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Review Article

Nanobiosensor Based Detection of Food Adulteration: Recent Trends and Their Significance

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ABSTRACT

The rapid progression of nanotechnology has created potential for innovative sensing of food materials tackling persistent difficulties in food industry to prolong shelf-life, minimize waste, evaluate safety, and enhance food quality. The identification of harmful chemicals and foodborne pathogens is a crucial component of food safety. This review examines the various effective ways for identifying food contamination, specifically utilizing nanobiosensors. This paper summarizes the role, characteristics, significance and applications of nano-based biosensors in detecting and monitoring food quality, emphasizing the detection of biological and chemical pollutants in food. Nanosensors have emerged as an essential instrument in food industry owing to their precision and sensitivity. The paper investigates the progress facilitated by nanotechnology, particularly focusing on essential nanomaterials that are pivotal in sensor development. A thorough examination of various applications of nanobiosensors in the food business is presented, encompassing their role in identifying foodborne infections, toxins, and other detrimental pollutants. The presented work evaluates the problems and opportunities of nanobiosensor applications, focusing on sensor sensitivity, specificity, cost-effectiveness, and regulatory issues. Additionally, current trends and future trajectories are also examined, including the transition towards more sustainable and environmentally friendly sensor technology. The analysis underscores the revolutionary influence of nanobiosensors on food safety, quality control, and innovation within the food industry. The article seeks to enhance the advancement of nanobiosensor applications in food safety by providing a comprehensive analysis of existing

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technologies and prospective future innovations.

INTRODUCTION

Recent days have seen an upsurge in nano biosensors that have been an area of active research and development, showing significant potential in various fields such as healthcare, environmental monitoring, and food safety. Researchers have been focusing on improving the sensitivity and selectivity of nano biosensors. This involves the development of novel nanomaterials and surface functionalization techniques to enhance the detection of analytes with high precision even at low concentrations.

Nano biosensors are sophisticated analytical devices utilizing nanotechnology for biomolecule detection and quantification that have a range of applications in environmental monitoring, food quality, and biomedical diagnosis. Nanobiosensors take advantage of the unique characteristics of nanomaterials to offer higher sensitivity, specificity, and fast response, which makes them useful in a wide range of applications outside the field of healthcare [1]. Nanobiosensors have an important role in detecting food adulteration, and there are many examples where their efficiency is evident [2]. Electrochemical nanobiosensors such as those employing nanotubes recognize contaminants such as heavy metals and pesticides through the detection of changes in electrical signals upon interaction with the surface of the sensor, demonstrating rapid discrimination of cations and anions in food [3]. Aptamer biosensors, which make use of specific DNA or RNA sequences to bind substances such as antibiotics and pesticides, recognize these substances based on structural changes following binding [4]. Nanoparticle-enhanced colourimetric sensors, e.g., gold nanoparticles for detecting melamine in milk, display visible color changes upon contact with some adulterants [5]. Fluorescent quantum dot-based sensors, made up of semiconductor nanomaterials that emit light upon stimulation, detect harmful microorganisms by binding to specific bacteria, providing an optical signal to indicate contamination [6].

Biosensors have revolutionized the fields of food industry by offering highly sensitive, rapid, and portable detection methods for various contaminants, pathogens, and quality parameters in food products. Nano biosensors enable the detection of contaminants such as pesticides, heavy metals, and toxins in food products at extremely low concentrations. This ensures the safety of food products by identifying potential hazards before they reach consumers. Nano biosensors can detect foodborne pathogens such as *Salmonella*, *E. coli*, and *Listeria* with high sensitivity and specificity. Rapid detection of these pathogens helps prevent foodborne illnesses and outbreaks, enhancing food safety. Nano biosensors can assess various quality parameters in food products, including freshness, spoilage, and nutritional content. They can detect indicators of spoilage such as microbial metabolites and gas emissions, allowing for timely interventions to maintain product quality and shelf life. Nano biosensors are capable of detecting allergenic ingredients in food products, such as peanuts, gluten, and soy, even at trace levels. Accurate allergen detection is crucial for preventing allergic reactions in sensitive individuals and ensuring compliance with labelling regulations. Biosensors can be miniaturized and integrated into portable devices, enabling on-site testing and real-time monitoring throughout the food supply chain. This facilitates rapid decision-making, reduces the need for centralized laboratory testing, and minimizes delays in product distribution. Nano biosensors offer cost-effective solutions for food testing compared to traditional methods, which often require expensive equipment and reagents. Their miniaturization and scalability contribute to reduced operational costs and increased accessibility to testing technologies. Nano biosensors can be used for traceability and authentication purposes, allowing stakeholders to verify the origin, authenticity, and compliance of food products with labelling and certification standards. Overall, nano biosensors have transformed the food industry by enhancing food safety, quality control, and efficiency throughout the supply chain, ultimately benefiting both consumers and food producers.

