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Review

Biosensors in Food and Healthcare Industries: Bio-Coatings Based on Biogenic Nanoparticles and Biopolymers

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Abstract: Biosensors use biological materials, such as enzymes, antibodies, or DNA, to detect specific analytes. These devices have numerous applications in the health and food industries, such as disease diagnosis, food safety monitoring, and environmental monitoring. However, the production of biosensors can result in the generation of chemical waste, which is an environmental concern for the developed world. To address this issue, researchers have been exploring eco-friendly alternatives for immobilising biomolecules on biosensors. One solution uses bio-coatings derived from nanoparticles synthesised via green chemistry and biopolymers. These materials offer several advantages over traditional chemical coatings, such as improved sensitivity, stability, and biocompatibility. In conclusion, the use of bio-coatings derived from green-chemistry synthesised nanoparticles and biopolymers is a promising solution to the problem of chemical waste generated from the production of biosensors. This review provides an overview of these materials and their applications in the health and food industries, highlighting their potential to improve the performance and sustainability of biosensors.

Keywords: bio-coatings; nano/biosensors; green-chemistry; biogenic nanoparticles; biopolymer composites; surface modifications; eco-friendly coatings

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1. Introduction

In the digital era, regardless of all the scientific advancements, we are witnessing profound climate change, the emergence of new diseases, and the extinction of many animal and plant species due to household and industrial pollution [1,2]. The use of nanoparticles and polymers in developing biosensors has improved their performance and sensitivity [3,4]. However, their chemical synthesis generates by-products in the environment [5,6]. The green-chemistry and white biotechnology domains explore alternatives to reduce the environmental impact across the whole value chain, including food and medical industries [7,8]. Figure 1 presents the elements of a biosensor, with emphasis on the coating choice, which is the main subject of this review.

Briefly, biosensors are devices used to analyse the concentration of a specific target component with the help of a sensitive biological element. They can detect, record, and transmit selective, quantitative, or semi-quantitative analytical information about biochemical reactions [9]. A biosensor includes a substrate, typically paper, glass, or silicon. The substrate must be chemically modified to ensure an effective immobilisation of the biorecognition elements. The biorecognition elements can be organic components (enzymes, antibodies, hormones, or nucleic acids), biological material (microorganisms, cellular organelles, tissues, or receptor cells), biologically derived material, or biomimetic components. Analyte detection is possible with a transducer which translates the biological response into a quantifiable signal (optical, electrochemical, amperometry) [10,11].

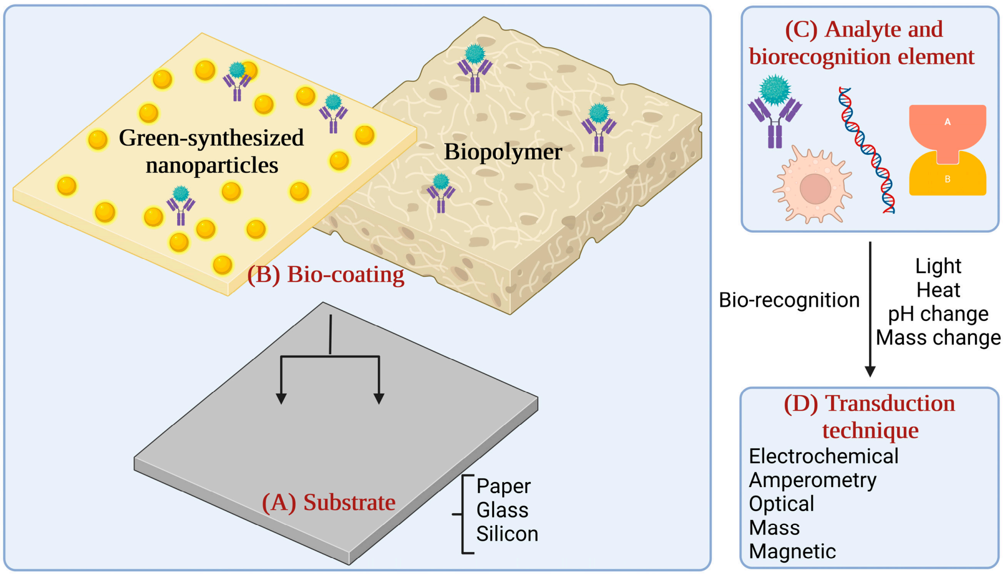

Figure 1. Schematic of biosensing elements. (**A**) Substrate; (**B**) Bio-coating; (**C**) Analyte and biorecognition element, and (**D**) Transduction technique (the graphical illustration has been created with BioRender software—BioRender Company, Toronto, ON, Canada).

One of the critical challenges in biosensor development is the immobilisation and stabilisation of the biological component on the transducer surface, which can affect the sensor's sensitivity, selectivity, stability, and reproducibility [12,13]. To address these challenges, bio-coatings have emerged as a promising approach for the functionalisation of biosensors. Bio-coatings refer to a wide range of natural and synthetic materials that can be utilised to immobilise and protect the biological component, enhance its performance, and prevent non-specific interactions with the sample matrix [14]. In this regard, green-synthesised metallic nanoparticles, and biopolymers, in which our group has significant expertise [15–23], were explored as ecologically safe alternatives for bio-coatings, and the role they adopt in biosensing applications in the health and food industries. In healthcare, bio-coatings can be employed to modify the surface of biosensors for specific binding to disease markers or pathogens. For example, bio-coatings containing antibodies or peptides can be used to detect specific proteins in the blood, saliva, or urine, enabling early diagnosis of various diseases. Additionally, bio-coatings can be used to enhance the biocompatibility and stability of implantable biosensors for long-term monitoring of health parameters [24].

In the food industry, bio-coatings can be utilised to modify the surface of biosensors for the detecting food contaminants (e.g., bacteria, toxins, chemicals), or can serve as food spoilage indicators (e.g., volatile organic compounds, pH). Bio-coatings can also improve biosensors' stability and shelf-life, allowing for more reliable and accurate food quality control [25].

The biological synthesis (Table 1) of NPs is a bottom-up approach that involves utilising bacteria, fungi, algae, and plant-derived materials [26,27]. The microbial-mediated synthesis of nanoparticles involves extracellular or intracellular culture filtrates employed as a reducing agent for nanoparticles production. Members of the Monera and Fungi kingdoms possess metallothioneins which make them capable of tolerating, accumulating, and converting metals into metal ions [28]. For instance, Beveridge and Murray (1980) were the first to synthesise gold nanoparticles from *Bacillus subtilis* [29]. Microorganisms were also employed to synthesise Ag, Pt, Pd, Cu, Fe, Ni, Zn, and Se nanoparticles [27,30]. Table 1 presents the utilised microorganism and the type of metallic nanoparticle obtained.

Table 1. Nanoparticles synthesised by green synthesis.

Green Synthetic Method	Type of Nanoparticles/Source	Ref.
Bacteria-Mediated Synthesis of Nanoparticles	AuNPs/*Delftia acidovorans*	[31]
	PdNPs/*Escherichia coli*	[32]
	AgNPs/*Bacillus licheniform*	[33]
	CuNPs/*Morganella morganii*	[34]
Nanoparticle Synthesis Using Yeast	AuNPs/*Pichia jadinii*	[35]
	AgNPs/Yeast strain MKY3	[36]
	AuNPs/*Yarrowia lipolytica* NCIM3589	[37]
Nanoparticle Synthesis Using Fungi	PtNPs/*Fusarium oxyporum*	[38]
	ZnNPs/*Fusarium* spp.	[39]
	HgNPs/*Aspergillus versicolor* mycelia	[40]
	AuNPs/*Rhizopus oryzae*	[41]
	AgNPs/*Verticillum* sp.	[42]
Nanoparticles Synthesis Using Cyanobacteria	AgNPs/*Spirulina platensis* and *Nostoclinckia*	[43]
	AuNPs/*Lyngbya majuscula* and *Spirulina subsalsa*	[44]
Nanoparticle Synthesis Using Algae	AgNPs/Au-AgNPs/AuNPs/*Sargassum wightii*	[45]
	AuNPs/*Euglena gracilis*	[46]
Nanoparticle Synthesis Using Plants	AgNPs/*Raphanus sativus* L.	[19]
	AgNPs/AuNPs/*Azadirachta indica*	[47]
	CuNPs/*Magnolia kobus*	[48]
	PtNPs/*Diospyros kaki*	[49]
Nanoparticle Synthesis Using Viruses	AgNPs/AuNPs/*China virus*	[50]
	AuNPs/Tobacco mosaic viruses	[51]

Biopolymers are ecologically safe alternatives to conventional polymers thanks to their biodegradable nature and their origin from renewable resources [52]. They can successfully be used as bio-coatings for developing new biosensors, as they act as immobilisation matrices for including the biorecognition elements [53]. Depending on the sources of origin and synthesis routes, they can be classified into natural polymers, biosynthetic polymers, or biopolymer composites.

