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Biosensors: The New Frontier of Next-Generation Food IndustryHoma Behmadi^{1*}, Negar Roshani-Dehlaghi², Ali Ekrami³

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Biosensors represent one of the most innovative technologies developed in recent decades in the field of the food industry. By integrating biotechnology, materials engineering, and data science, these systems enable accurate, rapid, and cost-effective monitoring of food quality and safety. Biosensors are designed based on sensitive biological elements such as enzymes, antibodies, or DNA, allowing them to detect chemical compounds, pathogens, and contaminants at very low concentrations. The present study reviews the theoretical foundations, historical development, and technological advancements of biosensors in the food sector, and analyzes their applications in areas such as microbial contamination detection, raw material quality control, supply chain monitoring, and the development of smart packaging systems. Advances in nanotechnology, micro-systems, artificial intelligence, and the Internet of Things (IoT) have significantly enhanced the sensitivity of biosensors and enabled their integration into intelligent monitoring networks. Despite advantages such as high accuracy, low cost, and real-time performance, several challenges remain, including biological stability, commercialization, and industrial standardization. The future of this technology lies in its integration with digital systems, biocompatible materials, and sustainable production processes. Such an approach can accelerate the transition toward a smart, transparent, and safe food industry, contributing significantly to the achievement of global food security.

1- INTRODUCTION

The food industry has been profoundly transformed in recent decades by population growth, increasing urbanization, changing consumption patterns, market globalization and the growing sensitivity of consumers regarding health, quality and sustainability [1]. Unprecedented pressure is being placed on the food industry by emerging economic and environmental trends to provide quality, minimize resource waste and ensure product safety at levels beyond what is currently available [2]. Under such circumstances, the development of new analytical technologies, particularly sensor technologies and more specifically biosensors, has become an important tool in revolutionizing the food industry [3]. Thanks to these technologies, which incorporate ideas from biology, chemistry, and electronic engineering, smart and accurate monitoring of the quality of food throughout the supply chain is enabled.[4]

The current state of the food industry shows that basic problems of ensuring safety and quality still remain despite the advancements in modern production and preservation techniques [5]. The demand for fresh and minimally processed products is increasing, so are the international supply chains, and the public awareness of microbial, chemical and environmental contaminants. Continuous and fast food quality control is an undeniable necessity. Many manufacturing facilities still use laboratory-based testing methods that are accurate but time consuming, costly, and limited to selective sampling procedures [6]. Thus, there is still a chance that unsafe or contaminated products enter the consumption chain. The lack of real-time and automated monitoring systems in most cases leads to a reactive rather than proactive approach to quality control, which can result in significant economic and reputational losses for producers.[7]

The scope of issues concerning safety, quality and sustainability has increased dramatically beyond these issues. On the safety side, threats caused by pathogenic microorganisms, mycotoxins, heavy metals, pesticide residues and non-standard additives are still among the most important global problems in the food sector [3]. In addition, the sensory and nutritional quality of the products must be ensured throughout the

entire process from production to packaging and storage [9]. Environmental sustainability has also become a key issue in recent food production policies. Industries are required to improve efficiency and reduce waste, but also to control greenhouse gas emissions, energy consumption and use of harmful chemicals [10]. Safety, quality and sustainability are so closely interlinked that a disruption in any one of these areas threatens the balance of the whole food supply chain [2]. To address these challenges, tools are required to assess product status in real time with high accuracy and minimum human intervention and provide actual environmental data throughout the production, storage and distribution stages. Sensor technologies, particularly biosensors, have a major role in this respect.[11, 12]

Here, the development and application of advanced and intelligent technologies have become the main driving force for change in the food industry. The advent of biosensors, nanotechnology, AI, Internet of Things (IoT) and automated monitoring systems has changed the quality surveillance from reactive and periodic to dynamic, continuous and integrated models [10]. Biosensors are able to perform specific recognition of target compounds with extremely high sensitivity [5] by combining biological recognition elements with physical analytical tools, such as electrochemical, optical or thermal transducers. They can instantly detect the presence of pathogens, contaminants or spoilage indicator molecules providing valuable information for rapid decision-making [3]. The integration of these sensors into production lines and intelligent packaging systems helps to reduce food waste, improve process control accuracy and improve supply chain transparency. Moreover, the integration of biosensors in IoT-based data networks allows the analysis and interpretation of big data on quality and prediction of possible spoilage or contamination events.[13]

The development of biosensors, however, is not only a technological response to the present demands, but also a foundation for a sustainable future in the food industry [2]. These technologies have a great potential for widespread use at many stages of production and distribution due to their low cost, miniaturization capability and compatibility with the environment [1]. Besides the technical advantages, the use of such systems offers increased transparency, improved consumer trust

and better public health [10]. Therefore, biosensors can create a bridge between technology and food safety, a bridge that makes it possible for the food industry to manufacture healthier and better quality products in accordance with the principles of sustainability through intelligent and science-based tools.[5]

The progress in the field of biosensors is leading to a new vision for the future of the food industry and opening the door to a smart and safe food sector. Given the importance and the wide range of this topic, the main aim of the present article is to give an overview of the roles, developments and applications of biosensors in the next generation of food industries. To this aim, in the present study, the theoretical basis and historical development of these sensors are firstly described, and then their main applications in the areas of contamination detection, quality control and intelligent packaging are analyzed. In addition, the advantages and limitations are evaluated by discussing emerging technologies converging with biosensors and finally, future perspectives and potential research directions are highlighted by the presentation of case studies.

