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Review Article

Edible Plant Based Sensors for Real Time Health Monitoring

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A B S T R A C T

Edible plant-based biosensors represent an emerging paradigm in non-invasive and sustainable health diagnostics. Leveraging food-grade materials such as plant-derived polymers (cellulose, pectin, starch), natural pigments (anthocyanins, chlorophyll, betalains), and edible enzymes (e.g. glucose oxidase), these ingestible systems detect physiological parameters—including gut glucose, pH, oxidative stress, and microbial activity—via colorimetric or electrochemical signals. This approach converts biomolecular interactions into quantifiable outputs through edible electrodes (e.g., activated charcoal paste), biofuel-cell energy harvesting, and RFID-like wireless telemetry. The sensors are biologically safe, biodegradable, and compatible with FDA/EFSA guidelines, providing real-time monitoring without surgical intervention. Potential applications span diabetes management, gut health diagnostics, stress and hydration monitoring, nutrient absorption profiling, foodborne pathogen detection, and precision nutrition. Key challenges include ensuring structural and functional stability in harsh gastric environments (low pH, high viscosity, peristalsis), preserving enzymatic activity during storage and digestion, scalable manufacturing of miniaturized devices, and navigating regulatory approval pathways. While many prototypes remain at proof-of-concept or preclinical stages, recent advances in eco-friendly conductive pastes and edible microlasers signal progress toward clinical viability. Integrating these biosensors with IoT and AI platforms could enable seamless health tracking pipelines. With further research in material innovation, bioelectronic design, and clinical validation, edible plant-based biosensors could redefine future healthcare by offering patient-friendly, eco-conscious, and real-time internal monitoring tools.

KEYWORDS: Plant -Biosensor, Monitoring, Biosensing, Challenges

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INTRODUCTION

Biosensors are analytical devices that have revolutionized the way we detect and monitor biological, chemical, and physiological processes. Biosensors can transform a biological reaction into a measurable and processable signal by combining a biological sensing element with a physicochemical transducer. With the use of this technology, a variety of analytes, such as glucose, pathogens, toxins, hormones, and disease biomarkers, can be detected quickly, sensitively, and specificallyBiosensors were first created for medical diagnosis, but they are now widely utilized in biotechnology, agriculture, food safety, and environmental monitoring. They are essential to continuous and real-time health monitoring in the medical field, providing minimally invasive or non-invasive approaches to disease management and personalized medication[i]. For instance, patients may now easily and precisely monitor their blood sugar levels thanks to glucose biosensors, which are becoming essential tools for managing diabetes. Modern biosensors combine advances in materials science, nanotechnology, and wireless communication, resulting in devices that are not only highly functional but also portable, wearable, and even ingestible[ii]. Biosensors are increasingly being incorporated into smart systems as research advances, allowing for proactive healthcare intervention, remote diagnostics, and real-time data transfer. Essentially, biosensors are a crucial nexus of biology and technology that propels advancements in monitoring and diagnostics while improving the effectiveness, accessibility, and responsiveness of healthcare to patient demands.Also biosensor technique offers rapid, sensitive, and selective detection in complex samples, often without the need for extensive sample preparation or laboratory infrastructure. biosensors represent a multidisciplinary innovation at the intersection of biology, chemistry, electronics, and data science. The advancement of health monitoring technologies has led to the development of innovative tools that can track physiological changes in real time, aiming to improve early diagnosis, personalized treatment, and preventive care[iii]. Among these innovations, edible plant-based sensors have gained attention as a ground-breaking approach for internal health monitoring. Unlike traditional wearable or implantable devices, these sensors are designed to be safely ingested, operate inside the body, and naturally degrade without causing harm. Their ability to provide real-time data from within the gastrointestinal tract or other internal systems marks a significant step toward more patient-friendly and sustainable healthcare solutions.Pharmacognosy is the scientific study of natural products, particularly those derived from plants, animals, and microorganisms, that have medicinal or therapeutic properties.Pharmacognosy has evolved with modern science to contribute to various interdisciplinary fieldsincluding biotechnology, food science, and biomedical engineering. The creation of edible biosensors is one new application area where pharmacognosy is becoming more significant[iv]. These are biocompatible, ingestible sensors or materials that are intended to identify particular biomarkers in the body, particularly in the gastrointestinal system, such as pH, glucose, or toxins. Through safe, consumable formats, edible biosensors seek to facilitate early illness detection, nutrient tracking, and non-invasive health monitoring.Pharmacognosy and edible biosensors are related since these sensors are constructed using natural, plant-based materials and chemicals. Flavonoids, pigments, enzymes, polysaccharides, and other bioactive compounds that are researched in pharmacognosy can all be used as sensing elements because of their biochemical reactivity, color-changing capabilities, or enzyme-like activity. Pharmacognosy also provides a supply of edible and biodegradable polymers (such as pectin, chitosan, and starch) that can be used as matrices or carriers for these sensors.Pharmacognosy gives you the raw materials and biological knowledge you need to make safe, effective, and nature-inspired edible biosensors[v].Edible plant-based biosensors are a revolutionary combination of natural product science, biotechnology, and sustainable engineering. They present a promising alternative to conventional sensing technologies by combining safety, functionality, and environmental sustainability. Plant-based biosensors are poised to play a critical role in the future of healthcare, food quality monitoring, and smart diagnostics, as demand for clean-label, eco-friendly, and personalized health solutions grows.