The most significant amounts of natural biopolymers are industrially extracted from plant and animal sources (e.g., chitosan obtained from shrimp shells, cellulose extracted from wood, cotton, collagen, gelatine extracted from pig and cow), and can play a considerable role in solving the environmental problems raised using polymeric materials [54,55].

Biosynthetic polymers, also known as bioplastics, are categorised into three divisions: non-biodegradable, biodegradable-petroleum, and biodegradable based on natural polymer [12,13]. The last two categories are of interest in this review. Bio-based biodegradable polymers can be produced by microbial fermentation processes starting from biomass or organic waste from agriculture, food processing, and landfills [52,56]. Biodegradable polymers can be obtained through bacterial biosynthesis from natural materials (polysaccharide polyesters) or through chemical synthesis from renewable natural materials (lactic acid polyesters—obtained by fermentation starting from starch [57]).

Biopolymer composites (Table 2) with metal nanoparticles, silica, metal oxides, carbon-based materials, and polymers were developed to overcome the 'biopolymers' drawbacks, such as low mechanical and low chemical resistance or hygroscopicity [53].

Table 2. Biopolymer types—used as a coating for food and health application.

Biopolymer	Electrode Materials	Analyte	Transduction Method	Limit of Detection (LOD)	Ref.
Natural polymers - polysaccharides - proteins - DNA	GOX/Co/chitosan	D-Glucose	Electrochemical	2.7 nM	[58]
	Carbon nanotubes/sol–gel-derived silica/chitosan	Cholesterol	Electrochemical	12 mg/dL	[59]
	Collagen–Poc matrix	*Escherichia coli*	Electrochemical	8×10^4 CFU to 8×10^7 CFU in 10 µL sample of YadA expressing *E. coli*	[60]
	Lox—BC	Lactate	Electrochemical	1.31 mmol L^{-1}	[61]
	Paper-based DNA biosensor	Cow, sheep, and goat yoghurt samples and adulterated food products (legumes, olive oil, meat)	Electrochemical	1.6 fmol (cow and goat) 3.1 fmol (sheep)	[62]
	Iron oxide/chitosan	Urea	Electrochemical	0.5 mg dL^{-1}	[63]
	Silk/polyols/glucose oxidase	D-Glucose	Electrochemical	1.7 mM L^{-1}	[64]
	Chitosan/Silver Nanowires	D-Glucose	Electrochemical	2.1 µM	[65]
Biosynthetic polymers - Biodegradable but not bio-based (PBAT—poly (butylene adipate-co-terephthalate) - Biodegradable and bio-based (cellulose-based thermoplastic starch—TPS, poly lactide—PLA, polyhydroxyalkanoates—PHA, poly-hydroxybutyrate—PHB, poly-glutamic acid—PGA)	Graphene Oxide/Polylactic Acid	Serotonin	Electrochemical	0.032 µmol L^{-1}	[66]
	Graphene/Polylactic Acid	Uric acid Nitrite	Electrochemical	0.02 µmol L^{-1} 0.03 µmol L^{-1}	[67]
	PBAT	Viral nucleic acid fragments (zika virus, Japanese encephalitis virus, West Nile virus, Dengue virus)	Optical	10 copies/µL	[68]
	PHB	*Acinetobacter baumannii*, *Escherichia coli*, *Klebsiella pneumoniae*, *Pseudomonas aeruginosa*	Optical	5 pM	[69]
	PGA	*Michigan Cancer Foundation-7* (MCF-7)	Electrochemical	25 cells	[70]

Nanoparticles and biopolymers can be incorporated into chemical or/and biological sensors to improve the analytical performance of selectivity, sensitivity, response time, and accuracy. It is a complex and ramified domain, as seen in Figure 2.

The analysis of the biosensor's domain has been performed using a tool for the construction and visualisation of bibliometric elements, namely VOS viewer 1.6.18 [71]. Figure 2 shows a bibliometric analysis of the data extracted from the ISI Web of Science (www.webofscience.com) database, using the following keywords: "biosensors in food industries" and "biosensors in health industries".

The analysis of bibliometric networks has received considerable attention during the last five years. Figure 2 shows the complexity of the domain, and it is practically impossible to cover all these aspects within a single review. It is a multidisciplinary domain at the confluence of chemistry, physics, biochemistry, and biotechnology, and the list is still open. For these reasons, we have chosen to discuss only biosensors from the food industry and medical applications, namely those that have bio-coating from biopolymers, nanoparticles, or combinations from these categories.

In this regard, Figure 3 shows the search on ISI Web of Science (using the keywords "biosensors in food industries" and "biosensors in health industries") of the number of papers published through the last 22 years in the biosensors domain. This graph shows an increasing number of articles describing biosensors' applications in medicine and the food industry. The exponential growth during the last 10 years is probably correlated with the importance of food safety and prevention in the medical domain. An increase in publications in the last two years for applications in healthcare can be observed, probably related to the COVID pandemic.

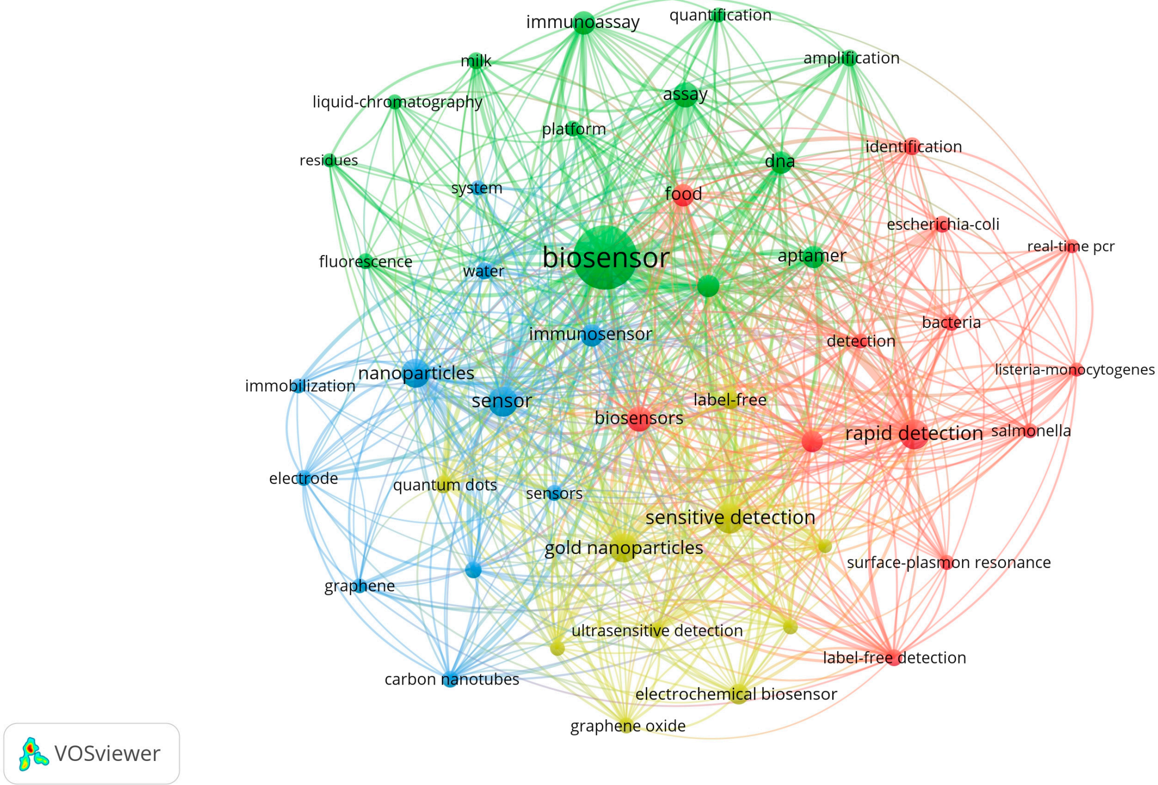

Figure 2. The bibliometric analysis of data extracted from the ISI Web of Science database using the keywords ”biosensors in food industries” and “biosensors in health industries”.