2. Theoretical Foundations of Biosensors

Biosensors are a more advanced generation of sensing and monitoring devices based on specific interactions between biological molecules and target compounds [10]. These systems are able to detect the presence or concentration of chemical, microbial and biological substances with high accuracy and transform them into measurable signals [3]. Biosensors employ living or bio-based components as recognition elements and due to their structural and functional features, they offer unsurpassed accuracy and selectivity in the detection of target analytes [2] compared to traditional chemical or physical sensors. Classical sensors mainly detect based on non-biological physical or chemical reactions such as surface adsorption or electrical conductivity change, while biosensors utilize specific biomolecular interactions such as enzyme-substrate, antigen-antibody or nucleotide pairing reactions [13]. This characteristic allows biosensors to show a much higher

accuracy and selectivity towards the target compounds in complex food matrices, despite the presence of similar or interfering substances.[14]

In general, every biosensor is composed of three main parts, namely a bioreceptor, a signal transducer and a readout and processing system. The bioreceptor is the most important part of the system and is responsible for the specific recognition of the target analyte [15]. This component can be enzymes, antibodies, nucleic acids (DNA/RNA), or even living cells and tissues [16]. The operation is based on selective biological reactions that are triggered by the presence of the target compound, which leads to a change in the physical or chemical properties of the surrounding environment [3]. The transducer translates these variations into measurable signals such as changes in current, voltage, optical absorption or surface mass. The transducers can be of electrochemical, optical, thermal or piezoelectric nature and are of importance for the sensitivity and stability of the sensor [17,18]. The readout system is then responsible for signal amplification, filtering and processing to convert the acquired data into interpretable digital or numerical formats [19]. The incorporation of these three components into a compact and efficient system allows the biosensors to be rapidly and accurately detected in complex environments.[20]

From a classification point of view, biosensors can be classified into several major classes according to the nature of the recognition element (bioreceptor) [21].

1. Enzymatic biosensors: These sensors utilize specific enzyme-substrate reactions and are commonly employed for the determination of compounds such as glucose, amines, lactate, or nitrites. This category is characterized by high accuracy, rapid response and is applicable to the quantitative detection of target compounds [22].
2. Immunosensors: These sensors operate based on the specific

interaction between antigens and antibodies and exhibit exceptionally high sensitivity for the detection of contaminants, pathogens, and food toxins [23].

3. Genomic (DNA/RNA) biosensors: In these sensors discrimination and detection are based on the hybridization of complementary nucleotide sequences. This technology has extensive applications in the rapid detection of pathogens, genetic alterations, and allergens [24].
4. Cellular or microbial biosensors: These biosensors employ the physiological or metabolic responses of cells and microorganisms in the presence of target compounds and are usually proved for the evaluation of biological toxicity and environmental impacts [25].

The combination of biological elements with physicochemical transducers in one entity has allowed biosensors to show an

impressive advantage over traditional laboratory techniques in terms of accuracy, response time and on-site applicability. These features make biosensors a perfect choice to monitor the quality, safety and health status of food products and form the basis for the transition to the intelligent generation of food industries[26, 27]

Figure 1. Schematic representation of structural components and working mechanism of biosensors in food industries. As shown in Figure 1, these systems are composed of conductive substrates, membranes and hydrogel matrices combined with signal-amplifying nanomaterials, to produce intelligent colorimetric, electrical or optical responses to stimuli such as changes in pH, temperature and biomolecule concentration. These responsive functionalities allow application of biosensors in quality control, spoilage and pathogen detection and smart food packaging systems.

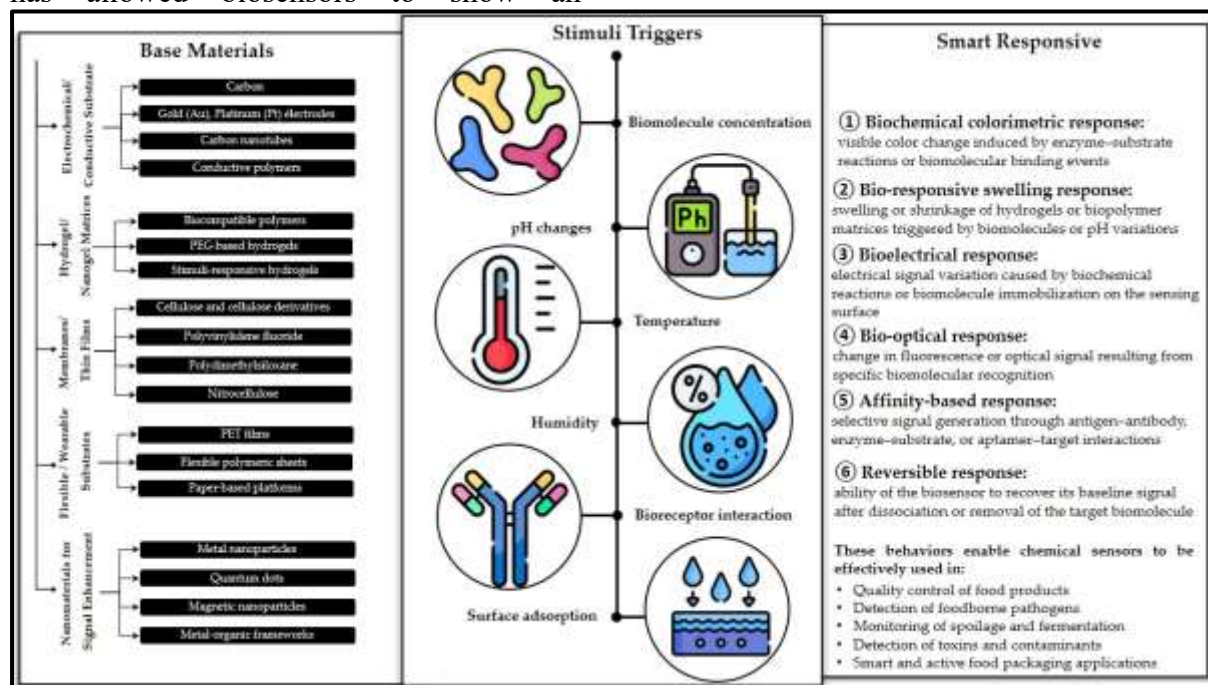


Figure 1- Theoretical foundations of biosensors

3. History and Evolutionary Trends of Biosensors in the Food Industry

The origins of biosensors date back to the 1960s when Clark and Lyons developed the

