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Biopolymers-based Electrochemical Sensors: An Overview of Synthesis and Applications

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ABSTRACT

The advancement of sensor technology has significantly impacted various scientific and industrial fields, particularly through electrochemical biosensors that convert biological data into electrical signals. This paper presents a comprehensive overview of biopolymer-based electrochemical sensors, which utilize natural materials such as cellulose, chitosan, alginate, keratin, etc. These biopolymers offer eco-friendly alternatives, enhancing sensor efficiency and sustainability while enabling customization for specific sensing applications. The synthesis of biopolymer-based composites through chemical, physical, and green methods is explored, with an emphasis on enhancing sensor performance by integrating conductive materials like metal oxides, graphene, and nanoparticles. The review explores their use in various fields, including medical diagnostics, environmental monitoring, agriculture, wastewater treatment, and wearable or implantable medical devices. Ultimately, this study aims to highlight the potential of biopolymer-based electrochemical sensors as innovative and sustainable solutions for a wide range of applications.

Keywords: *Electro-chemical sensors, Biopolymers, Nanoparticles, Green synthesis.*

1. INTRODUCTION

The development of Sensor technology has been a key driver in advancing numerous Scientific and Industrial fields, from healthcare to Environmental monitoring. Electrochemical Biosensors are basic apparatus that convert biological data generated by a redox reaction into an Electrical Signal [1]. Through the identification of several bio-analytes and Chemicals, they are crucial in detection of Biomarkers and the monitoring of Environmental Pollutants. Their extensive adoption can be attributed to their simplicity, ease of use, great Sensitivity, Portability, low cost, Quick Response and Eco-Friendliness [2].

Biopolymers provide a green alternative since they are sourced from Natural Materials including Plants, Animals and Microbes. These materials have distinct functional groups that may be customized for certain Sensing Applications in addition to their Biocompatibility. Electrochemical Sensors that include Biopolymers offer a means of producing gadgets that are not only highly efficient but also sustainable [3]. Polysaccharides such as Cellulose, Chitosan, Lignin, Starch and Pectin are among the most commonly used Biopolymers due to their exceptional Structural properties, diverse chemical compositions and ease of modifications. In Electrochemical Sensors, Biopolymers are primarily utilised for biochemical modifications, including enhancing bio-functionality, conductivity and biochemical responsiveness. However, Biopolymers offer face challenges such as Poor Solubility, Susceptibility to chemical and thermal degradation and limited mechanical strength. To address these limitations, Conductive additives like Metal Oxides, Conducting Polymers and Nanoparticles are frequently incorporated. Comparing to non-Biopolymer alternatives like Graphene or Graphene Oxide which require hazardous Chemicals and lengthy processing, these Biopolymer-based composites offer a more Environmentally friendly option [4,5]. Biosensor performance is determined by three key components: a bioreceptor, a transducer and a signal processing system.

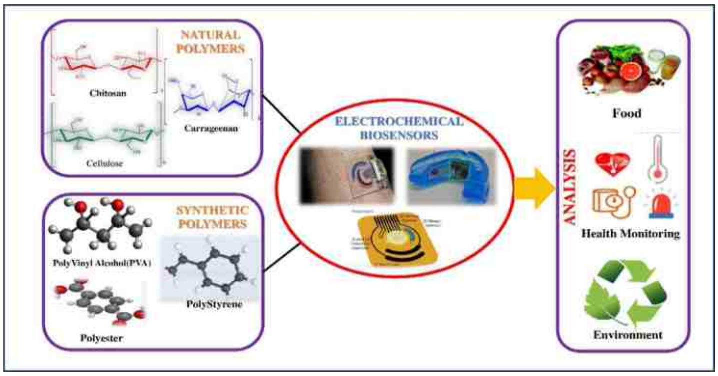

Fig.1: Overview of Sensors based on Biopolymers

The Bioreceptor consists of an immobilized biological component that can specifically detect an analyte. Biocomponents used as bioreceptors include antibodies, nucleic acids, enzymes, cells and biomarkers. When the bioreceptor interacts with the analyte, it triggers chemical changes, such as the production of new compounds, heat generation, electron flow, or alterations in pH and mass. The transducer then converts these biochemical changes into an electric Signal, which is subsequently amplified and processed to produce a digital display, printout, or optical change [6].Applying layers of probe material to the transducer enhances the response signal in terms of current, potential or impedance.

The more layers that are applied, the stronger the signal. Various electrochemical measurement techniques, including electrochemical impedance Spectroscopy (EIS), Differential Pulse Voltammetry (DPV), Linear Sweep Voltammetry (LSV), Anodic Stripping Voltammetry (ASV), Differential Pulse Stripping Voltammetry (DPSV), Differential Pulse Anodic Stripping Voltammetry (DPSAV), Square Wave anodic Stripping Voltammetry (SWASV), Square Wave Voltammetry (SWV) and Cyclic Voltammetry (CV) are commonly employed to monitor the interaction between an analyte and its target. When an analyte interacts with an electrode, it induces measurable changes in the current and potential of the biosensor, which are influenced by the concentration of the analyte on the electrode's sensing surface [7,8].

