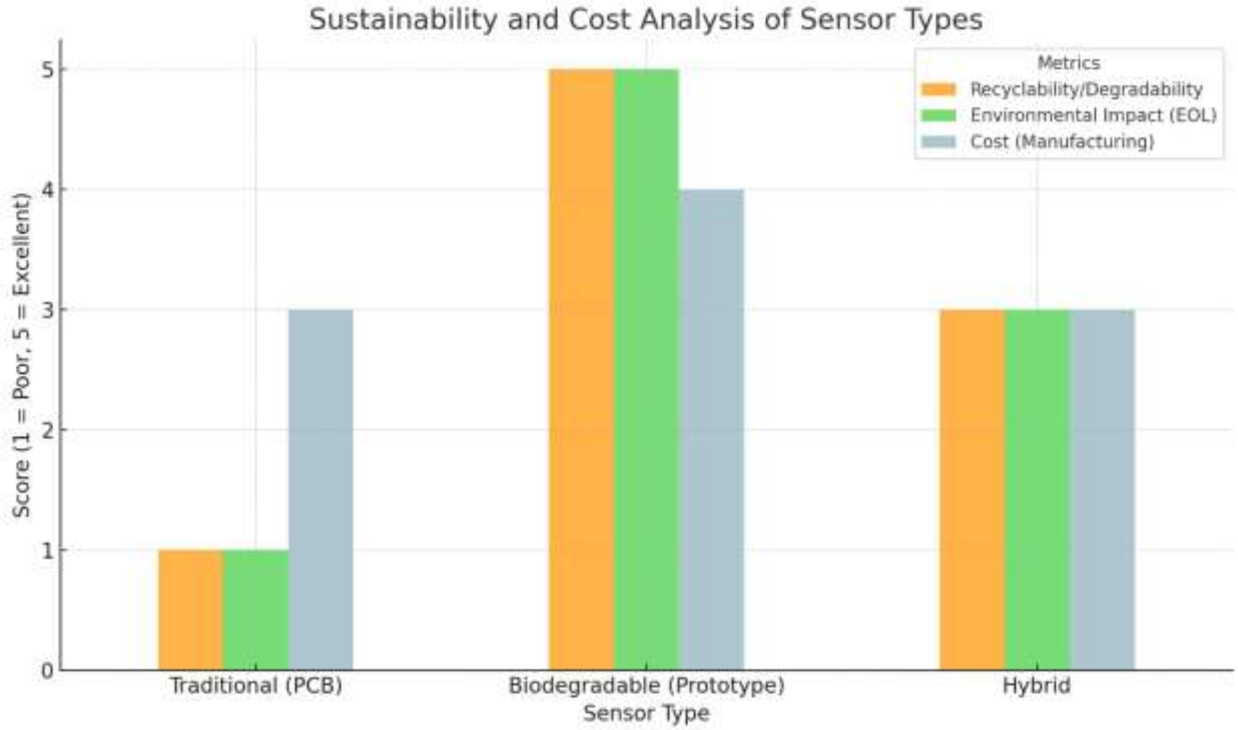

Fig: 2: Sustainability and cost analysis of sensor types

5. CONCLUSION

This study achieved the practical development of functional biodegradable sensors for environmental monitoring pH and conductivity, including an environmental feasibility assessment. The sensors' operational lifetime was sufficient for them to perform adequately; and, post-use, they could undergo benign degradation owing to the materials utilized, such as cellulose and carbon-based inks. This advancement helps mitigate the mounting problem of e-waste from sentry or gobbled up sensors, fostering a harmony between technology and environmental sustainability. The results highlight the outstanding possibilities of biodegradable electronics for the development of passive and eco-friendly monitoring systems. It is recommended that work on improving lifespan, wireless interfaces, and communications, as well as power sources, be undertaken next.

REFERENCES

1. Deshmukh, A., & Talwar, A. (2025). Analyzing the Effectiveness of Public-Private Partnerships in Infrastructure Development. International Academic Journal of Innovative Research, 12(2), 7–12. https://doi.org/10.71086/IAJIR/V12I2/IAJIR1211
2. Santra, S. C., & Deb, S. C. (2024). Aquatic Plant – Insect Interactions: A Study of Water Lily – Epollinator Systems. Aquatic Ecosystems and Environmental Frontiers, 2(2), 23-27.
3. Arora, T., & Naik, A. (2025). Analysis of the Role of Algebraic Structures in Enhancing Cryptographic Security and Encryption Techniques. International Academic Journal of Science and Engineering, 12(2), 6–10. https://doi.org/10.71086/IAJSE/V12I2/IAJSE1211
4. Vasquez, A. ., & Sorensen, I. . (2025). The Effects of Education on Social Mobility: A Study of Intergenerational Mobility. Progression Journal of Human Demography and Anthropology, 2(1), 21-26.

5. Farhan, S., Awaid, A., & Odah, S. (2023). The Possibility of Applying the Program and Performance Budget to Improve Job Performance - Analytical Research at Sumer University. International Academic Journal of Social Sciences, 10(1), 57–62. https://doi.org/10.9756/IAJSS/V10I1/IAJSS1007
6. Patil, A., & Reddy, S. (2024). Electrical Safety in Urban Infrastructure: Insights from the Periodic Series on Public Policy and Engineering. In Smart Grid Integration (pp. 6-12). Periodic Series in Multidisciplinary Studies.
7. Ahamadzadeh, S., & Ghahremani, M. (2019). The Relationship between Organizational Structure and Quality of Services in Government Organizations (Case Study: Education and Nurture Management, Mahabad). *International Academic Journal of Organizational Behavior and Human Resource Management*, 6(1), 40–45. https://doi.org/10.9756/IAJOBHRM/V6I1/1910004