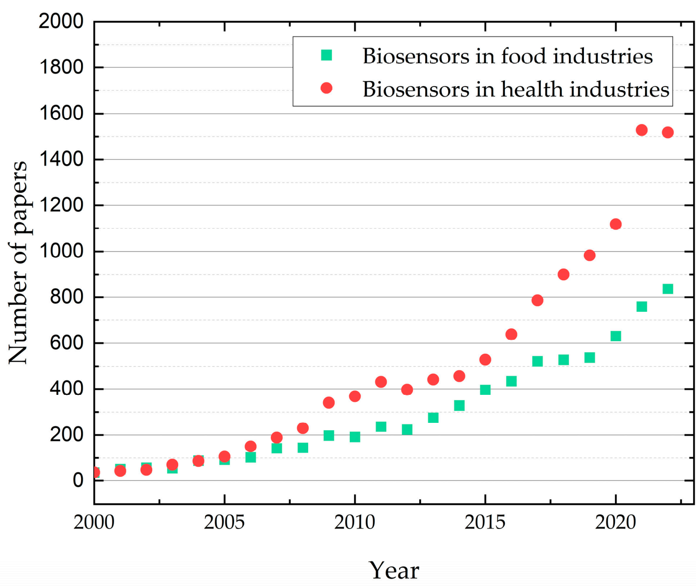

Figure 3. Publication trend (2000–2022) in the application of biosensors—applications in health and food industries (Source of raw data: ISI Web of Science; search keywords: biosensors in food industries, biosensors in health industries).

While there are reviews addressing biosensors in food and health [72–78], there are few publications on biosensors based on sustainable materials with applications in these sectors. For instance, one review focused on developing hydrogels for biosensing applications in diagnostics [79], while another concentrated on biodegradable sensors for invasive and non-invasive health monitoring [7]. Concerning the food sector, a complex review addressed the application of eco-friendly biopolymer composites for food packaging [80].

Aside from the ecological consequences of mass farming, agriculture, and food production processes in the food industry, there are concerns related to the increasing levels of food waste and the usual usage of plastics in food packaging. Food packaging is the third-largest global industry and the single-largest contributor to solid waste. Thus, food packaging and waste management are two critical elements in the race to address climate change. In this respect, several recent studies present innovative solutions for intelligent, sustainable food packaging alternatives to petroleum-based plastics and synthetic dyes [25,81].

Correspondingly, in the healthcare sector, there are also rising concerns regarding the clinical use and disposal of biosensors, especially after the COVID pandemic [5]. The emergence of biodegradable materials represents a legitimate solution to the fast-depleting fossil-based materials. This represents a solution to reducing environmental pollution, as nowadays, the trend is towards developing wearable or implantable biosensors that naturally degrade [7]. Several state-of-the-art studies present sustainable biosensors based on biopolymers, green-synthesized NPs, or biopolymer nanocomposites with increased performance [82,83].

The novelty of this review lies in its comprehensive analysis of the latest research and development in biosensors from the food and healthcare sectors that use bio-coatings based on green-synthesized nanoparticles and biopolymers. Such an approach can help identify the current challenges and opportunities in the development of bio-coatings for specific applications, which can further guide research and development efforts. We explored the potential impact of bio-coatings in enhancing biosensors' sensitivity, selectivity, stability, and durability, which could ultimately improve the safety and quality of food and healthcare products. Viewed from another angle, this review also aims to highlight the eco-friendly and sustainable bio-coatings which can be employed in the biosensor's development. As the world becomes more environmentally conscious, there is a growing need for sustainable solutions in various industries, including food and healthcare. Thus, a review that emphasizes the sustainability and potential impact of bio-coatings could be of great interest to policymakers, industry professionals, and the general public.

2. Biosensors with Bio-Coatings and Applications in the Food Sector

Nanotechnology has brought significant advancements in the food sector by bringing biosensors and food additives in the form of nanoparticles to ensure safety and traceability for packaging food products [84,85] and the development of food production [86]. Despite the extraordinary advantages of food packaging and biosensors in agriculture and the food industry, public opinion expresses concern about toxicity and its effect on the environment. There is slight knowledge of long-term adverse effects on soil, plants, and ultimately humans [87]. Thus, research nowadays focuses more on developing sustainable, non-toxic, and environmentally friendly materials for food packaging and biosensing. In this section, we focus on the development of bio-coatings based on nanoparticles obtained through green synthesis methods and biopolymers with applications in the food sector (Figure 4).

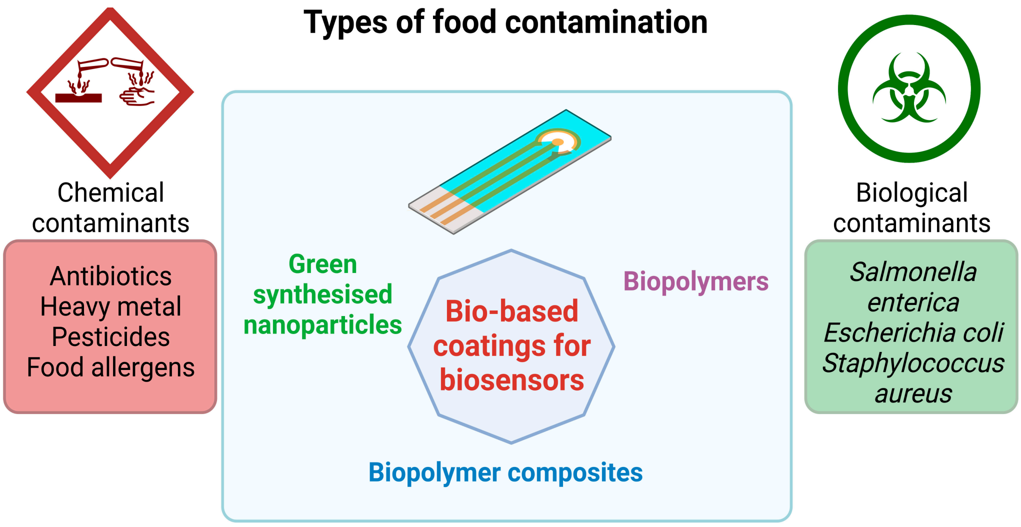

Figure 4. Applications of bio-based coatings for biosensors used for monitoring food contamination (the graphical illustration has been created with BioRender software—BioRender Company, Toronto, ON, Canada).

Nanotechnology enabled the rapid evolution of biosensors for detecting food components in an easy and timely manner. For example, biosensors were developed to detect external and internal conditions in food packaging, organic compounds, cations, anions, pesticides, antibiotics, heavy metals, microbial cells, and toxins [88]. Biosensors assure consumers that they are purchasing fresh products, reducing the frequency of foodborne infections and food poisoning, contributing thus to food safety [89].

For food analysis, biosensors based on nanoparticles, electrochemical biosensors, and optical biosensors are employed [90]. They can be introduced directly in the packaging material, serving as an "electronic tongue" or "nose" for the identification of the chemical substances released during food alteration [91], or indirectly, using microfluidic devices (ex: Si-based microfluidic systems) for the detection of pathogens, in real-time and with high sensitivity [92].

The biosensors containing nanoparticles were developed to detect and neutralise pathogens or other contaminants, most being used for pathogen detection in fish [93]. Gold nanoparticle biosensors use a surface resonance detection method to detect ochratoxin A, a mycotoxin produced by *Aspergillus* and *Penicillium* moulds that often contaminate raw materials and food products and have strong toxic effects on the visceral organs of both humans and animals [94]. The applications of nanoparticles in food preservation and packaging are expected to reach USD 125.7 billion by 2024 and a staggering USD 44.8 billion by 2030 [95].