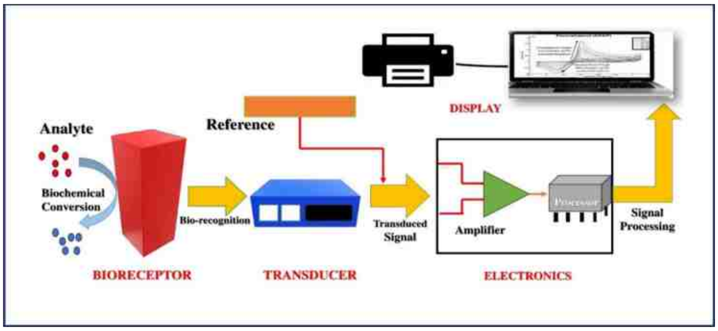

Fig. 2: Schematic Diagram of the Components of Electrochemical Biosensor

Electrochemical Sensing typically involves a Reference Electrode, a Counter (or auxiliary) Electrode, and a Working Electrode, also referred to as the Sensing or redox Electrode [9]. The reference Electrode, often constructed from Ag/AgCl, is positioned away from the reaction site to maintain a consistent and known potential. The Working Electrode functions as the transduction Element in the Biochemical interaction, while the Counter Electrode connects to the Electrolytic Solution, enabling current flow to the Working Electrodes. It is essential that these Electrodes are both Conductive and Chemically stable [10].Electrochemical Biosensors can be categorised based on the type of Transducer and measurement technique employed: Potentiometric Biosensors (which detect variations in Potential or Voltage without drawing Substantial Current), Amperometric Biosensors (which measure changes in Current resulting from redox reactions at Electrode Surface), Conductometric Biosensors (which monitor alterations in the Solution's Conductivity) and Impedimetric Biosensors (which assess changes in impedance including both Resistance and Reactance, within the System) [11].

Chemical modification of Electrodes can improve their Electrochemical Sensing capabilities. Typically, these electrodes are modified using toxic, non-biodegradable active materials such as Carbon derivatives and Synthetic polymers. However, Biopolymers have recently gained attention as an environmentally friendly alternative to Synthetic Polymers in Electrolytes [12].

The Solubility of Biopolymers depends on the Strength of Hydrogen Bonding within Intramolecular or Intermolecular interactions. In general, weak Hydrogen Bonds with amino groups enhance the dissolution of Biopolymers in common organic and diluted aqueous solvents. The presence of amino groups also influences the solvent's pH, altering the charge state and properties of Biopolymers. The primary cause of Biopolymers biodegradability and Solubility is their susceptibility to biomolecules including proteins, enzymes, and bodily tissues. Consequently, it is necessary to modify Biopolymers using both Organic and Inorganic elements. For instance, by adding conductive elements and changing the hydroxyl, Carboxyl and Amino groups in a Biopolymer, its electrical conductivity may be improved even more [13,14].

The adaptability of Biopolymers is a significant factor driving their increasing use in Sensor Technology. Biopolymers like Cellulose, Chitosan, Alginate and Silk Fibroin have distinct chemical Structures that allow for extensive modifications. This flexibility facilitates the optimization of Sensor Properties such as Selectivity, Sensitivity and Stability, all of which are essential for practical applications. Furthermore, Biopolymers can be readily combined with Nanomaterials like Graphene, Carbon Nanotubes (CNT's), and Metal Nanoparticles, enhancing their Electrochemical Performance and paving the way for the Creation of High-Performance Composite Sensors [15].

A Comprehensive Overview of several investigations on Electrochemical Sensors based on Biopolymers is given in Table 1, which also highlights the variety of Biopolymers, their modifications and their uses in the detection of diverse biomolecules.

Table1: An Overview of Biopolymers based Electrochemical Sensors

Biopolymers Used	Type of Modification	Significant Findings	Targeted Biomolecules	Reference
Chitosan	Surface Modification	Enhanced sensitivity and selectivity for Glucose detection	Glucose	[16]
Alginate	Composite Formation	Improved Biocompatibility and Stability in physiological conditions	Lactate	[17]
Cellulose	Conductive Polymer Blend	Demonstrated high conductivity and responsiveness to Uric acid	Uric Acid	[18]
Starch	Crosslinking	Achieved significant reduction in detection limits for Cholestrol	Cholestrol	[19]
Polyvinyl Alcohol (PVA)	Crosslinked Hydrogels	Developed a Sensor with improved Sensitivity	Alcohols	[20]
Chitosan Carbon Nanotubes	Composite Formation	Enhanced electrocatalytic activity for H_2O_2 detection	H_2O_2	[21]
Polylactic Acid (PLA)	Electrochemical polymerisation	Developed a Sensitive and Selective sensor for Creatinine monitoring	Creatinine	[22]

Although Biopolymers offer benefits, there are drawbacks to using them in Electrochemical Sensors. Sensor performance and Stability may be impacted by the sensitivity of Biopolymers to environmental factors including Humidity and Temperature [23,124]. Furthermore, there may be variations in Sensor performance due to the heterogeneity in the characteristics of Biopolymers generated from natural sources. To improve the qualities of Biopolymers while preserving their advantages for the environment and Biocompatibility, creative synthesis and Functionalization techniques are needed to overcome these obstacles [24].