first enzymatic glucose electrode as an early example of a biosensor [28]. This design was based on the reaction of the enzyme glucose oxidase with oxygen and served as a basis for the emergence of a new direction in

analytical instrumentation [3]. In the medical field, biosensor applications were initially designed to accelerate and simplify the measurement of biological compounds, but the value of the technology for the food and agricultural industries gradually became apparent [5]. The first industrial applications of biosensors were mainly associated with the quality control of fermented products such as beverages, dairy products and meat products where there was an urgent need to develop rapid measurement methods for compounds such as sugars, alcohol, lactic acid and ammonia. At this time, simple enzymatic biosensors were successfully used for monitoring of fermentation processes and determination of optimal production times, and thus paved the way for the industrial application of this technology.[۱۳۲۹]

In the subsequent decades, the advances in material science, electronics and molecular biology resulted in the rapid increase of biosensor applications [29]. The development of immunosensors and DNA-based sensors in the 1980s and 1990s enabled the specific detection of microbial contamination and pathogenic agents in food products [30]. Meanwhile, electrochemical methods gained particular importance because of their high accuracy, low cost and potential portability. The development of microsystem technologies and the micro-liter chip fabrication in the 2000s paved the way to sensor miniaturization and simultaneous multiparametric analysis [31]. Furthermore, progress in bioengineering led to the creation of new bioreceptors, such as monoclonal antibodies, aptamers and nanozymes, which were more stable and sensitive than their predecessors [32]. Thus, during this period biosensors have evolved from laboratory tools to practical industry devices, assuming an important position in pathogen detection, spoilage assessment and food freshness evaluation.[۵]

The dawn of 21st century has seen a new stage of evolution for biosensors, where emerging technological trends played a decisive role. Nanotechnology has opened the way for a new generation of nanosensors

whose sensitivity and detection limits have been greatly enhanced by the incorporation of carbon nanotubes, metallic nanoparticles, quantum dots and two-dimensional materials such as graphene [33]. These nanostructures provide opportunities for surface functionalization and increased areas for biological interaction, thus allowing the recognition reactions to take place with improved speed and accuracy [3]. Simultaneously, the development of microsystem and microfluidic technologies has enabled the simultaneous execution of multiple biochemical reactions on miniaturized chips, which is highly beneficial for rapid and real-time food monitoring [34]. Moreover, smart biosensors combined with the Internet of Things (IoT) have led to a new class of automated monitoring systems [35]. In these systems, data from sensors are wirelessly transmitted and stored and interpreted in analytical platforms, thus allowing real-time control of food quality and safety.[۱۵]

In the last decade, the research efforts have been increasingly directed towards improving the sustainability, reusability and environmental friendliness of biosensors. Due to advances such as the use of biodegradable materials, 3D printing to allow for large scale production, and incorporation of artificial intelligence algorithms to analyze the data, the scope of this technology has been extended beyond conventional analytical tools. The evolution of biosensors from simple laboratory devices to intelligent, automated systems in the food industry reflects not only the continuity of scientific progress but also the transition of food industries towards a sustainable, precise, and data-driven generation [2,3,36].

4. Applications of Biosensors in the Food Industry

The application of biosensors in the food industry has, in recent years, become one of the key pillars of innovation in the fields of food safety, quality, and sustainability [10]. These technologies take advantage of the selective recognition properties of

biomolecules and allow the detection of a wide range of compounds and contaminants in short time scales and have moved food monitoring from traditional laboratory-based approaches to real-time and non-destructive surveillance approaches [3]. A framework has been created by the integration of biosensors with digital and data-driven systems, which provides a safe and transparent food quality information flow from the farm to the consumer table [3].

4.1. Detection of Microbial and Chemical Contaminants

One of the most significant applications of biosensors is the detection of microbial and chemical contaminants in food products [3]. Foodborne pathogens, mycotoxins (e.g. aflatoxins), pesticide residues, and heavy metals have always been serious threats to food safety [37,38]. While traditional detection methods such as microbial culturing and chromatography are highly accurate, they are time-consuming, expensive and usually require sophisticated laboratory equipment [2]. Biosensors use biological recognition elements such as antibodies, aptamers, DNA or enzymes to detect these contaminants with high specificity and rapidity [30]. For example, DNA biosensors based on complementary nucleotide sequences are capable of detecting pathogens in less than an hour with very low detection limits [29]. Immunosensors based on antigen–antibody interactions have been widely utilized for the monitoring of mycotoxins, drug residues and allergens. The progress of nanotechnology has led to the creation of nanosensors that increase the reactive surface area, thus improving the sensitivity of detection to the femtomolar level and enabling fast on-site monitoring of contaminants in the course of food production [39].

4.2. Quality Control of Food Raw Materials

Another important application of biosensors lies in the quality control of food raw

materials. The main indicators of food quality are chemical compounds, which contribute to the nutritional value and sensory characteristics of food products, including proteins, sugars, fatty acids, vitamins, and volatile compounds [28]. These compounds are often measured quickly and accurately using enzymatic biosensors. Lactate oxidase and glucose oxidase based sensors are used in the dairy industry to measure the sugar content and to control the fermentation parameters [40]. Amine oxidase and putrescine sensors are used for quantifying the compounds derived from protein breakdown and evaluating the freshness of meat products [41]. The use of these analytical tools allows evaluating the quality of the raw material before it enters the production line to avoid adding unsuitable or contaminated samples [42].