Nanoelectromechanical systems (NEMS) are already in use in the food sector; these systems contain parts with sizes ranging from mm to nm, which could serve to develop sensors used to preserve food [96]. NEMS could also be used in food control, consisting of advanced transducers for detecting specific chemical and biochemical signals [97].

As previously mentioned, biosensors also evaluate food contamination with antibiotics, preservatives, and mycotoxins. Estimating the residual amount of antibiotics in milk, dairy products, and meat is an essential analysis in food technology. Biosensors with gold nanoparticles that use pyrocatechol violet interact with the hydroxyl and amide groups of antibiotics through hydrogen bonding. As a result, the colour changes even for small concentrations, resulting thus in the detection of antibiotics such as kanamycin, neomycin, streptomycin, and bleomycin, etc. Silver biosensors serve to detect clusters of nitrites in food, which is a frequently used preservative, but also a carcinogenic pollutant [98,99].

The purpose of intelligent packaging is the real-time assessment of product quality by monitoring the interactions between the product, the packaging, and the environment, through a series of sensors or indicators. The sensor readings should be translated into a clear message about quality, safety status, or shelf life. The signal must then be communicated to different actors in the supply chain, including the consumer [100]. The main goal of biosensors is to reduce the time for pathogen detection from days to hours or even minutes. Microbial sensors are biosensors used in the food industry to detect and monitor any alteration occurring during packaging and storage [101].

Globally, the use of active and smart packaging systems has expanded as the European Union and international legislation have put an accent on food safety, decreasing foodborne diseases. At the same time, the new intelligent packaging systems became particularly useful to processors, to the extent that new packaging increases the shelf life of products [102–105].

The advancements of bio-nanotechnology have considerably improved the wrapping/packaging of food, increasing their quality and safety [106–108]. Food packaging can be comprised into four types: passive (no interaction with the product), active (capable of interacting with the product), intelligent (reactive to the environment), and smart (involves the use of technology) [109,110].

The use of metal oxides in food packaging metal nanoparticles with their strong antimicrobial properties are used as "active packaging". The metallic nanoparticles with pronounced biocidal properties are Ag, Cu, Zn, Ti, and Au. They also contribute to an increase in the mechanical resistance, light resistance, and barrier properties of the packaging [111].

Silver nanoparticles (AgNPs) have been proven to have the best antimicrobial activity against various microorganisms [112]. AgNPs showed better antimicrobial activity than metallic silver due to their extensive relative surface area, which can ensure better contact with microorganisms.

The antifungal effect of LDPE (decorated with nanosilver) was also presented against yeasts and moulds; this fact allowed a significant decrease in the pasteurization temperature of orange juice by 10%. The nano-packaging obtained with low-density polyethylene and nano-silver was able to maintain the sensory, physicochemical, and physiological qualities of blueberries and strawberries at a higher level compared to the usual packaging made with polyethylene bags [113].

Mahdi and collaborators [114] evaluated the antimicrobial effect of the PVC-nano Ag nano packaging used for minced beef, stored at refrigeration temperature (+4 °C). After 7 days of study, it was found that this nano packaging inhibited microbial growth. The inhibitory effect is stronger against the growth of *Escherichia coli* compared to *Staphylococcus aureus*. Growth bacteria allowed an increase in the shelf life compared to the usual food packaging. The effects of Ag and TiO_2 nanoparticles embedded in polyethylene (PE) on the contents of solid, liquid, high-fat, and highly acidic food samples compared to conventional containers were studied by Metak et al [115].

Copper and its compounds have been known as biocidal substances for centuries, being used today as effective antimicrobial and antiviral agents. Unfortunately, the direct use of copper and its compounds can be toxic to fish and other organisms and can cause environmental damage. The copper nanoparticles can substitute the copper and its compounds, allowing to avoid these issues.

Copper nanoparticles can also be used as cheap alternatives for silver nanoparticles [116,117]. Nevertheless, the use of copper nanoparticles in the food industry raises concerns. Copper is one of the micronutrients necessary for the normal functioning of the human body; it contributes to maintaining homeostasis. If copper intake exceeds the limits of human tolerance, it can present toxic effects such as haemolysis, jaundice, and eventually death. Similarly, if the intake of copper nanoparticles enters the human body in excess by any route, such as ingestion or inhalation, it causes toxic effects in the respiratory tract, the gastrointestinal tract, and other tissues. Chen Z. and co-authors demonstrated that copper nanoparticles are more toxic than copper microparticles because the nanoparticles can quickly enter the body. Copper nanoparticles also cause pathological damage to the liver, kidney, and spleen [118].

Zinc oxide (ZnO) nanoparticles can be used in food preservation due to their antimicrobial properties [117]. Espitia P. and co-authors [119] evaluated the antimicrobial activity of ZnO nanocomposites on Gram-negative bacteria such as *Escherichia coli*, *Pseudomonas aeruginosa*, *Campylobacter jejuni*, as well as Gram-positive bacteria such as *Bacillus subtilis*, *Staphylococcus aureus*, and *Lactobacillus plantarum*. ZnO nanoparticles also showed significant antifungal activity against phytopathogenic fungi of fruits in the post-harvest period: *Botrytis cinerea* and *Penicillium expansum* in concentrations higher than 3 mmol/L^{-1}. Antimicrobial food packaging manufactured using ZnO nanoparticles represents an impact on consumers. The balance of positive and negative effects on the food safety of ZnO must be thoroughly assessed. Research on the toxicological impact of ZnO nanoparticles on the 'consumers' health focused on migrating ZnO nanoparticles from the package into the contained food. This research emphasised toxicity, inflammatory and carcinogenic effects for in vitro experiments on colon cell cultures [119].

Additionally, edible films containing antimicrobial components are crucial for extending product shelf life and reducing the risk of pathogens. Biodegradable polymer films represent an alternative option in food packaging, as they can be obtained at low cost from renewable sources without causing environmental pollution. Polysaccharides such as cellulose, pullulan, agarose, starch, and chitosan are the most used. Covering films with cellulose and silver nanoparticles in their composition have good antimicrobial effect against *Escherichia coli* and *Bacillus* sp. [120]. Based on these properties, Muthulaksmi L., and collaborators [121] consider that cellulose/AgNPs composite films can be used for antimicrobial packaging and health applications.

Pullulan (α-1,4-; α-1,6-glucan) is an edible polysaccharide polymer consisting of maltotriose units. This polymer is produced from the starch of the fungus *Aureobasidium pullulans*. Pullulan films are colourless, tasteless, resistant to oil, and have low permeability to oxygen but are sensitive to high humidity. As a food additive, it is known by the numerical code E1204. It is a non-toxic, water-soluble packaging material to prevent the oxidation of food [122].

Khalaf H.H and collaborators [123] studied the antimicrobial activity of complex pullulan films incorporating silver nanoparticles (100 nm) and zinc oxide nanoparticles (110 nm). These films also contained oil of oregano (OR) 2% and rosemary oil (RO) 2%. Antibacterial activity was determined during meat preparation and storage at 4, 25, 37, and 55 °C. The test was conducted on *Listeria monocytogenes* and *Staphylococcus aureus* bacteria. The study's results demonstrated that the films obtained from pullulan with the addition of Ag nanoparticles, ZnO, and essential oils of rosemary and oregano inactivated pathogens, especially *Listeria monocytogens*, and *Staphylococcus aureus* bacteria, cause meat spoilage. The antimicrobial activity was more pronounced in films with Ag nanoparticles and oregano essential oil. The edible films did not change the physical and organoleptic properties of the product. Active packaging of agar hydrogel using silver nanoparticles effectively extends the shelf life of Fior di Latte cheese [124].

Italian researchers Longano D., Ditaranto N., Cioffi N., et al. [125] developed a new antibacterial additive composed of copper nanoparticles incorporated in polylactic acid, thus combining the antimicrobial properties of copper nanoparticles with the biodegradability of the polymer matrix. It has been experimentally demonstrated that this nanocomposite prevents the proliferation of *Pseudomonas* spp. bacteria, with great potential in smart packaging.

Table 3 summarizes some applications of Biosensors (obtained through green chemistry) in the food industry.

Table 3. Various sensing nanoplatforms utilised in the food industry.