The goal of this study is to present a thorough overview of the state of Biopolymer-based Electrochemical Sensors. The Synthesis techniques of several Biopolymers will be covered, with an emphasis on how these materials are customized for certain sensing applications. The paper will also discuss functionalization strategies that improve sensor performances and illustrate the many uses of Biopolymer-based Sensors, ranging from Environmental monitoring to biomedical diagnostics. Ultimately, the study will address the difficulties pertaining to Biopolymer-based Electrochemical Sensors and suggest future avenues for investigation and advancement in this quickly developing sector.

2. Types of Biopolymers used in Sensors

2.1 Polysaccharides-based Biopolymers for Electrochemical sensing

I. Chitosan

Chitosan, a natural biopolymer, is recognized for its non-toxic and environmentally friendly properties, aligning with green chemistry principles to promote environmental safety. It exhibits hydrophilicity, excellent gel-forming ability, and compatibility for doping with various materials, contributing to enhanced mechanical stability and high permeability. Additionally, chitosan possesses reactive functional groups, which facilitate chemical modifications, making it a highly versatile and efficient material for sensor applications [25-27, 128]. Chitosan, on its own, does not conduct electricity. To overcome this issue, it is often combined with conductive materials like graphene [28] and multi-wall carbon nanotubes [29], as well as conducting polymers such as polypyrrole [30] and polyaniline [31]. These additions improve chitosan's electrical conductivity, making it more effective for use in sensors.

ii. Alginate

Alginate, a biopolymer derived from brown seaweed, is increasingly used in electrochemical sensors due to its excellent biocompatibility, non-toxicity, and ability to form hydrogels. It serves as an ideal matrix for immobilizing enzymes, proteins, and nanoparticles, thereby enhancing the sensitivity and selectivity of sensors. Alginate's capacity to form hydrogels in the presence of divalent cations like calcium provides a stable environment for sensor components. It is often combined with conductive nanomaterials, such as carbon nanotubes or metal nanoparticles, to improve the electrochemical properties of the sensor, making it suitable for detecting a wide range of analytes, including glucose, heavy metals, and other bioactive molecules. For instance, alginate-based hydrogels are commonly used in glucose sensors, where they immobilize glucose oxidase, enhancing the sensor's performance in clinical diagnostics. Additionally, alginate composites are utilized to detect heavy metals in environmental samples, offering a sensitive and stable platform. Its pH sensitivity and polyanionic nature also make it adaptable for various electrochemical sensing applications. Research has demonstrated that alginate-based electrochemical sensors not only provide enhanced detection capabilities but also maintain the functional stability of the biological components used, underscoring its potential in biosensing technologies [32-35].

iii. Cellulose

Cellulose, a natural and abundant biopolymer, has gained significant attention in developing electrochemical sensors due to its biocompatibility, renewability, and versatile chemical modification potential [36]. Its unique structural properties, such as high surface area, porosity, and functional hydroxyl groups, make it an ideal material for immobilizing various sensing elements, including enzymes, nanoparticles, and conductive polymers [37]. Cellulose-based sensors are particularly effective in detecting biomolecules, heavy metals, and environmental pollutants. Furthermore, cellulose nanomaterials, such as cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs), enhance the electrochemical performance by providing excellent conductivity and stability [38].

2.2 Proteins and peptides-based biopolymers (Collagen and gelatin)

Collagen and gelatin, both peptide-based biopolymers, are being increasingly utilized in electrochemical sensors due to their favourable properties. Gelatin is particularly valued for its biocompatibility, film-forming ability, and environmental friendliness, making it an ideal matrix for immobilizing biorecognition materials. This characteristic effectively detects various analytes, including glucose, hydrogen peroxide, urea, and pesticides. Gelatin-based electrochemical biosensors have shown excellent sensitivity, accuracy, and stability, which are critical for applications in medical diagnostics, food testing, and environmental monitoring. Recent advancements highlight the potential of gelatin in developing wearable biosensors that can monitor physiological parameters non-invasively, such as through skin analysis of sweat and interstitial fluid. The unique sol-gel property of gelatin provides flexibility, enhancing the adaptability of these sensors to human body movements. Additionally, gelatin is being explored as a matrix for immobilizing aptamers in electrochemical aptasensors, which improves sensitivity and stability by facilitating electron exchange between target molecules and electrodes. Despite the promising applications, challenges remain in enhancing the thermal and mechanical stability of gelatin-based matrices, which are crucial for the long-term performance of these sensors. Overall, the integration of collagen and gelatin in electrochemical sensors presents a significant opportunity for innovation in biosensing technologies [39-41].