4.3. Supply Chain Monitoring and Shelf-Life Prediction

Biosensors are important in the next phase for monitoring supply chains and estimating the shelf-life of food products. These sensors are also capable of monitoring physicochemical changes related to spoilage, temperature, humidity, and gaseous compounds during various stages of storage and transportation [43]. The deployment of intelligent Internet of Things (IoT)-based networks with biosensors provides the ability to collect and analyze data regarding the status of the product in real time [34]. For example, optical and gas biosensors based on enzymes such as catalase or amine oxidase can detect the production profiles of spoilage gases, such as ammonia and sulfides, providing early indications of product deterioration [44]. These systems have been shown to be able to predict actual product shelf life with higher accuracy and help to optimize distribution processes. Furthermore, the use of artificial intelligence models for the analysis of data generated by sensors has enabled the predictive evaluation of the shelf life and the quality of the products [35].

4.4. Intelligent Packaging and Bio-Based Labels

Intelligent packaging and sensor based bio-labels are one of the emerging and highly promising application areas of biosensors [45]. In this technology, biosensors are embedded in the packaging structures to automatically monitor changes related to spoilage or storage conditions [5,6]. Optical, colorimetric, electrochemical or immunological sensors could be used. For example, colorimetric labels with enzymes sensitive to volatile amine compounds can be used to indicate the freshness status of meat or fish through color changes during storage [10,46]. Other examples are packaging systems which integrate DNA or antibody based sensors translating biological reactions to visual or digital signals [30]. Furthermore, the integration of these packaging systems with wireless technologies such as RFID or NFC has allowed the transmission of data to centralized monitoring platforms [47]. These systems have a double role: ensure product quality and safety and at the same time enhance consumers' confidence by increasing transparency in product information [35,48].

Biosensors have become important tools for food quality and safety management due to their biological specificity, high sensitivity and use in real conditions. The synergy of this technology with intelligent systems, nanomaterials and advanced data analytics is leading the food industry towards intelligent, reliable and sustainable models, where quality control is no longer limited to laboratories but cleverly performed at each step of the production and distribution chain [2,28].

As illustrated in Table 1, biological sensors, as sophisticated recognition indicators, occupy a distinguished place in food safety, quality and spoilage monitoring. This table gives the systematic classification and comparison between different types of biosensors based on the nature of active biological element, target analyte, recognition indicator and biological recognition mechanism. Furthermore, the advantages and disadvantages of each sensing system are discussed to evaluate their efficiency, accuracy, and suitability for laboratory and industrial environment. Table 1 shows the great potentiality of the biological sensors for the creation of new, intelligent and specific recognition-based systems for the future food industry.

Table 1- Applications of biological sensors as identification indicators in the food industry

References	Limitations	Advantages	Biological Recognition Mechanism	Identification Indicator	Target Analyte	Active Biological Element	Type of biological sensor
[۴۹]	Enzyme instability	High selectivity	Enzymatic reaction and signal generation	Microbial activity	Glucose, lactate, amines	(Oxidase, Dehydrogenase) Specific enzymes (oxidase, dehydrogenase)	Enzymatic sensor
[۵۰]	Long response time	High sensitivity	Change in biological signal	Microbial growth	Spoilage metabolites	Live bacteria/yeast	Microbial sensor
[۵۱]	High cost	High accuracy	Antigen-antibody binding	Microbial contamination	Toxins, pathogens	Antibody	Immunosensor
[۵۲]	Requires specialized equipment	Very high accuracy	Nucleic acid hybridization	Presence of microorganisms	Pathogen genes	Aptamer, genetic probe	DNA/RNA DNA/RNA sensor
[۵۳]	Complex development	High stability	Selective analyte binding	Specific spoilage	Toxins, metabolites	Synthetic aptamer	Aptamer-based sensor
[۵۴]	Difficult maintenance	Realistic biological simulation	Cellular physiological response	Toxicity	Food toxins	Living cells	Cell-based sensor
[۵۵]	Optical instrumentation required	High sensitivity	Change in fluorescence intensity	Microbial activity	Spoilage metabolites	Fluorescent protein	Biofluorescent sensor

[ΔF]	High fabrication cost	Rapid response	Biological signal amplification	Early spoilage	VOCs, amines	Enzyme/aptamer + nanoparticles	Nano-based biological sensor
[ΔV]	Limited lifespan	Safe, sustainable	Bio-chemical reaction	Overall spoilage	pH, gases	Enzyme/natural biomolecule	Packaging-compatible bio-based sensor

5. Emerging Technologies Associated with Biosensors

Recent developments in interdisciplinary sciences have brought about fundamental changes in the design, performance and efficiency of biosensors. New technologies such as nanotechnology, artificial intelligence, the Internet of Things and 3D printing have led to a new generation of biosensors, which are significantly more sensitive, accurate, faster to respond and have a greater potential for integration than previous biosensors. These technologies have opened a new avenue for intelligent and environmentally compatible biosensors in the food industry by establishing a connection between biotechnology and materials engineering [58].