Nanomaterial	Source of Green Synthetic Method	Analyte	Transduction Method	The Limit of Detection (LOD)	Ref.
AgNPs	Quercetin	Lactose	Electrochemical	3.5 µM	[126]
AgNPs	Onion peel	Mercury	Colorimetric	-	[127]
AgNPs	Pine-nut extract (*Araucaria angustifolia*)	Drugs	Electrochemical	8.50×10^{-8} mol L^{-1}	[128]
AuNPs	Chitosan	the target antigen (Ag)	Optical	1 µg/mL	[129]
AuNPs	Papaya juice	L-lysine	Fluorescence	6.0 µmol/L	[130]
AuNPs	The protein from soybeans	Bismerthiazol	Fluorescence	5 µg/mL	[131]
AuNPs	Soybean extract	Copper ions	Optical	10 µM	[132]
PdNPs	*Ogataea polymorpha*	Bisphenol A	Amperometry	0.145 mM	[133]
gold nanoclusters	Onion membranes	Sucrose	-	-	[134]
Graphene oxide decorated with AuNPs	Rose water	Glucose	Electrochemical	10 µM	[135]
CuNPs	*Ocimum tenuiflorum* leaf extract	Glucose	Electrochemical	0.038 µM	[136]
Carbon Quantum dots	Bamboo leaves	Copper ions	Optical	115 nM	[137]
Copper oxide nanoparticles (CuONPs)	*Caesalpinia bonducella* seed extract	Riboflavin	Electrochemical	1.04 nm	[138]
CuONPs	Stem latex of peepal (*Ficus Religiosa*)	Pesticides	Electrochemical	-	[139]
AuNPs	*Bischofia javanica* Blume leaves	Chloramphenicol determination in milk, powdered milk, honey, and eye drops	Amperometry	0.25 µM	[140]
Au NPs	*Syzygium aromaticum* extract	Urease from milk	Electrochemical	-	[141]
Ag-AuNPs	*Citrus × sinensis* (L.) Osbeck peels	Caffeine	Electrochemical	2.02 µM	[142]
AgNPS, AuNPS, PdNPS	*O. polymorpha* NCYC495-pGAP1-HsARG1 (leu2car1 Sc: LEU2)	Phenolic compounds and alcohols	Amperometry	-	[133]
AuNPs	*Radix pueraria* flavonoids	Cholesterol	Electrochemical	0.259 µmol/L	[143]

Bollella et al. [126] described the green synthesis and characterisation of gold and silver nanoparticles and their application for developing a third-generation lactose biosensor. The researchers developed a lactose biosensor using synthesised nanoparticles, which showed high sensitivity and selectivity for lactose detection. The biosensor had a linear range from 10 to 300 mM, a high sensitivity (5.4 µA mM^{-1} cm^{-2}) and was stable and reproducible, indicating its potential for practical applications.

Santhosh and co-workers [127] discussed the green synthesis of silver nanoparticles using onion peels, which are a waste product. The authors of the study used a simple, cost-effective, and eco-friendly method to synthesise the nanoparticles. The study found that the silver nanoparticles showed intense antimicrobial activity against various bacterial strains and antiproliferative activity against cancer cells. Overall, the study highlighted the development of a biosensor for the determination of mercury.

Another article [129] presented a novel method for synthesising chitosan-gold nanoparticles (CS-GNPs) and their application in optical biosensing. The CS-GNPs were synthesised using a green chemistry approach, which avoids the use of toxic chemicals typically used in nanoparticle synthesis. The green synthesis of the CS-GNPs was achieved using chitosan, a natural polymer derived from the shells of crustaceans. The results showed that the sensor had high sensitivity and specificity towards the target antigen, with a detection limit of 1 μg/mL. The sensor also showed good stability and reproducibility over time. The authors conclude that their green synthesis approach for CS-GNP synthesis, combined with the use of a specific antibody, provides a promising platform for developing optical biosensors to detect various analytes.

Yu et al. [130] studied a green synthesis approach to produce gold nanoclusters (AuNCs) using papaya juice as a reducing agent. The AuNCs were synthesised in a one-step process, using chloroauric acid as the precursor and papaya juice as the reducing agent. The results showed that the synthesised AuNCs exhibited strong fluorescence properties with a maximum emission wavelength of 440 nm. The fluorescence properties of the AuNCs were afterwards used to develop a sensing platform for detecting L-lysine, an amino acid commonly found in food products.

A new method for detecting bismerthiazol [131], a commonly used fungicide in cabbage was developed using protein-capping gold nanoclusters (PC-GNCs). The PC-GNCs were synthesised using a simple, green method, and were then functionalised with the protein from soybeans to enhance their stability and biocompatibility. The sensor's performance was evaluated by measuring the fluorescence intensity of the PC-GNCs in the presence of different concentrations of bismerthiazol. The results showed that the sensor had a linear response to bismerthiazol concentrations in the range of 5–100 μg/mL with a detection limit of 5 μg/L. The detection time for bismerthiazol was less than 5 min, making this approach a fast and efficient method for detecting the fungicide in cabbage.

The same author [132] described a green synthesis approach to produce gold nanoclusters (AuNCs) using soy protein as a template. The synthesised AuNCs were used to develop a sensing platform for detecting copper ions (Cu^{2+}). The sensor's performance was evaluated using several techniques, including fluorescence spectroscopy and transmission electron microscopy. The fluorescent AuNCs were employed to develop a visual detection method for Cu^{2+}, involving the addition of a Cu^{2+} solution to the AuNCs, followed by observation of the change in colour of the solution. The detection limit for Cu^{2+} using this method was 10 μM, below the permissible limit for Cu^{2+} in drinking water set by the World Health Organization [144].

Bagal-Kestwal et al. [134] developed a fluorescence-based sucrose sensor using plant membranes decorated with invertase-nanogold clusters (INV-NGCs). Invertase is an enzyme that catalyses the hydrolysis of sucrose into glucose and fructose, and nanogold clusters (NGCs) are small clusters of gold nanoparticles. The INV-NGCs were synthesised using a green synthesis method (on the surface of the inner epidermal membranes of onions (*Allium cepa* L.). The sensor's performance was evaluated by measuring the fluorescence intensity of the INV-NGC-decorated plant membranes in the presence of different concentrations of sucrose. The results showed that the sensor had a linear response to sucrose concentrations in the range of 2.25×10^{-9} to 4.25×10^{-8} M. The sensor also exhibited good selectivity towards sucrose over other sugars and was stable and reproducible over time.

Another article [135] described the synthesis of reduced graphene oxide (rGO) decorated with gold nanoparticles (AuNPs) using a green chemistry approach. The rGO-AuNP composite was synthesised using rose water as a reducing agent. The synthesised composite was then used as a sensing platform for glucose detection. The sensor's performance was evaluated by measuring the change in the electrochemical response of the rGO-AuNP composite in the presence of different glucose concentrations. The results showed that the sensor had a linear response to glucose concentrations in the range of 1-8 mM, with a detection limit of 10 μM.

Dayakar and co-workers [136] synthesised pristine copper nanoparticles (CuNPs) (using *Ocimum tenuiflorum* leaf extract) and studied their use in a non-enzymatic sensing platform for the detection of glucose. The CuNPs were synthesised using a simple, one-pot reduction method and were then characterised using several techniques, including transmission electron microscopy and X-ray diffraction analysis. The sensor's performance was evaluated by measuring the electrochemical response of the CuNP-modified electrode in the presence of various glucose concentrations. The results showed that the sensor had a linear response to glucose concentrations in the 1–7.2 mM range, with a detection limit of 0.038 μM. Using pristine CuNPs as a sensing platform simplifies the biosensor design and reduces the cost and complexity associated with enzymatic biosensors. The CuNPs synthesised using this approach have the potential to revolutionise the field of biosensing.

The green synthesis of fluorescent carbon nanodots (CNDs) from bamboo leaves was reported by Liu at al. [137] and their use as a sensing platform for the detection of copper (II) ions (Cu^{2+}). The CNDs were synthesised using a one-step hydrothermal method and were then functionalised with sodium hydroxide to enhance their fluorescence properties. The sensor's performance was evaluated by measuring the change in the fluorescence intensity of the CNDs in the presence of different concentrations of Cu^{2+}. The results showed that the sensor had a linear response to Cu^{2+} concentrations in the range of 0.333 to 66.6 μM, with a detection limit of 115 nM. Using bamboo leaves as a precursor for CND synthesis reduced the cost and environmental impact of nanoparticle synthesis and provided a new avenue for developing biosensors based on natural materials. The CNDs synthesised using this green synthesis method have the potential to revolutionise the field of biosensing.