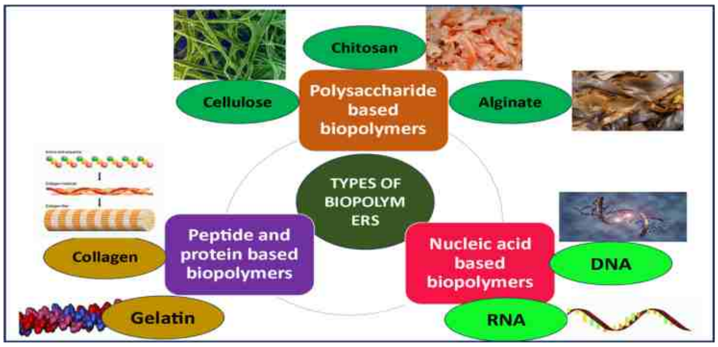

Fig. 3: Types of biopolymers for electrochemical sensors

2.3 Nucleic acid-based biopolymers as electrochemical sensors (DNA, RNA)

Nucleic acid-based electrochemical biosensors represent a cutting-edge approach for the sensitive and selective detection of cancer biomarkers using DNA and RNA. These biosensors operate on the principle of a sandwich-type genosensor model, where a capture probe is immobilized on an electrode surface to bind the target nucleic acid. A reporter probe, often conjugated with a redox signal amplifier such as an enzyme or nanomaterial, then attaches to the captured target, facilitating an oxidation/reduction reaction that generates a measurable electrical signal. Several signal amplification strategies have been developed to enhance sensitivity, including isothermal exponential amplification, rolling circle amplification, and enzyme-based amplification techniques like horseradish peroxidase (HRP). These biosensors have shown significant potential in early cancer diagnosis by targeting key biomarkers such as prostate-specific antigen, microRNA-21, and carcinoembryonic antigen, providing high sensitivity and selectivity compared to traditional antibody-based methods [42-44].

3. Synthesis methods of biopolymers composite for electrochemical sensors

The synthesis of biopolymers for electrochemical sensing has emerged as a promising approach due to the inherent properties of biopolymers, such as renewability, biocompatibility, and ease of functionalization. Biopolymers like chitosan, alginate, cellulose, and proteins provide a versatile platform for sensor development, as they can be easily modified to incorporate conductive materials, such as nanoparticles or carbon-based nanostructures, enhancing their electrochemical performance. Various synthesis techniques, including chemical modification, physical blending, and green synthesis, enable the fine-tuning of biopolymer properties to meet the specific requirements of electrochemical sensors, such as improved sensitivity, selectivity, and stability. Advances in biopolymer synthesis are helping to create greener sensor technologies that can be used in areas like environmental monitoring, healthcare, and food safety. These developments make sensors more effective and eco-friendlier, broadening their applications [45-47, 127].

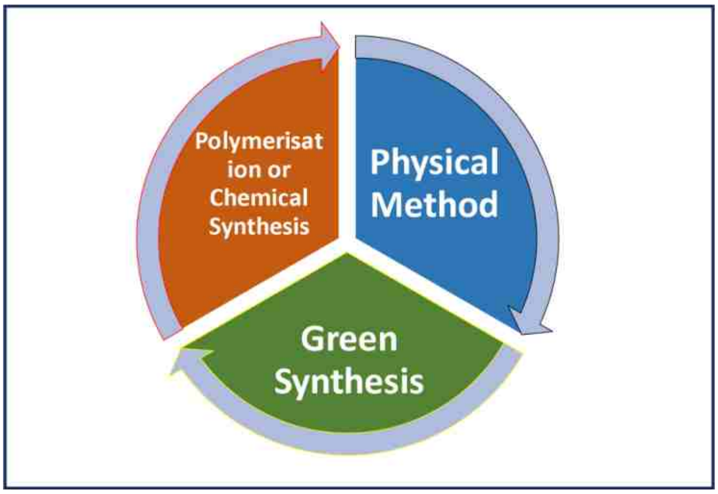

Fig.4: Synthesis methods of biopolymer composite for electroschemical senor

3.1 Polymerization or Chemical Synthesis

Electrochemical sensors have gained significant attention due to their ability to provide rapid and sensitive detection of various analytes. A critical aspect of enhancing the performance of these sensors lies in the choice of materials and fabrication techniques. Polymerization methods, particularly electropolymerization, in-situ polymerization, precipitation polymerization, and suspension polymerisation, are widely utilized to create conductive polymer composites that facilitate the electrochemical reactions necessary for sensor functionality. Electropolymerization allows for the direct deposition of polymer films onto electrode surfaces, enabling precise control over film thickness and morphology, which is crucial for optimizing sensor sensitivity and selectivity [48-49, 131].