NEED FOR BIOSENSOR BASED TECHNOLOGY

Biosensor is an analytical device that detects changes in biological processes and converts them into an electrical signal. The term biological process can be any biological element or material like enzymes, tissues, microorganisms, cells, acids, etc. Biosensors are employed in applications such as disease monitoring, drug discovery, for the detection of pollutants, disease causing microorganisms and markers that are indicators of a disease in bodily fluids (blood, urine, saliva, sweat). Biosensors help in the rapid detection of contaminants, pathogens, and spoilage indicators in food, ensuring the safety and quality of food products. Recent application of nano in biosensors have significantly enhanced the capabilities of biosensors, leading to innovative applications across various fields. Biosensors are used to detect contaminants, pathogens, toxins, and allergens in food products. Rapid and sensitive detection of these hazards ensures that contaminated products are identified and removed from the supply chain before reaching consumers, thereby safeguarding public health and preventing foodborne illnesses. Biosensors are employed to monitor various quality parameters in food products, including freshness, spoilage, nutritional content, and authenticity. By detecting indicators of spoilage and degradation, biosensors help ensure that food products meet quality standards and maintain their integrity throughout storage and distribution. Biosensors assist food manufacturers in complying with regulatory standards and labelling requirements. By detecting allergenic ingredients, genetically modified organisms (GMOs), and other regulated substances, biosensors help ensure that food products are accurately labelled and comply with food safety regulations

- Biosensors are used for real-time monitoring of food processing operations, such as fermentation, pasteurization, and sterilization.
- By monitoring critical process parameters, biosensors help optimize production processes, reduce waste, and ensure consistency in product quality. Biosensors enable traceability and authentication of food products throughout the supply chain.
- By tracking the origin, handling, and distribution of food products, biosensors help prevent food fraud, counterfeit products, and adulteration, thereby ensuring transparency and accountability in the food industry.
- Biosensors offer rapid and cost-effective methods for food testing compared to traditional laboratory techniques. By providing quick results on-site or in the field, biosensors minimize the time and resources required for sample preparation, transportation, and analysis, leading to increased efficiency and productivity in food testing operations.
- Biosensors are indispensable tools in the food industry for ensuring food safety, quality control, regulatory compliance, process optimization, supply chain management, and consumer satisfaction.

COMMERCIAL ASPECTS BEHIND FOOD ADULTERATION

Adulteration of food is the act of adding unwanted things to food products, normally for the sake of deceiving consumers or increasing profits [7]. Artificial coloring in foods like Red 40 and Yellow 5 is added to foods like candies and drinks for color enhancement, yet overdosing could have negative effects on one's health [8]. Starch is normally added to milk products to bulk them up, creating a false impression of their real make-up. Likewise, water is added to fruit juices and milk at times to increase quantity, which reduces their nutritional quality. Artificial sweeteners such as saccharin and aspartame are employed to impart sweetness with no extra calories, though there are still questions regarding their safety [9]. Toxic metals such as lead, mercury, and cadmium can find their way into food due to environmental contamination or defective processing techniques, and they present serious health hazards [10]. Low-cost flours are at times mixed with high-quality ones to reduce production costs, while ghee and edible oils could be adulterated by mixing them with poor-quality fats, changing their flavor and nutritional value [11]. Honey is often mixed with sugar or corn syrup to increase quantity, which reduces its natural flavor and health properties [12]. Spices such as turmeric and chili powder may contain synthetic coloring agents or fillers, compromise their quality and potentially lead to health concerns [13].

Food adulteration, which is primarily motivated by dishonest business practices and economic incentives, is a serious public health concern that involves the intentional addition of subpar or dangerous ingredients to food products. It presents serious health risks, such as organ damage, systemic diseases, and cancer. With their own advantages for detecting adulterants, detection techniques have evolved to include chromatography, spectroscopy, immunoassays, DNA-based tests, and sensor technologies. To protect food safety and preserve confidence in the food supply, preventive measures prioritize stronger laws, better detection technologies, consumer education, and international collaboration. To effectively address this enduring issue, a multimodal strategy integrating technology, policy, and awareness is needed.

RECENT ADVANCES IN NANOBIOSENSOR TECHNOLOGY

Nanobiosensors are critical in identifying food adulteration using a transducer, which converts biological interactions to digital signals for accurate identification of contaminants [14]. Their high sensitivity and selectivity enable them to identify even trace amounts of toxic substances and pathogens, leading to enhanced food safety [15]. Nanobiosensors have nanocarriers that bind to pollutants and impurities, increasing their capability to detect toxins like mycotoxins and toxic microorganisms across various stages of food processing from production to packaging [16]. Most of these devices employ enzyme-based catalysts that react to environmental conditions such as temperature and pH, requiring careful evaluation to ensure stability and functionality [17]. Some of the nanobiosensors are integrated into intelligent packaging systems that provide instant feedback on food quality and notify consumers and manufacturers alike of potential contamination or degradation [18].