5.1. Nanotechnology and the Application of Nanomaterials

Nanotechnology and the integration of nanostructured materials in biosensors are one of the most important areas of advancement in this field [59]. The high surface-to-volume ratio, good electrical and thermal conductivity and surface functionalization capability of nanomaterials have significantly improved the performance of biological recognition elements and transducers. The application of carbon nanotubes, graphene, metallic nanoparticles (gold, silver, platinum) and metal–organic frameworks has resulted in faster electron transfer, higher stability and better signal amplification [60]. For example, gold nanoparticles have been used as biocompatible platforms to immobilize enzymes or antibodies on transducer surfaces, which have greatly improved the detection sensitivity at nanomolar level [61]. Graphene and MXenes are two dimensional materials that accelerate the response of the

sensors and minimize the noise phenomena due to their high electronic conductivity and large reactive surface area [62]. Moreover, the application of hybrid nanostructures (nanocomposites) possessing multifunctional properties, such as the combination of metallic nanoparticles with conductive polymers, has allowed the development of sensors with both high sensitivity and long-term stability [63]. These advances have enabled the application of biosensors in complex food environments which are generally considered among the most difficult matrices for accurate detection [64].

5.2. Artificial Intelligence and the Internet of Things

The next step in the evolution of biosensors is to intelligently integrate and connect them with data-driven systems using artificial intelligence (AI) and Internet of Things (IoT). In this context, biosensors are not only measurement devices, but have been turned into elements of intelligent networks that collect, store and analyze quantitative and qualitative data related to food products in real time [59,65]. IoT technology allows the continuous monitoring of critical parameters, such as temperature, humidity, volatile organic compounds, and the presence of microbial agents [35], by connecting sensors to databases in the cloud. These data are then analyzed using machine learning algorithms and artificial intelligence techniques to detect patterns related to contamination, spoilage, or quality deterioration [65]. Intelligent algorithms can classify sensor signal patterns and distinguish between healthy and contaminated samples even if the concentration of target compounds is below the direct detection threshold [66]. The main contributions of these systems in the food industry are: automated decision-making,

generation of early warnings and quality prediction based on storage conditions. In addition, the combination of biosensors with process control systems has enabled the automatic optimization of production stages and reduction of food waste [67].

5.3. Three-Dimensional Printing and Microsystems

Innovative routes such as three-dimensional printing and microsystems have also been carried out for the development of biosensors [68]. The design of 3D printing has made it possible to produce complex and highly refined architectures for transducers and reaction channels, allowing the design of precise micrometer-scale structures [69]. The technology has turned the making of sensors from a slow and expensive process to a quick, cheap and customizable one. Among the most significant applications of 3D printing are porous substrates for immobilizing biological entities, which can simultaneously promote mass transfer and improve reaction efficiency [70]. Three-dimensionally printed sensors are especially suited for intelligent packaging and food supply chain monitoring systems [71] because they can be manufactured in large quantities with bespoke designs. Meanwhile, microfluidic microsystems as miniature and portable platforms facilitate the analysis of food samples at ultra-low volumes and high speed. The combination of microfluidic technology and biosensors has led to the development of “lab-on-a-chip” systems; platforms that can perform multiple

biological reactions simultaneously, greatly reducing the costs and enabling rapid analysis [72].

The combination of nanotechnology, artificial intelligence, the Internet of Things and three-dimensional printing technologies has opened broad prospects for the next generation of biosensors in the food industry. These technologies provide a foundation for designing systems capable of rapid detection of contamination or spoilage as well as data analysis, pattern prediction for quality variation and even automatic implementation of corrective decision making. Eventually, this technological convergence can reinforce the base of the future food industry, an industry built on intelligence, sustainability and complete transparency and lay the path towards achieving global food safety [38,65,69,72].

Figure 2 shows the convergence of emerging technologies in the development of biosensors for the food industry. The integration of artificial intelligence and Internet of Things with three-dimensional printing, micro-/nanosystems, and nanotechnology enables real-time monitoring, early warning, and prediction of quality control in dairy and beverage production lines as shown in Figure 2. This technological synergy, by improving detection sensitivity, reducing food waste and increasing traceability and supply chain transparency, enables the deployment of intelligent biosensors at industrial scale.