In addition to polymerization techniques, the chemical modification of natural biopolymers such as chitosan, cellulose, and proteins is essential for improving their properties for electrochemical applications [50]. These modifications can include grafting functional monomers to introduce specific binding sites, crosslinking to enhance mechanical stability, and incorporating conductive materials like carbon nanotubes or metal nanoparticles to boost electrical conductivity [51, 134]. Furthermore, ionic modifications can improve the ion exchange properties of these biopolymers, making them suitable for potentiometric sensors. The strategic combination of polymerization techniques and chemical modifications enables the development of electrochemical sensors with enhanced performance characteristics, paving the way for their application in various fields, including environmental monitoring, biomedical diagnostics, and food safety [52].

3.2 Physical Methods

Natural biopolymers like chitosan, alginate, cellulose, and starch are increasingly used in electrochemical sensors due to their sustainable, biocompatible, and distinct physicochemical properties. By employing various physical modification techniques, these materials are adaptable for diverse applications in healthcare, environmental monitoring, and food safety.

3.2.1 Electropolymerization

One of the most promising methods for modifying natural biopolymers is electropolymerization. This technique involves the formation of polymeric coatings through electrochemical processes, which facilitate the immobilization of enzymes and other sensing agents on the biopolymer surface [53]. For instance, electropolymerized natural phenolic antioxidants have demonstrated significant potential as sensitive layers in electrochemical sensors, enhancing their detection capabilities [54].

3.2.2 Composite Formation

Another effective strategy is the formation of composites by combining biopolymers with conductive nanomaterials such as metal nanoparticles, graphene, and carbon nanotubes. These composites leverage the unique properties of both components, resulting in enhanced electrical conductivity and improved sensor performance. The synergistic effects of biopolymers and conductive nanomaterials not only improve sensitivity but also broaden the range of detectable analytes, making them highly versatile for various applications [55, 133].

3.2.3 Hydrogel and Film Fabrication

Natural biopolymers can also be processed into various physical forms, including hydrogels, films, and sponges, which can be tailored for specific sensing applications. For example, cellulose nanocomposite films incorporating iron coordination bonds and hydrogen bonds have exhibited excellent mechanical, electrical, and self-healing properties, making them ideal candidates for electronic skin sensors. These diverse morphologies allow for greater flexibility in sensor design and functionality [56, 129].

3.3 Green Synthesis

The green synthesis of biopolymer-based electrochemical sensors is a sustainable and eco-friendly approach that leverages biopolymers from natural sources for sensor development. In this method, biopolymers like cellulose, chitosan, alginate and gelatin are used as matrices or functionalizing agents in sensor construction [57, 125]. These materials offer several advantages, such as biocompatibility, biodegradability, and reduced toxicity, making them ideal for applications in environmental monitoring and medical diagnostics. Incorporating green synthesis techniques, such as using plants extract, microbes, or other natural reducing agents, ensures the production process is non-toxic and minimizes environmental impact [58]. This approaches also promotes cost-effectiveness by eliminating the need for harmful chemicals typically used in traditional sensor fabrication. Biopolymers-based electrochemical sensors can detect pollutants, heavy metals and biological molecules with high sensitivity. As green chemistry continues to evolve, this method represents a promising direction for developing sustainable, efficient and eco-friendly electrochemical sensors [59, 135].

4. APPLICATIONS

The high Sensitivity and Specificity of Electrochemical Sensing are combined with the benefits of Biopolymers such as Biocompatibility, Biodegradability and Adaptability to create Biopolymer-based Electrochemical Sensors. Numerous fields, including Food Safety, the Environment and Health, utilize these Sensors. A comprehensive list of applications are explained below:

4.1 Medical Diagnostics

Biopolymer Based Electrochemical Sensors are becoming more and more significant in medical diagnostics because of their properties and the accuracy of Electrochemical detection. These Sensors provide crucial information for the diagnosis, monitoring and treatment of wide range of disorders because they can identify different biological markers in bodily fluids including Blood, Urine, Sweating or Saliva [60]. For example, Alginate-based Sensors have been used for the point-of-care testing of Infectious disorders, while Chitosan-based Sensors have been designed to detect Cancer biomarkers. These Sensors offer advantages such as low Cost, Biocompatibility and ease of use [61, 136].

I. Glucose Monitoring for Diabetes Management: One of the most widespread applications of Biopolymer-based Electrochemical Sensors is in Glucose monitoring is in Glucose monitoring for diabetic patients. The Glucose oxidase (GOx) enzyme is frequently immobilized on sensor surface by these sensors using Biopolymers like Chitosan or Alginate [62]. An Electrochemical Response between enzyme and Blood Glucose causes an Electrical Signal that is proportionate to blood glucose levels. These sensors are built into Glucose Monitoring, which eliminate the need for finger-prick testing by offering real time Glucose monitoring [63].

II. Detection of Infectious Diseases: Biopolymers based Electrochemical Sensors are used to identify pathogens such as Viruses (COVID-19, HIV) and Bacteria (E. Coli, Salmonella). These Sensors can identify specific pathogen-related proteins or Nucleic Acid using Biopolymer matrices. The pathogen interacts with the recognition element on the Sensor to produce an Electrochemical Signal that indicates the Pathogen's presence [64].