Plant Based Biosensors

Plant-based biosensors offer a viable, environmentally aware alternative to standard biosensors. They use plant components' natural chemical sensitivity to provide safe, effective, and sustainable solutions for diagnostics, environmental analysis, and food quality management. As biotechnology and materials science develop, biosensors will become more durable and commercially viable.Plantbased biosensors are analytical devices that incorporate biological materials derived from plantssuch as enzymes, pigments, or polymersto detect specific physical, chemical, or biological signals. Plant derived components includingNatural polymers (matrices) like starch, pectin, cellulose, and chitosan can be used as substrates for sensor building due to their biocompatibility and ability to form films[vi].Colorimetric markers, such as anthocyanins found in berries and red cabbage, can be used in packaging and ingestible films due to their pH-sensitivity.

Other natural pigments, such as curcumin, chlorophyll, and betalains, act as visual cues in response to pH or redox changes.Plant enzymes & metabolites enzymes such as horseradish peroxidase catalyze oxidation reactions (e.g., detecting hydrogen peroxide), while flavonoids and alkaloids function as biological recognition elements[vii,viii].Plant-based biosensors use plants' natural sensing skills, which can be enhanced through genetically encoded switches or bioelectronic interfaces, to pick up on environmental or physiological signals in real time. In order to build genetically encoded plant-based biosensors (GEPBs) that can convert chemical stimuli, such as hormones, metabolites, or pollutants, into measurable signals, researchers have engineered plants with reporter modules, such as fluorescent proteins or transcription factors. To supplement existing methods, biohybrid systems allow for continuous monitoring of ion fluxes, sap composition, or transpiration dynamics without compromising plant health by implanting organic electrochemical transistors or flexible electronics based on nanomaterials directly into stems or leaves[ix]. Biomarkers are essential indicators in plant-based biosensors that allow for the identification of pathogen infections, environmental stressors, and physiological alterations.Biomarkers in plant-based biosensors function as particular signals or chemicals that alter in reaction to physiological processes, stressors, or environmental influences. A plant that is under drought stress, for instance, produces more abscisic acid (ABA), a hormone. As a biomarker, this rise in ABA shows that the plant is experiencing water stress. Biosensors identify these biomarkers, which include metabolites, hormones, ions, and reactive oxygen species, and translate changes in their quantity or existence into signals that may be detected, such as electrical or fluorescent signals[x].

Plant PartForBiosensing

Plants that serve as effective candidates for biosensing typically combine ease of genetic modification,wellcharacterized physiology, and clear responses to environmental or physiological changes. Because of differences in accessibility, function, and physiological responses, various plant sections provide distinct benefits for biosensing applications. Choosing the right plant tissue is critical for successful sensor integration and precise detection of biomarkers or environmental stimuli. Plant-based biosensors use current sensing technology in conjunction with the natural structures and biochemical characteristics of plants to monitor human health. For instance, the complex and pliable networks of leaf veins make them ideal scaffolds for strain or pressure sensors, which measure changes in electrical resistance or capacitance to identify minute mechanical changes like respiration, pulse, or joint motions.

- **Leaves**

Leaves are the major sites for photosynthesis and gas exchange, hence they are sensitive to environmental changes like light, humidity, temperature, and pollution. Their huge surface area enables easy sensor connection or integration. For example, flexible electronic sensors or nanomaterial-based patches can detect water loss by measuring leaf transpiration or monitor stress-induced changes in metabolite levels like reactive oxygen species (ROS) or hormone concentrations. Fluorescent biosensors genetically encoded in leaf cells can report on physiological changes by emitting signals in response to specific biomarkers.Leaf biosensors are developing as critical instruments for real-time plant health monitoring, providing early identification of stress signals before obvious symptoms appear. The sensors detect hydrogen peroxide (H_2O_2), a reactive oxygen species produced by plants in response to stresses like dehydration, infection, or mechanical damage.Leaf biosensors designed for human health monitoring take advantage of the inherent structure and features of plant leaves, such as their flexible veins, to build wearable, skin-friendly devices. These biosensors monitor physiological signals including pressure, movement, and even vital signs in real time by combining leaf-inspired materials or genuine leaf veins with electrical elements (such as silver nanowires). When worn on the body, leaf vein-based pressure sensors can detect small mechanical deformations, allowing them to monitor joint movements. Their permeable and biodegradable properties make them suitable for long-term use while minimizing environmental effect. These sensors can be connected to electronic systems to collect continuous, real-time data, allowing for individualized health tracking and early detection of anomalies[xi].