Sukumar et al. [138] synthesised rice-shaped copper oxide nanoparticles (CuONPs) using the extract of *Caesalpinia bonducella* seeds as a reducing and stabilising agent. The synthesised CuONPs were characterised using several techniques, including transmission electron microscopy and X-ray diffraction analysis. The CuONPs exhibited good photocatalytic activity towards the degradation of methylene blue under visible light irradiation and exhibited good antibacterial activity towards *Aeromonas* and *Staphylococcus aureus*. The authors concluded that their approach for the green synthesis of rice-shaped CuONPs using *Caesalpinia bonducella* seed extract is facile and cost-effective. The CuONPs synthesised using this green synthesis method have the potential to revolutionise the field of photocatalysis and antibacterial materials and carry out electrochemical detection of riboflavin.

A new method for the biogenic synthesis of copper oxide nanoparticles (CuONPs) [139] using the aqueous extract of the latex of *Ficus religiosa* as a reducing and stabilising agent was described by Singh et al. The performance of the CuONPs was evaluated for their biosensing applications, particularly for pesticide detection.

Karthik et al. [140] synthesised gold nanoparticles (AuNPs) decorated graphene oxide (GO) using *Bischofia javanica* Blume leaves as a reducing and stabilising agent. The synthesised AuNPs-GO composite was used as a sensing platform for detecting chloramphenicol in various food samples (in milk, powdered milk, honey, and eye drops). The sensor's performance was evaluated by measuring the change in the electrochemical response of the AuNPs-GO composite in the presence of various chloramphenicol concentrations. The results showed that the sensor had a linear response to chloramphenicol concentrations in the range of 1.5–2.95 μM, with a detection limit of 0.25 μM. The sensor also exhibited good selectivity towards chloramphenicol over other antibiotics and was stable and reproducible over time.

A new green synthesis of gold nanoparticles (AuNPs) using the extract of *Syzygium aromaticum* and their application in enhancing the response of a colourimetric urea biosensor was reported by Kaur and coworkers [141]. The biosensor's performance was evaluated by measuring the change in the absorbance of the AuNPs in the presence of different concentrations of urease. The biosensor using AuNPs exhibited a significantly enhanced response than the biosensor without AuNPs.

Masibi [142] reported the green synthesis of bimetallic Au-Ag nanoparticles (NPs) using the extract of *Citrus* × *sinensis* (L.) Osbeck peels as a reducing and stabilising agent. The Au-Ag NPs exhibited good electrocatalytic activity towards the oxidation of caffeine, with a linear response in the range of 0–59 μM. The electrochemical sensor based on the Au-Ag NPs exhibited good selectivity towards caffeine over other interfering species.

Han et. al. [143] described the green synthesis of reduced gold nanoparticles (AuNPs) using the extract of *Radix Pueraria* flavonoids as a reducing and stabilising agent. The performance of the synthesised AuNPs was evaluated for their electrochemical sensing applications, particularly for the non-enzymatic detection of cholesterol in food samples. The electrochemical sensor based on the AuNPs exhibited good sensitivity and selectivity towards cholesterol, with two linear ranges of 1–100 and 250–5000 μmol/L. The electrochemical sensor exhibited good stability and reproducibility over time.

The authors concluded that their approach for the green synthesis of reduced AuNPs using *Radix Pueraria* flavonoids extract is simple and cost-effective. The AuNPs synthesised using this approach exhibited high stability and biocompatibility, making them suitable for developing electrochemical sensors. The reduced AuNPs synthesised using this green synthesis method have the potential to revolutionise the field of electrochemical sensing for the non-enzymatic detection of cholesterol in food samples.

3. Biosensors with Bio-Coatings and Applications in the Health Sector

Humankind experiences a death toll of around 2 million lives yearly from increasing bacterial resistance to antibiotics and viral infections [9]. An increasing need to develop new diagnostic tools for better detection of pathogens was revealed during the COVID-19 pandemic. Moreover, COVID-19 revealed the worrisome facet of the increased environmental impact of biosensors.

In addition, the development of sustainable biosensors proves to be valuable for continuously monitoring body signals and biomarkers and therapeutics and diagnostics purposes (Figure 5). In this respect, the materials must be biocompatible, biodegradable, and offer high detection performance. Consequently, biosensing using sustainable materials will also aid in minimising waste production [7].

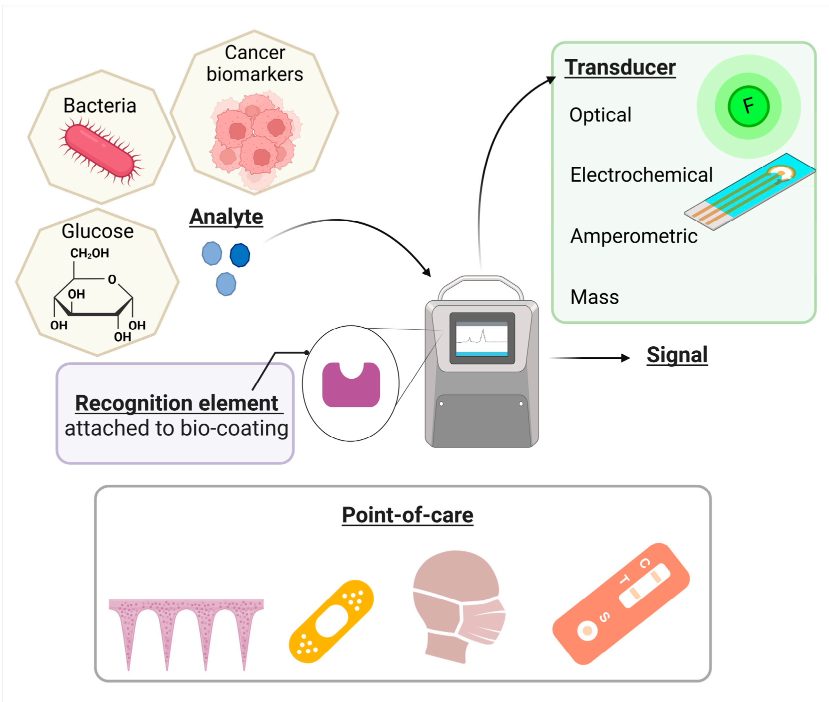

Figure 5. Potential point-of-care applications for biosensors with bio-based coatings (the graphical illustration has been created with BioRender software—BioRender Company, Toronto, ON, Canada).

In a biosensor, adding functionality to the substrate plays a crucial role in maintaining the 'biosensor's stability, increasing operational usage, and regulating the interactions between the sensing surface and analytes. The 'biosensor's functional bio coating also plays a significant role in amplifying the detection signal and reducing the non-specific binding, thus increasing the specificity of the analyte detection. Natural polymers were explored as coatings in biomedical applications through their non-toxicity, biodegradability, and biocompatibility. Even though natural polymers offer several advantages, they possess certain drawbacks, such as hygroscopicity, and low mechanical and chemical resistance, which restricts their application in biosensors. These downsides can be overcome by preparing biopolymer composites with nanoparticles, carbon-based materials, metal oxides, polymers, and so on [53].

Cellulose- and paper-based biosensors have the following advantages: (a) rapid diagnosis of infectious diseases due to their safe environmental disposal, (b) availability for mass-production, and (c) simple recycling process [9,145]. They are used for the detection of antibodies, antigens, or nucleic acids from saliva, sputum, and blood, by using colourimetric, fluorescent, or electrochemical detection approaches [146]. Notably, various gold nanoparticle-based tests for SARS-CoV-2 were FDA-approved under EUA designation for large-scale COVID-19 testing. Briefly, they are lateral-flow test strips on which colloidal gold-conjugated recombinant SARS-CoV-2 antigens are dried at the end of the membrane strip. Each test strip contains a pad for the sample addition, a pad containing COVID-19 antigen conjugated with gold nanoparticles, and gold-rabbit IgG, a nitrocellulose membrane with a control line coated with anti-human IgG, an IgM line coated with anti-human IgM, and finally, a pad for absorbing the waste [147–150]. However, sustainable biosensing can be limited by inadequate storage conditions, which could tamper the shelf-life of sustainable diagnostics, and by the emergence of mutated SARS-CoV-2 variants [9]. Lateral flow assays, which typically consist of a sample pad based on cellulose and a nitrocellulose pad onto which the specific antibodies are immobilised (the test line) were also primarily reported to be used for the detection of antimicrobial-resistant bacteria [151].