III. Cancer Biomarker Detection: In body fluids like Blood or Urine, Biopolymer-based Electrochemical Sensors may identify Cancer Biomarkers including Prostate-specific Antigen (PSA), Carcinoembryonic Antigen (CEA) and Circulating tumor DNA (ctDNA). Collagen, Chitosan or Alginate are examples of Biopolymers that are employed to immobilize aptamers or antibodies that bind to these biomarkers selectively [65].

IV. Cardiovascular Disease Monitoring: Electrochemical Sensors that measure Blood troponin levels are essential for diagnosing heart attacks. A protein called Troponin is produced when damage occurs to Cardiac muscle cells. Troponin-specific antibodies are rendered immobile by Biopolymer-based Sensors which provide an Electrochemical Signal proportional to the Protein's concentration. This makes it possible to diagnose Cardiac events quickly and accurately. These Sensors can also be used to measure Cholestrol and other lipid markers [66].

V. pH and Blood Gas Monitoring: Blood pH, Oxygen(O_2) and Carbon-di-Oxide (CO_2) levels are frequently monitored using Electrochemical Sensors, which is important for treating patients with respiratory or metabolic diseases. By offering a steady environment for sensing gases and ions in blood, Biopolymers enhance Sensor performance [67, 130].

VI. Harmone Monitoring: Thyroxine (T_4) and Triiodothyronine (T_3) are detected by Sensors, these levels are critical for diagnosis of thyroid conditions, including hyperthyroidism and hypothyroidism. In order to facilitate Electrochemical detection, Biopolymers are utilized to immobilize antibodies or receptors that bind to these harmones precisely. The main stress harmone, Cortisol can be tracked via Biopolymer-based Electrochemical Sensors [68].

VII. Genetic Testing: Electrochemical Sensors based on Biopolymers are engineered to identify certain sequences of DNA or RNA linked to hereditary illnesses. For example, DNA probes that hybridize with target sequences in Genetic testing can be rendered immobile by Biopolymer Matrices, which will then provide an Electrochemical Signal upon binding. These Sensors are able to detect genetic abnormalities that cause disorders such as Muscular Dystrophy, Sickle Cell anaemia and Cystic fibrosis [69].

4.2 Environmental Monitoring

Environmental Monitoring relies heavily on Biopolymer-based Electrochemical Sensors, which provide Sensitive, Cost-effective and Environmentally acceptable means of identifying a wide range of Contaminants and potential threats to the Environment. These Sensors use the inherent biocompatibility, biodegradability and Versatility of Biopolymers- Alginate, Chitosan, Cellulose and Collagen to identify biological pollutants, heavy metals and hazardous Compounds in Soil, Water and the Air [70]. An extensive explanation of how these Sensors are used in Environmental Monitoring is provided below-:

I. Water Quality Monitoring: Biopolymer based Electrochemical Sensors are very applicable in the crucial field of Water Quality, especially for the detection of organic Pollutants, heavy metals and Microbial pathogens.

Heavy Metal Detection: Major contaminants in the Environment are Heavy metals such as Lead (Pb), Mercury (Hg), Cadmium (Cd) and Arsenic (As). Biopolymer matrices such as Chitosan or Alginate, offer an ideal environment for detecting metal ions and Biopolymer-based Electrochemical Sensors immobilize certain recognition components (e.g Aptamers, Enzymes or Antibodies). These extremely Sensitive Sensors can identify even minute concentrations of heavy metals in water bodies assisting in the prevention of human exposure and preservation of Ecosystems monitoring water in real time close to mining activities [71,72].

Organic Pollutant Detection: Hazardous Concentration of Pesticides and Herbicides, including Atrazine, Glyphosate and Organophosphates are frequently found in agricultural runoff. An Electrochemical Signal is produced by the sensors in proportion to the Pollutant Concentration in Water sources, including lakes, rivers and Ground Water. In wastewater or water bodies, these Sensors may also identify industrial pollutants including Dyes, Phenols and Polychlorinated biphenyls (PCB's) [73].

Detection of Microbial Pathogens: For recreational Water bodies and Safe drinking Water to be maintained, microbiological contamination must be closely monitored. Biopolymer-based Sensors are capable of immobilizing antibodies or aptamers that are specific to bacterial surface proteins, hence enabling detection of pathogenic bacteria such as Salmonella and Escherichia Coli. These Sensors offer quick and affordable ways to find evidence of Microbial Contamination in Water Sources [74].

II. Air Quality Monitoring: Ecosystem and Public Health are seriously endangered by Air Pollution, and Biopolymer-Based Electrochemical Sensors provide a Sensitive, real-time method of identifying dangerous Chemicals and particles in the Atmosphere.