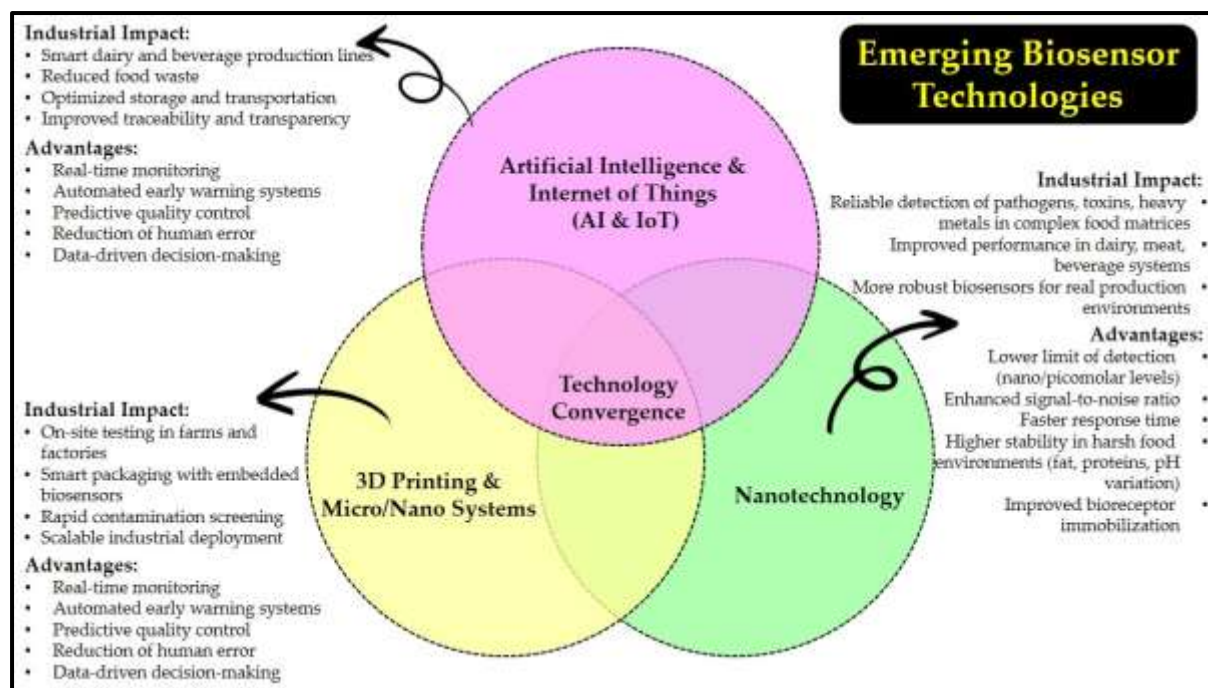


Figure 2- Emerging biosensor technologies

6. Advantages and Limitations of Biosensors in the Food Industry

Biosensors, as one of the transformative technologies in the food industry, has successfully overcome many of the limitations related to conventional quality control methods and has brought the monitoring of product health and safety to more accurate, rapid, and cost-effective levels [73]. These devices are based on selective biological elements such as enzymes, antibodies or DNA and offer the possibility of specific detection of contaminants, chemical compounds and spoilage agents in a short time without sophisticated laboratory equipment [2]. These features have made biosensors one of the fundamental pillars in the development of intelligent food industries.[10]

One of the most important advantages of biosensors are their high accuracy, fast response, low cost and operational reliability [3]. Biosensors can provide reliable results in seconds or minutes compared to conventional methods, such as chromatography or microbial culturing, which are expensive and time-consuming, as they require expensive laboratory instruments, high-purity chemical solvents, complicated sample preparation steps, and

long analysis time. Bioreceptors have increased selectivity and reduced interference of signal by interfering substances in food matrices [10]. Now, the accuracy of these systems is at the molecular level with some biosensors having detection limits as low as picomolar or femtomolar concentrations [5]. From an economic point of view, many biosensors have a simple structure and are mass-produced, greatly reducing the cost of testing and allowing the widespread use of biosensors in production lines and supply chains [22]. Although the development of biosensors for all applications is still in progress, in many cases these technologies have already become standard methods for quality control in the food industry. For instance, Delvotest® and SNAP® kits are employed globally in the dairy industry as standard for the obligatory testing of raw milk tankers and AflaTest® and AgraQuant® products are approved by the FDA for the determination of aflatoxins in cereals. Moreover, kits such as Veratox® and RIDASCREEN® are widely used in the production lines of large companies (e.g., Nestlé or Unilever) for allergen monitoring, and the BAX® system has become mandatory for suppliers of brands such as McDonald's, being recognized as a standard by the United States Department of

Agriculture (USDA) for the detection of Salmonella. These examples show that biosensors not only have wide applications in real life but in many cases have become a mandatory and essential standard for the food industry [28]. In addition, the developments of nanomaterials and conductive polymers allow these sensors to be used repeatedly and to sustain good performance stability under different environmental conditions. In addition, the integration of biosensors with digital systems and the Internet of Things has enabled real-time monitoring of product quality and automated data analysis, which has contributed to the optimization of decision-making processes in production and increased consumer confidence in product safety.[5,35]

Notwithstanding these advantages, the widespread use of biosensors in the food industry still faces technical, economic and regulatory challenges. One of the major challenges is the low stability of biological bioreceptors under real conditions of food production and storage [35]. Temperature, pH, lipid compounds and naturally occurring enzymes can reduce the sensor sensitivity and shorten sensor life [10]. Accurate calibration procedures are also challenging because of the complexity of food matrices and the presence of interfering compounds [5]. When working with biologically active materials or nanoparticles, it is necessary to adhere to strict regulations from a health and safety perspective in order to minimize the potential risks to human health and the environment [74]. In the commercialization arena, the production costs of high-performance biosensors have been reduced compared to the past, but they still have

limitations for large-scale deployment in some industries [3]. The lack of international standards and unified guidelines for performance evaluation and validation of these sensors is also a major barrier for industrial acceptance. Moreover, the integration of advanced sensing technologies into existing production lines requires the redesign of processes and the training of the workforce, which both require significant time and financial resources.[45]

The future view of development of biosensors in food industry is very promising. With the ongoing improvement in the design of bioreceptors, nanostructures and biocompatible materials, it is anticipated that the longevity, precision and dependability of this technology will be further improved. Furthermore, the development of technical standards and industrial acceptance criteria may pave the way for commercialization. The combination of high performance, sufficient stability and acceptable production costs paves the way for a future in which biosensors become an essential part of the quality and safety control systems in the food industry.[3,44,45]

The main benefits of the use of biosensors in the food industry are summarized in Figure 3. As shown in Fig. 3, these systems are very appropriate for field and industrial applications due to their small size, portability and low cost, while at the same time they allow fast detection and real-time monitoring due to their high sensitivity and selectivity. Also, features like multi-analyte capability, reusability and environmental compatibility strengthen their role as a key technology for the next generation of food safety and quality monitoring systems.