Chitosan and carboxymethyl cellulose are other polysaccharides extensively explored for developing new biosensors thanks to their natural abundance, biocompatibility, biodegradability, non-toxicity, and the capability to create adherent thin films on electrochemical surfaces [152]. Real-time detection of glucose in a range of concentrations from 1 to 15 mM was achieved by Kim et al. using an electrochemical biosensor based on graphene oxide/cobalt/chitosan nanocomposite [61]. Ambrosetti et al. reported the fabrication of carboxymethyl-dextran-based protein-patterned surfaces for enhanced biomolecular recognition using SPR [153].

A unique patented electrochemical biosensor was developed by NovioSense BV to be worn under the lower eye lid to continuously monitor glucose levels in the basal tear fluid. The measurements have shown a good correlation for blood glucose values, with clinical feasibility. The polysaccharide material acts as a barrier between the metal surface and the soft tissue of the eye, allowing the free diffusion of the analyte into the coating while stabilising and preventing the enzyme migration out of it. Furthermore, the polysaccharide-coated device did not produce pain or irritation [154].

Heparin was for the first time reported to be used instead of an antibody as a biorecognition element in a single-walled carbon nanotube-based (SWNT) chemiresistive biosensor, for the detection of Dengue virus. This was possible because heparin is a structural homologue of heparan sulphate, a receptor for Dengue virus serotypes [155].

Hasanah et al. reported a pectin-based optical biosensor for the detection of triglycerides for the first time. Pectin was employed for increasing lipase absorption. A detection limit of 15 mg/dL was obtained [156].

Poly-L-lysine (PLL) is biocompatible, stable, soluble in water, and useful for enzyme immobilisation, as the negatively charged proteins can be immobilised with ease onto the positively charged PLL via electrostatic interactions. The functionalisation of the electrodes with PLL can be accomplished through electro-polymerisation. A study involving a graphene field effect transistor modified with PLL was conducted by Gao et al. for ultrasensitive detection of miRNA biomarkers in breast cancer and SARS-CoV2. A detection limit of 1 fM was achieved within 20 min by using 2 μL of the sample [157].

A zein/gelatine-based electrochemical biosensor for glucose detection was reported. The gelatine top-coat of the biocompatible sandwich supported the covalent attachment of glucose oxidase (GOx), ensuring the access of the substrate to the enzyme, while the zein base-coat protected from interferents caused erroneous detection of hydrogen peroxide. The group reported a sub-μm detection limit, a long shelf life, and accurate recovery of glucose in model samples [158].

Protein-based biopolymers are regarded as excellent candidates for 'biosensors' coating due to their biocompatibility, cross-linking ability, and biodegradability. Of particular interest are enzymes, which are primarily exploited in biosensing because of their catalytic nature, selectivity, and low energy requirements [52,159]. However, the challenge posed by developing enzyme-based biosensors is related to maintaining their catalytic activity. In this respect, electrospray ionisation (ESI) has been employed for the deposition of laccase on a carbon substrate. This deposition method has the advantage of retaining the enzyme activity and the analytical performances in terms of working and storage stability for up to two months, with a limit of catechol detection of 1.7 μM, in the linear range of 2–100 μM [159]. Another study involved the use of a tyrosinase biosensor based on chitosan nanoparticles for catecholamine detection. A detection limit of 0.17μM, with an excellent sensitivity of 0.583 $\mu A\ \mu M^{-1} cm^{-2}$ was reported in [160].

Sartori et al. used botryosphaeran as a matrix for immobilising and maintaining the enzymatic activity of laccase stability onto a glassy carbon electrode (GCE) functionalised with MWCNTs. The electrochemical biosensing platform was applied for dopamine determination. A good selectivity was reported in the presence of uric acid, ascorbic acid, and other phenolic compounds. The limit of detection was 0.94 $\mu mol\ L^{-1}$ [152].

DNA polymers gained lately significant attention as coatings for improved performance biosensors. DNA hydrogels are particularly interesting thanks to their biocompatibility, non-toxicity, programmable assembly, molecular recognition, and high loading capacity [161,162]. DNA hydrogels have been reported to detect small molecules, proteins, viruses, or toxins. For instance, a high affinity-based electrochemiluminescence biosensor for the detection of miRNA let-7a was reported. The biosensor exhibited good sensitivity within 10 fM–10 nM and a detection limit of 1.49 fM [161]. Mao et al. demonstrated the working principle of a DNA hydrogel-based three-dimensional electron transporter. They have shown that, compared to conventional functionalised electrodes, DNA hydrogels improve the efficiency of electron transfer. Moreover, DNA hydrogels allow the incorporation of electroactive molecular elements (e.g., DNAzyme) which further increases the biosensing performance [163].

Due to their superior physicochemical properties, synthetic biodegradable polymers are considered as biocoatings for biosensors. Poly(lactic acid) (PLA), polycaprolactone (PCL), polyhydroxybutyrate (PHB), and polyhydroxyvalerate (PHV) are among the most employed synthetic biodegradable coating polymers in the development of biosensors [7]. Marzo et al. demonstrated a new concept of a 3D-printed enzymatic graphene Poly(lactic acid) electrode for direct electron transfer using peroxidase enzyme for hydrogen peroxide (H_2O_2) detection. They demonstrated that the detection mechanisms of the 3D-printed biosensors are associated with the direct electron transfer between the horse radish peroxidase (HRP) and the activated electrode, without employing electron mediators. This process proves their future utility for real sample detection of biomarkers [164]. Silva et al. developed a 3D-printed enzymatic reduced graphene oxide-PLA electrode for the detection of serotonin with a detection limit of 0.032 $\mu mol\ L^{-1}$ [66]. Cardoso et al. achieved a detection limit of 0.02 for uric acid and 0.03 $\mu mol\ L^{-1}$ for nitrite within a linear range from 0.5–250 $\mu mol\ L^{-1}$ on a 3D printed graphene-PLA electrode [67].

"Green chemistry" of nanomaterials plays a vital role in developing eco-friendly sensors in biomedical bio-applications (due to their biocompatibility and low toxicity). For example, Zamarchi and Vieira [128] reported that AgNPs synthesised by using the extract *Araucaria angustifolia* are used to manufacture an electrochemical biosensor to detect paracetamol.

Table 4 summarises the nanomaterial obtained by green chemistry used in the healthcare domain.

Table 4. Sensing nanoplatforms used in healthcare.

Nanomaterial	Green Synthetic Method	Analyte	Transduction Method	The Limit of Detection (LOD)	Ref.
AgNPs	*Allium cepa* peels	toxic mercury	Optical	-	[127]
AgNPs	*Araucaria angustifolia*	paracetamol	Electrochemical	8.50×10^{-8} M	[128]
AuNPs	chitosan	nitrocellulose	Optical	1 µg/mL	[129]
CuNPs	*Ocimum tenuiflorum* leaf extract	glucose	Nonenzymatic electrochemical	0.038 µM	[136]
CuONPs	*Caesalpinia bonducella* seed extract	riboflavin	Electrochemical	1.04 nm	[138]
ZnO NPs	Peach extract	glucose	Amperometry	4 µM	[165]
Graphene oxide decorated with AuNPs	Rose water	glucose	Electrochemical	10 µM	[135]
Au NPs	*Mentha aquatic* extract	tramadol	Electrochemical	6.0 nM	[166]
SeNPs	*Bacillus subtilis*	H_2O_2	Electrochemical	8×10^{-8} M	[134]
Au NPs	*Syzygium aromaticum extract*	urea	Optical	-	[167]
Chitosan nanoparticles	Chitosan	Catecholamine	Amperometry	0.17 µM	[160]

The synthesis of ZnONPs via the green route is possible by employing plants, moulds, bacteria, and algae [168,169]. The most used ZnONPs-based biosensors are the ones that detect small molecules such as glucose, cholesterol, and urea [170]. The synthesis of ZnONPs with the help of *Caesalpinia bonducella* seed extract is considered for obtaining a biosensor employed in the detection of vitamin B2.