Mechanism

The process by which biosensors based on plant parts monitor human health is the conversion of physiological or biochemical inputs into quantifiable electrical outputs. The natural structure of plant tissues, such as cellulose fibres or leaf veins, is typically used by these biosensors as flexible substrates combined with conductive substances like carbon nanotubes or silver nanowires. Applying mechanical changes like pressure, strain, or motion to the human body causes the sensor to deform, changing its electrical resistance or capacitance. This change is then recorded as a signal that corresponds to physical activity, such as a pulse or joint movement.

***Mechanical Sensing*:** Plant leaf veins embedded with conductive nanowires act as strain sensors that detect joint movements, muscle contractions, or pulse by measuring changes in electrical resistance caused by deformation.

***Biochemical Detection*:** Plant-based membranes functionalized with specific enzymes detect biomarkers such as glucose, lactate, or electrolytes from sweat, enabling real-time metabolic monitoring.

***Environmental Sensing*:** Plant materials incorporated in wearable can also monitor environmental parameters like humidity or pollutants, which impact human health.

In these systems, the electrical resistance of the sensor is changed by mechanical signals (like strain or pressure from movement) while electrochemical currents are produced by biological interactions (like the conversion of analytes by enzymes).Theon-going monitoring, these signals are gathered by tiny, frequently wireless devices, processed in real time, and sent to smartphones or medical systems. With its roots in plant materials, this integration provides a biocompatible, breathable, and sustainable foundation for non-invasive, individualized health tracking[xii,xiii].

Mechanism of Action of Edible Plant-Based Biosensors

1. ***Edible Biocompatible Materials & Bio recognition***

- These sensors use food-grade materials such as edible enzymes, redox mediators, conductive substrates (e.g. activated charcoal) that comply with FDA standards
- Enzymes (such as glucose oxidase), edible carbon electrodes, and redox mediators that catalyze target analyte reactions inside the gastrointestinal (GI) tract are examples of common biorecognition components[14].
- *Interaction with Physiological Media*
- The sensors detect analytes such as glucose, uric acid, ascorbic acid, dopamine, pH variations, etc., by performing electrochemical or voltammetric measurements in environments like simulated saliva, gastric, and intestinal fluids[15].

2. ***Signal Transduction & Measurement***

- Voltametric detection is enabled by edible electrodes (e.g. carbon paste inside hollow pasta, cookies, and green beans). When analytes are present, these electrodes provide current-voltage patterns that allow for quantification[15].
- Some ingestible systems are battery-free, powered by enzymatic biofuel cells (e.g. glucose-based biofuel cells), which harvest energy from gut metabolites to power sensing and wireless telemetry[16].

3. ***Data Transmission***

- Signals are encoded via integrated circuits or passive RFID-like configurations using silk substrates and edible metallic antennas, enabling wireless tracking or external reading while passing through the GI tract.
- In some designs, the onboard electronics convert analyte concentration to a frequency-coded wireless signal that can be detected via external receiver[15, 16].
- 5.*Real-Time Monitoring*
- Such ingestible sensors can continuously track biomarkers (e.g., gut glucose), providing real-time data on metabolic processes as the sensor transits the GI lumen with digestion[16].

Applications of Edible Plant-Based Biosensors

- ***Monitoring Glucose for Diabetic Patients*:** Biodegradable conductive polymers like cellulose or chitosan combined with glucose oxidase enzymes enable edible plant-based glucose sensors to detect glucose in intestinal or salivary fluids[17].
- ***Ingestible Biosensors for Gut Health Monitoring*:**The gastrointestinal (GI) tract's pH, enzyme levels, temperature, and microbial activity are all monitored. Use of plant celluloseorpectin-based micro beads that detect changes in gut microbiota and metabolic byproducts such as short-chain fatty acids

(SCFAs) or pH shifts. Detects imbalances in gut microbiota, useful for managing conditions like IBS, IBD, or dysbiosis and also detect early signs of GI diseases such as ulcers, inflammation, or infections[18, 19].