Monitoring of Toxic Gases: The incomplete burning of fossil fuels releases Carbon monoxide, a Colourless and Odourless Gas that poses a threat to public Health. CO may be found in restricted locations like Parking Garages, Industrial sites and Urban Areas using Biopolymer Based Electrochemical Sensors [75]. The Biopolymer Matrices used in the Sensors operation immobilize enzymes or nanoparticles which then react with CO to produce an Electrochemical Signal. The Combustion of fossil fuels, industrial operations and automobile emissions release Sulphur-di-Oxide (SO_2) and Nitrogen Oxides (NO_x) which are pollutants that cause Smog and Acid-rain, Low conc. Of SO_2 and NO_x in the Environment can be detected using Electrochemical Sensors that use Biopolymers like Chitosan or Gelatin [76].

Detection of Particulate Matter: There are significant Respiratory Hazards associated with particulate matter (PM), particularly PM 2.5 (particles having a diameter of 2.5 microns or smaller). Electrochemical Sensors based on Biopolymers are able to identify airborne particulate matter and notify local populations of dangerous pollution levels. These Sensors employ Biopolymers like Cellulose or Alginate to give a stable Substrate for collecting particles and determining their concentration [77].

III. Soil-Quality Monitoring: Biopolymer-based Electrochemical Sensors offer effective tools for monitoring Soil contamination, nutrient levels and Environmental Health, especially in Agricultural and Industrial Areas.

Detection of Pesticide Residues: Pesticides called Carbamates and Organophosphates, which are often used in Agriculture, can pollute Soil and Water and endanger both human health and the Environment. Pesticide residues in Soil are detected by Biopolymer-based Sensors that immobilize Enzymes such as Acetylcholinesterase in Biopolymer matrices. These Enzymes interact with the Pesticides and cause an Electrochemical reaction that may be detected [78].

Nutrient Monitoring: Sustainable Agriculture depends on keeping the proper ratio of Nutrients in the Soil. Biopolymer based Electrochemical Sensors are able to track the important soil nutrients, including Potassium (K), Phosphorus (P) and Nitrogen (N), Real-time Soil health monitoring may be achieved by farmers through the use of Chitosan or Alginate based Sensors, which can optimize fertilizer use and increase the crop output. In Polluted Soils, Heavy Metals including Cadmium, Lead and Mercury may also be found using Electrochemical Sensors [79,80].

IV. Sustainable and Renewable Energy: Biopolymer based Electrochemical Sensors are also explored for applications in Sustainability, such as detecting Contaminants in Biofuel production or monitoring emissions from Renewable Energy technologies [81].

Biofuel Production Monitoring: The purity and effectiveness of BioEnergy production are guaranteed by Sensors that can identify impurities in Biofuels. When producing Biofuels, undesirable byproducts or contaminants are detected during fermentation process using Biopolymer-based Electrochemical Sensors [82].

Hydrogen Peroxide and Storage: In Hydrogen Production Systems, Sensors are used to detect impurities and monitor purity levels, which can have an impact on fuel cell and Hydrogen Storage Efficiency. Eco-friendly and Sustainable Sensors based on Biopolymers are available to track these activities [83].

4.3 Agriculture

Biopolymer-based electrochemical Sensors are gaining increasing attention in Agriculture for their ability to provide real-time, sensitive and environmentally friendly solutions to monitor various factors critical for crop health and productivity. These Sensors offer practical applications for nutrient

Erosion and Nutrient leaching. Farmers can maintain ideal Soil moisture levels for Crop development while achieving greater water-use efficiency [100].

4.4 wastewater treatment:

Biopolymer-based electrochemical sensors are emerging as a promising solution in wastewater treatment due to their eco-friendly nature, biocompatibility, and ability to detect a wide range of contaminants [101]. Biopolymers such as chitosan, alginate, and cellulose derivatives serve as effective matrices for immobilizing electroactive materials, enhancing the sensitivity, selectivity, and stability of these sensors. These sensors are particularly useful for detecting pollutants like heavy metals (e.g., lead, cadmium), organic contaminants, and hazardous chemicals in water [102, 126]. The incorporation of nanomaterials into biopolymer matrices further improves the performance of these sensors, enabling rapid and accurate detection of even trace amounts of contaminants. Biopolymer-based electrochemical sensors are not only capable of real-time monitoring of water quality but also contribute to the sustainability of wastewater treatment processes by offering biodegradable alternatives to synthetic polymers [103, 132].

The table below provides an overview of biopolymer-based electrochemical sensors developed for the detection and removal of water pollutants. The table highlights the types of biopolymers used, target pollutants, and electrode used, in pollutant removal from wate water.