Another type of biosensor [128] obtained by green chemistry is a new sensor for detecting paracetamol, a widely used pain reliever, based on silver nanoparticles synthesised from plant extracts. The plant extract used in this study was obtained from a pine nut (*Araucaria angustifolia*). The synthesised silver nanoparticles were then used to modify the surface of a glassy carbon electrode, creating a sensor capable of detecting paracetamol in solution. The sensor's performance was tested by measuring the current response of the modified electrode in the presence of different concentrations of paracetamol. The results showed that the sensor had good sensitivity and selectivity towards paracetamol, with a detection limit of 8.50×10^{-8} mol L^{-1}. The sensor also showed good stability and reproducibility over time.

Bollella and co-workers [126] reported the synthesis of AgNPs and AuNPs by green chemistry using quercetin to make a lactose biosensor (based on cellobiose dehydrogenase from *Trametes villosa*). Additionally, the gold nanoparticles obtained through green synthesis [171] can be used to obtain biosensors with applications in medicine, such as determining the glucose content in commercial glucose injections.

The research on environmentally friendly and biodegradable sensors for healthcare applications is still in its early stages, as many issues remain to address. These issues are related to detection performances, biocompatibility, and safety when using biopolymer nanocomposites, or nanoparticles, even though they are obtained through green synthesis methods.

4. Conclusions and Future Perspectives

The choice of functionalisation strategy to attach the biorecognition element to the active element is fundamental in biosensing to achieve the desired performance. This strategy also ensures reusability with a limited impact on the environment. Nowadays, alternatives to conventional functionalisation strategies are being explored to obtain ecologically friendly and sustainable biosensors. This review gives an overview of bio-coatings derived from nanoparticles synthesised via green chemistry, biopolymers, and biopolymer composites and their role in biosensing applications with usage in the health and food sectors.

Substantial research efforts have been made to develop environment-friendly biosensors for smart packaging to increase food safety and quality by detecting pathogens promptly and inhibiting the 'microorganisms' growth. In this regard, biopolymers, biogenic nanoparticles, and biopolymer composites as bio-coatings in biosensors and smart packaging represents a milestone. However, biosensors must meet the market demands in terms of specificity, sensitivity, and detection limit. Moreover, the potential risks for human health posed by the integration of biosensors into smart packaging will need to be addressed before commercialisation. The possible migration of nanoparticles from packaging into food and their toxic effect on the human body and the environment are of great importance and are given special attention from regulatory bodies.

In healthcare, particularly in developing biosensors, the use of bio-coatings minimises their impact on the surrounding environment. Moreover, the switch towards sustainable, biocompatible, and eco-friendly biosensors opens the path towards wearable biosensors for continuous monitoring of various health parameters. The biosensors will be expected to play a big part in human well-being as they are expected to detect infections and life-threatening diseases in a fast manner. Improvements and tests need to be done to ensure their best performance and safety, especially for biosensors coming directly into contact with the human body. Thus, toxicity assessments for various bio-coatings employed in biosensors must be accomplished before taking them a step forward toward commercialisation.

The future direction of research in this field is likely to be focused on the following areas: (a) improving the sensitivity and stability of bio-coatings: researchers will continue to work on developing bio-coatings that have improved sensitivity and stability, allowing for more accurate and reliable biosensor readings; (b) expanding the range of applications: eco-friendly bio-coatings are expected to expand into new applications, such as wearable biosensors and real-time monitoring systems; (c) developing alternative materials: researchers will continue exploring alternative materials, such as biodegradable polymers and natural products, for synthesising bio-coatings; (d) enhancing biocompatibility: efforts will be made to improve bio-coatings' biocompatibility further, ensuring their safe and effective use in biomedical applications; (e) improving the sustainability of biosensor production: bio-coatings synthesised via green-chemistry methods are expected to reduce biosensor production's environmental impact, making it more sustainable.

Overall, future research in this field will likely focus on improving biosensors' performance and sustainability using eco-friendly bio-coatings.

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Abbreviations

Au	Gold
Ag	Silver
WHO	World Health Organization
QD	quantum dots
ASTM	American Society for Testing and Materials
NP	nanoparticle
mm	millimetre
nm	nanometre
NM	nanomaterial
HPLC-MS	High-performance liquid chromatography-mass spectrometry
PCR	Polymerase chain reaction
ELISA	Enzyme-linked immunosorbent assay
Pt	Platinum
Pd	Palladium
Zn	Zinc
Cd	Cadmium
Cu	Copper
Fe	Iron
Ni	Nickel
Co	Cobalt
$HAuCl_4$	Tetrachloroauric Acid
H_2PtCl_6	Hexachloroplatinic acid
$RhCl_3$	Rhodium (III) chloride
$PdCl_2$	Palladium (II) chloride
cm	centimetre
TiO_2	*Titanium dioxide*
RF	radio frequency
K	Kelvin
kHz	kilohertz
MHz	megahertz
kW	kilowatt
MW	megawatt
atm	atmosphere
sec	seconds
N	Nitrogen
DMF	dimethylformamide
PEG	polyethylene glycol
UV	ultraviolet
AuNPs	gold nanoparticles
°C	degrees Celsius
min	minutes
ZnO	Zinc oxide
SnO_2	Tin oxide
PbO	Lead (II) oxide
EC-SPR	Electrochemical—surface plasmon resonance sensor
DNA	Deoxyribonucleic Acid.
LSPR	Localised surface plasmon resonance
SERS	Surface-enhanced Raman scattering
E. coli	*Escherichia coli*
PMNCs	polymeric nanocomposites
antibodies	ABs
GOX	glucose oxidase
PDA	polydopamine
DA	dopamine
CFU	colony-forming unit
mL	millilitre

PtNPs	platinum nanoparticles
PBNCs	polymeric bionanocomposites
L. monocytogenes	*Listeria monocytogenes*
μm	micrometre
LOD	Limit of detection
g	gram
β-Gal	β-galactosidase
S. typhimurium	*Salmonella typhimurium*
h	hours
PBS	phosphate buffered saline
EC	Commission Regulation
No	Number
S. boydii	*Shigella boydii*
ICS	immunochromatographic strip
S. aureus	*Staphylococcus aureus*
ATCC	American Type Culture Collection
MNPs	metal nanoparticles
MOs	metal oxides
CuO	copper oxide
Ag_2O	silver oxide
CuNPs	Copper nanoparticles
pg	picograms
Fe_3O_4	Iron oxide
SeNP	Selenium nanoparticle
FeNP	Iron nanoparticle
kg	kilogram
K	Potassium
Mg	Magnesium
Ca	Calcium
Hg	Mercury
IC	inhibition concentration
LC	lethal concentration
CMT	maximum permissible concentration
FDA	Food and Drug Administration
LOx	lactate oxidase
BC	Bio-cellulose
Co	Collagen
CuONPs	Copper oxide nanoparticles
fmol	femtomole
COVID-19	Coronavirus Disease 2019
SARS-CoV-2	Severe acute respiratory syndrome coronavirus 2
USD	The United States dollar
LDPE	Low-density polyethylene
RFID	Frequencies radio
EFSA	The European Food Safety Authority
MNTS	Micro- and Nanotechnologies
LDPE	Low-density polyethylene
OR	oil of oregano
RO	rosemary oil
SWNT	single walled carbon nanotube based
PLL	Poly-L-lysine
ESI	electrospray ionisation
GCE	glassy carbon electrode
PCL	polycaprolactone
PHB	polyhydroxy butyrate
PHV	polyhydroxy valerate
PE	polymers polyethylene
PVC	polyvinyl chloride

EVOH	ethylene vinyl alcohol
IgG	Immunoglobulin G
IgM	Immunoglobulin M
PBAT	poly (butylene adipate-co-terephthalate
TPS	cellulose-based thermoplastic starch
PLA	poly lactide
PHA	poly-hydroxyalkanoate
PHB	poly-hydroxybutyrate
PGA	poly-glutamic acid
MCF-7	Michigan Cancer Foundation-7

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