- ***Saliva-Activated Edible Biosensors*:** Monitor biomarkers such as glucose, cortisol, and lactate in saliva non-invasively. Employ plant-based conductive polymers or cellulose-based paper strips for sensing. Used for stress monitoring, diabetes management, and hydration tracking[17].
- ***Sweat-Based Wearable Biosensors***: Detect glucose, sodium, urea, lactate via sweat analysis using plant-derived hydrogels and cellulose films. Enable ongoing, real-time metabolic health and hydration monitoring while exercising or performing daily tasks[20].
- ***Hydration and Electrolyte Balance*:**Continuous monitoring of hydration levels and electrolyte imbalances, particularly for athletes or patients recovering from illness. Edible biosensors embedded withplant-derived nanomaterial (e.g., carbon dots from spinach) that detect hydration levels by sensing changes in saliva conductivity[21].
- ***Edible Optical Biosensors*:** Use plant pigments (chlorophyll) and natural fibers as biodegradable fluorescent sensors. Detect changes in pH, sugar concentration, bacterial contamination via optical signals. Can be embedded directly into food or used as ingestible diagnostic agents[22, 23].
- ***Pathogen Detection and Foodborne Illness Monitoring*:**Plant-derived bioreceptorslikeantibody-functionalized starch or cellulosethat change color or release a detectable signal when interacting with pathogens such as E. coli, Salmonella, or toxins like aflatoxin. Early warning system for foodborne diseases or contamination, helping to mitigate health risks [24].
- ***Monitoring Stress and Hormonal Levels*:**Edible biofilmsormicrocapsulesderived from plant-based materials (e.g.,cellulose or alginate**)** that release fluorescence or color signals when interacting with stress biomarkers**.** Useful for mental health management and chronic stress reduction [25].
- ***Nutrient Absorption Monitoring*:**Monitoring the absorption of essential nutrients (e.g., vitamins, minerals, proteins) post-consumption, especially in patients with malabsorption disorders. Edible polymericbiosensors with plant-based enzymatic coatings capable of detecting nutrient biomarkers in the digestive system. Helps track nutrient deficiencies and absorption rates in real-time, potentially beneficial for people with metabolic disorders or those on specialized diets[26].
- ***Paper- and Nanocellulose-Based Biosensors***: Biodegradable paper strips functionalized with enzymes or nanoparticles for detecting ions, glucose, and pathogens. Suitable for non-invasive sampling (saliva, sweat) and food safety monitoring[27].

Challenges and Limitations

- ***Regulatory & Safety Constraints*:** Ingredient toxicity, absence of standardized edible biosensor approvals[28]. Even plant-derived substances may be harmful at high doses, necessitating careful dosage control and clinical validation[29].
- ***Hostile Gastrointestinal Environment*:** Edible sensors must function in low gastric pH (~1.5), high temperature (37–40 °C), and highly viscous fluids that cause biofouling and degrade performance. They must withstand compressive stresses (numerous Newtons), peristaltic movement, gastric mixing, and variable GI geometries—challenges for mechanical integrity and retention[28].
- ***Stability concern:***Biological components (enzymes, bacteria, pigments) are sensitive to temperature and humidity, compromising long-term stability and storage. Exposure to GI mucus, enzymes, and microbial flora can degrade sensor surfaces and reduce signal reliability over time[28].
- ***Manufacturing, Scalability & Cost*:** Miniaturized edible devices require high-precision printing or nanoengineering, potentially raising manufacturing costs and technical complexity. While some prototypes may be low-cost, scaling up to clinically approved, reproducible devices with integrated electronics remains expensive and resource-intensive[30].
- ***Sustainability*:** Even biodegradable sensors contribute to waste if not fully consumable. Life-cycle analysis (LCA) is essential to quantify environmental footprint and guide sustainable material choices. Materials chosen for biodegradability may have limited durability or sensitivity, creating a tension between sustainability and performance[29].
- ***Clinical Translation & Adoption*:** Most edible plant-based biosensors remain at proof-of-concept or animal-study stages. Human trials and regulatory approvals are still pending for most systems. Data handling, reimbursement policies, and acceptance by physicians/patients remain unclear for ingestible health sensors[31].

CONCLUSION

In summary, edible plant-based biosensors leverage naturally derived, food-safe materials—such as plant polysaccharides, pigments, activated-carbon pastes, and edible enzymes—to enable non-invasive, real-time monitoring of key physiological markers including glucose, pH, oxidative stress signals, and gut microbial metabolites via electrochemical, optical, or RFID-like modalities. Recent advances such as FN-CoP edible conductive pastes and chlorophyll-based microlasers demonstrate significant strides toward robust, biocompatible ingestible devices. Despite these innovations, critical challenges remain, namely ensuring mechanical and functional stability in the harsh gastrointestinal environment, preserving biomolecular activity during storage and transit, achieving scalable fabrication, and satisfying regulatory standards—issues still largely unresolved beyond prototype stages. To fully realize their potential in personalized health monitoring, future research must address these hurdles through multidisciplinary efforts in green nanomaterials, flexible electronics, wireless biosensing, and clinical validation. Successfully integrating edible biosensors with IoT and AI systems may pave the way for seamless internal diagnostics, transforming healthcare with sustainable, patient-centric, and minimally invasive technologies.

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