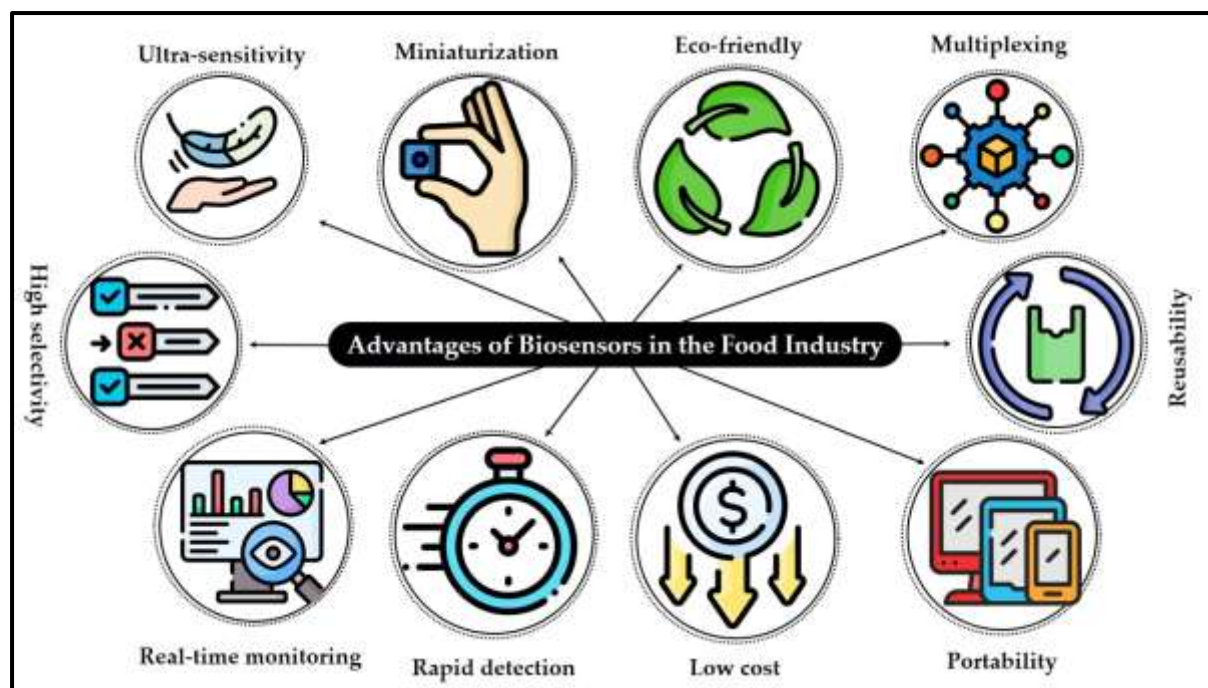


Figure 3- Advantages of biosensors in the food industry

7. Case Studies

In the last years, biosensors have been widely applied in the different sectors of the food industry, thus supporting the transition from laboratory research to industrial application [3]. Case studies of these applications show that biosensors have been important in quality assessment, contamination detection, and shelf-life extension of food products .[٣٥]

The dairy industry has always been challenged with the task of maintaining product quality and preventing microbial contamination. Enzymatic biosensors based on lactate oxidase, glucose oxidase or peroxidase are used for monitoring fermentation processes, determination of milk sugar content and detection of spoilage-related compounds [35]. Antibody-based immunosensors have also allowed the rapid detection of *Listeria monocytogenes* and *Staphylococcus aureus* in dairy products within a few minutes [76]. DNA biosensors have recently been developed for the detection of aflatoxin M1 in milk, with detection limits in the nanograms per liter range [2]. Intelligent packaging systems utilizing nanomaterial-stabilized enzymes have also been implemented for monitoring

dairy products' storage conditions, offering spoilage alerts via color change.[٧٧]

The control of spoilage and bacterial contamination is of special importance in the meat and meat products industry [43]. Amine biosensors built on aptamers and gold nanoparticles have been created for the direct detection of biogenic amines (e.g. putrescine, cadaverine) associated with meat freshness [60]. The application of amperometric biosensors to measure the change of volatile nitrogen compounds is also considered a good method to determine the shelf life of meat products . Biosensors based on fluorescent proteins for the detection of *Escherichia coli* contamination have been successfully used in industrial research to reduce the detection time from 24 hours to less than 30 minutes.[٧٨]

Biosensors are essential tools in the beverage industry, particularly in fermented beverages, to monitor the production processes [79]. Now enzymatic biosensors for precise control of sugars, alcohol, and lactic acid are common. Potentiometric sensors are widely used for the measurement of pH during beer and fruit beverages fermentation [80]. The safety and quality of the final products have been improved by using electrochemical biosensors to detect methanol or heavy metals in mixed drinks

[81]. DNA- and immuno-based biosensors have been developed for the rapid detection of mycotoxins in the industries of flour and cereal products, such as aflatoxins B1 and G1. These sensors find extensive application in the quality control of corn, wheat and stored grain products [82]. Moreover, enzymatic biosensors have been utilized to determine glucose, maltose and amylase during the fermentation processes of bread and confectionery, which improves the quality of the final products through the optimization of baking time and textural properties.[^{٨٣}]

The findings from these case studies reveal that biosensors provide a more dependable and rapid performance than traditional techniques in all areas of the food industry, ranging from dairy products to cereals. In particular, their combination with nanostructured technologies and digital monitoring systems has made it possible to commercialize these tools, thereby increasing their importance in food safety and food quality [3,10].