Table.2: Pollutant removal from wastewater by different biopolymer

Biopolymer	Nanomaterial	Electrode	Pollutant removal	References
Chitosan	TiO2	CS@TiO2/CPE	Pb(II)	[104]
Chitosan	TiO2	CS@TiO2/CPE	Pb(II)	[104]
Chitosan	Cu	Chitosan/Cu Ag/AgCl	Pb(II)	[105]
Cellulose nano filler	Graphene oxide	GO/CNF/CPE	p-nitrophenol	[106]
Sodium alginate	-	Alg-S/Ag/AgCl	Cr(III) and Cr(VI)	[107]
Sodium Alginate	CuO	SA-GPM-RGO@CuO	Cd(II)	[108]
Thermoplastic starch	Graphene Oxide	TSP/Gr/Ag/AgCl	Catechol	[109]
Guar gum	Cu	Cu/GG/Ag/AgCl	Cu(II) and Ni(II)	[110]
Guar gum	Cu	Cu/GG/Ag/AgCl	Pb(II) and Mn (II)	[110]
Sulphated Carboxymethyl Cellulose	MWNT	CMC-S/MWNT/GCE	As(III)	[111]

4.5 wearable and implantable medical devices:

Biopolymer-based electrochemical sensors have become a promising approach in wearable and implantable medical devices due to their inherent biocompatibility, flexibility, and biodegradability [112]. Common biopolymers used in these sensors include chitosan, alginate, and polyaniline. These materials offer excellent electrochemical properties and are often combined with nanomaterials to enhance sensor performance for real-time, non-invasive health monitoring [113]. In wearable devices, biopolymer-based sensors can detect physiological parameters such as glucose levels, pH, and electrolytes from sweat, saliva, or interstitial fluid [114]. For instance, biopolymer films combined with nanomaterials enhance the sensitivity of glucose sensors in wearable patches, providing accurate monitoring for diabetic patients [115].

In implantable devices, biopolymer-based sensors are integrated into the body to monitor various biomarkers, such as lactate, oxygen, or electrolytes, directly from tissues or blood [116]. The biodegradable nature of biopolymers minimizes long-term side effects and reduces the need for surgical removal. These implantable sensors are particularly useful for post-surgical monitoring, chronic disease management, and personalized medicine applications [117].

The table below highlights various biopolymers used in electrochemical sensors for wearable and implantable medical devices, outlining their specific roles and benefits in enhancing the performance and compatibility of these devices.

Table.4: Biopolymer showing wearable medical devices applications

Biopolymer	Nanomaterial	Medical Applications	Wearable Device	References
Chitosan	Fe3O4 – graphene oxide	Dopamine detection	Wearable microneedle based electrochemical sensor	[118]
Chitosan	Graphene oxide	Tyrosine detection	Wearable point of care device	[119]
Chitosan	Graphene oxide – silver	Monitoring serotonin	Wearable microneedle based sensor	[120]
Polyvinyl alcohol (PVA)	-	Sweat detection	Wearable sweat sensors	[121]
Cellulose	Graphene	Human motion monitoring	Skin wearable physiological sensor	[122]
Polyaniline – Carboxymrthyl chitosan	Multi walled carbon nanotube	Glucose detection	Glucose-oxidase immobialization	[123]

5. Research direction in coming time

The future of biopolymer-based electrochemical sensors is poised for significant advancements through the optimization of functionalization, integration with nanomaterials, and implementation of sustainable synthesis methods. Research will focus on improving biocompatibility and biodegradability while incorporating conductive nanomaterials for better performance. These sensors hold promise in various sectors, including medical diagnostics for real-time biomarker monitoring, environmental applications for detecting pollutants in water and soil, and precision agriculture for assessing soil health and nutrient levels. Additionally, they can support food safety by detecting contaminants and pathogens. The development of portable, multi-analyte systems leveraging artificial intelligence will further expand their applicability in biotechnology and wearable technology. Effective scaling and field trials will be essential for transitioning these innovations into commercially viable solutions across diverse industries.

Conclusion

In summary, biopolymer-based electrochemical sensors hold significant promise for advancing sensor technology, offering a sustainable alternative to conventional materials. Biopolymers such as cellulose, chitosan, alginate, keratin, DNA, and RNA possess inherent biocompatibility, biodegradability, and versatile chemical functionalities, positioning them as ideal candidates for high-performance electrochemical sensors. The synthesis of biopolymer-based composites through various methodologies, including chemical polymerization, physical synthesis, and environmentally friendly green synthesis, enables the incorporation of conductive materials such as metal oxides, graphene, and nanoparticles, enhancing sensor sensitivity, stability, and overall performance.These biopolymer-based electrochemical sensors find extensive applications across diverse fields, including medical diagnostics, environmental monitoring, agriculture, wastewater treatment, and wearable and implantable medical devices. They exhibit excellent capabilities in the detection of biomarkers, environmental contaminants, and analytes, underscoring their versatility and potential. Despite these advantages, challenges remain, including the solubility, chemical and thermal stability, and mechanical limitations of biopolymers. Addressing these challenges requires continued research into novel synthetic routes and functionalization strategies to enhance sensor properties while maintaining environmental compatibility. Future research focused on improving the synthesis and functionalization of biopolymer-based composites is expected to unlock the full potential of these materials, enabling the design of next-generation sensors with enhanced performance for a wide array of applications in both scientific and industrial domains.

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