8. Future Outlook and Research Directions

The rapid technological progress in the field of biosensors has created a promising future for the revolution of the food industry [3]. Research trends show that the next decade will see these sensors move from laboratory applications to industrial and consumer applications driven by efforts to improve accuracy, stability, and intelligence [84]. Here, interdisciplinary developments in biotechnology, advanced materials and data engineering will provide tools to monitor food quality, freshness and safety throughout the supply chain in real time and at low cost .[^{١٠}]

The use of new and environmentally friendly nanomaterials, that will increase sensitivity, avoiding degradation and biotoxic effects is an important axis of expected progress in the next decade [84]. Green nanocomposites, bio-based conductive polymers and recyclable metal organic frameworks would play an important role to improve the

durability and safety of biosensors [35]. At the same time, artificial bioreceptors engineered (e.g. aptamers, nanozymes) will allow detection of complex compounds with higher stability than natural receptors [3]. In addition, the application of microfluidic technologies and lab-on-a-chip systems will remove the need for large sample volumes and allow on-site monitoring from factories to retail environments [85]. At the data level, the integration of artificial intelligence and machine learning with biosensors will enable the analysis of spoilage patterns, prediction of shelf-life and automated decision making. This trend may ultimately lead to the realization of “predictive food quality monitoring” in reality.[^{٨٤}]

This is followed by the change to sustainable and intelligent food systems. The future of this industry will rely on a network of biosensors and digital sensors at all levels of the supply chain [3]. These networks will collect and deliver real-time information about safety, composition, storage conditions and even the product origin to centralized systems [84]. This structure ensures transparency, traceability and consumer confidence. Biodegradable or environmentally degradable biosensors will also help to reduce the environmental footprint of the food industry and bring it in line with the principles of the circular economy. Future research will be oriented toward the design of wireless, low-cost, self-powered sensors integrated with cloud computing and blockchain technologies to ensure data security and product authenticity .[^{٢١٠}]

The future of biosensors is not only in simple analytical tools but also in intelligent and autonomous systems driven by sustainability, learning and trust. Such vision will ensure not only the food safety and quality, but also the drive of the global food value chain towards a green, secure and data-driven ecosystem [2,84].

9. Conclusion

The integration of biotechnology, nanotechnology and data science in the form

of biosensors has brought about a paradigm shift in ensuring food quality and safety. These systems make use of highly specific biological recognition elements that allow rapid and accurate detection of microbial and chemical contaminants at very low concentrations and hence pave the way for a transition from traditional laboratory-based methods to real-time and non-destructive monitoring approaches. The various applications of this technology to pathogen detection, raw material quality control, supply chain monitoring and intelligent packaging demonstrate its strong potential to increase transparency and lower food waste. The marriage of biosensors with novel nanomaterials, 3D printing, microfluidic systems and artificial intelligence has led to a new generation of smart sensors with improved sensitivity and selectivity. However, large-scale commercialization is still facing significant challenges, such as the limited stability of biological recognition elements under real-world conditions, calibration issues in complex food matrices, high production costs, the lack of unified international standards, and strict regulatory requirements. To overcome these barriers, coordinated efforts among researchers, industry stakeholders and policy-makers are needed.

The future perspective is the development of multifunctional, portable, biocompatible systems connected to intelligent cloud-based networks. Key research priorities include development of stable bioreceptors through protein engineering, multifunctional nanocomposites, integration with blockchain technology for transparent traceability, and intelligent shelf-life prediction algorithms. Standardized protocols and industrial validation studies are also required to accelerate commercialization.

Biosensors, in the end, are a strategic infrastructure for the development of a smart and sustainable food industry in the 21st century. The convergence of this technology with the digital revolution and the circular economy has the potential to be a game-

changer in reducing waste, improving public health and achieving global food security. The key to this vision is targeted investment into interdisciplinary research and the strengthening of university-industry collaboration.

Data Availability

The data of this study are available from the corresponding author upon reasonable request.

Conflict of Interest

The authors declare no conflict of interest.

Authors Contributions

All authors reviewed and approved the final manuscript for submission.

10. References

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حسگرهای زیستی؛ گامی به سوی نسل نوین صنایع غذایی

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حسگرهای زیستی،

ایمنی مواد غذایی،

نانوفناوری،

بسته‌بندی هوشمند،

پایش برخط

حسگرهای زیستی یکی از نوآورانه‌ترین فناوری‌های چند دهه اخیر در حوزه صنایع غذایی است که با تلفیق دانش زیست‌فناوری، مهندسی مواد و علوم داده، امکان پایش دقیق، سریع و اقتصادی کیفیت و ایمنی مواد غذایی را فراهم کرده است. این سامانه‌ها براساس عناصر زیستی حساس مانند آنزیم‌ها، آنتی‌بادی‌ها یا DNA طراحی می‌شوند و قادرند حضور ترکیبات شیمیایی، عوامل بیماری‌زا و آلاینده‌ها را در غلظت‌های بسیار پایین تشخیص دهند. مطالعه حاضر به بررسی مبانی نظری، روند تاریخی و تحولات فناورانه حسگرهای زیستی در صنعت غذا می‌پردازد و کاربرد آن‌ها را در زمینه‌هایی همچون تشخیص آلودگی‌های میکروبی، کنترل کیفیت مواد اولیه، پایش زنجیره تأمین و توسعه بسته‌بندی‌های هوشمند تحلیل می‌کند. پیشرفت در حوزه‌های نانوفناوری، ریزسامانه‌ها، هوش مصنوعی و اینترنت اشیا موجب افزایش حساسیت و قابلیت اتصال این حسگرها به شبکه‌های پایش هوشمند شده است. با وجود مزایایی نظیر دقت بالا، هزینه پایین و عملکرد برخط، چالش‌هایی شامل پایداری زیستی، تجاری‌سازی و استانداردسازی همچنان پیش‌روی توسعه صنعتی آن قرار دارد. آینده این فناوری بر ادغام آن با سامانه‌های دیجیتال، مواد زیست‌سازگار و فرآیندهای تولید پایدار استوار است؛ رویکردی که می‌تواند مسیر گذار به صنعت غذایی هوشمند، شفاف و ایمن را تسریع کند و گامی مؤثر در جهت تحقق امنیت غذایی جهانی باشد.

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