- Nano biosensors have been applied in various ways within the food industry to enhance safety, quality control, and efficiency. Some of the developments are mentioned below:
- Nano biosensors have been developed to detect foodborne pathogens such as Salmonella, E. coli, Listeria, and

Campylobacter in food products. These biosensors utilize nanostructures such as nanoparticles and nanowires functionalized with specific biomolecules to selectively capture and detect pathogens with high sensitivity and specificity. Nano biosensors are used for the rapid and sensitive detection of food allergens, including peanuts, gluten, milk, eggs, and soy. Functionalized nanoparticles or nanomaterial-based platforms enable the detection of allergenic proteins in food samples, ensuring compliance with labelling regulations and preventing allergic reactions in sensitive individuals [19].

- Nano biosensors are employed to detect various toxins and mycotoxins in food products, including pesticides, heavy metals, aflatoxins, and cyanotoxins. Functionalized nanomaterials enable the selective capture and detection of these toxins at trace levels, ensuring food safety and quality assurance. Biosensors equipped with nanomaterial-based transducers enable real-time monitoring of pH, temperature, gas emissions, and metabolite concentrations, providing insights into product quality and shelf life. Nano biosensors are applied for the authentication and traceability of food products throughout the supply chain. Functionalized nanoparticles or nanotags embedded in packaging materials enable the tracking and verification of product origin, authenticity, and compliance with labelling standards, reducing the risk of food fraud and counterfeit products [20,21].
- Nano biosensors are used to detect food adulterants and contaminants, including adulterated ingredients, counterfeit additives, and adulterated beverages. Nano biosensors enable on-site and rapid testing of food samples, reducing the time and resources required for laboratory-based analysis. Portable biosensor devices equipped with nanomaterial-based sensors allow for real-time detection of contaminants, pathogens, and quality parameters in food products, facilitating timely decision-making and interventions in food processing and distribution [22,23].

Fig.1: Evolution of Nanobiosensors

3.1. ADVANTAGES OF NANOBASED SENSORS

Nanotechnology is at the core of advances in biological research. Nanotechnology plays vital role in biosensors by enabling the development of miniaturized, highly sensitive, and precise detection systems using nanomaterials and nanostructures, revolutionizing the field of biosensing. Maximizing the surface area of nanomaterials and functionalizing them with specific ligands enhances the binding affinity and selectivity of biosensors, improving the detection sensitivity. Nanomaterials, particularly Nanoparticles, often exhibit quick and real-time detection of biological molecules. Nanomaterials can enhance the stability and longevity of biosensors. Functionalizing biosensors surfaces with nanoparticles can protect the biological components from degradation, improving the shelf life and reliability of biosensors. Nanotechnology enables multifunctional biosensors, development of Wireless and remote biosensors by integrating different types of nanomaterials. Nano Biosensors play a crucial role in enhancing food safety and security by enabling sensitive, rapid, multiplex, and portable detection of adulterants in food samples.

- Nanostructures such as nanoparticles, nanowires, and nanotubes provide a high surface area-to-volume ratio, enhancing the sensitivity of biosensors to detect analytes at extremely low concentrations. Functionalization of these nanostructures with specific biomolecules further improves selectivity, enabling the detection of target molecules amidst complex biological matrices.
- Nano-enabled biosensors support multiplexed detection of multiple analytes simultaneously, offering comprehensive insights into complex biological processes and diseases. By incorporating arrays of nanostructures and functionalized surfaces, biosensors can detect and quantify multiple biomolecules in a single assay, improving efficiency and throughput in diagnostics and research.
- Nanotechnology facilitates real-time monitoring of dynamic biological processes and responses. Biosensors equipped with nanomaterial-based transducers enable continuous monitoring of physiological parameters, drug concentrations, and biomolecular interactions in living organisms, providing valuable insights into disease progression, treatment efficacy, and personalized medicine. Nano biosensors play a crucial role in environmental monitoring by detecting pollutants, pathogens, and toxins in air, water, and soil. Functionalized nanomaterials enable selective capture and detection of environmental contaminants with high sensitivity and specificity, contributing to environmental surveillance, pollution control, and public health protection. Nano-enabled biosensors are employed for rapid and on-site detection of foodborne pathogens, allergens, and contaminants in food products [24].
- Nanotechnology facilitates advanced bioimaging techniques and theragnostic applications by incorporating nanomaterials into biosensors. Nanoparticle-based contrast agents and probes enable high-resolution imaging of biological structures and functions, while nano-enabled drug delivery systems offer targeted therapy and real-time monitoring of treatment responses. Recent advancements in nanotechnology have propelled the development of biosensors with enhanced sensitivity, selectivity, portability, and functionality, enabling a wide range of applications in healthcare, environmental monitoring, food safety, and beyond [25,26].

The implementation of nano biosensors in the food industry is not just desirable but imperative. These cutting-edge technologies offer unparalleled capabilities in detecting contaminants, ensuring food safety, and enhancing quality control measures. Embracing nano biosensors holds the promise of revolutionizing food safety protocols, thereby safeguarding public health and consumer confidence in the integrity of the food supply chain. As we navigate increasingly complex challenges in food production and distribution, the integration of nano biosensors stands as a crucial step towards a safer, more efficient, and sustainable food industry.

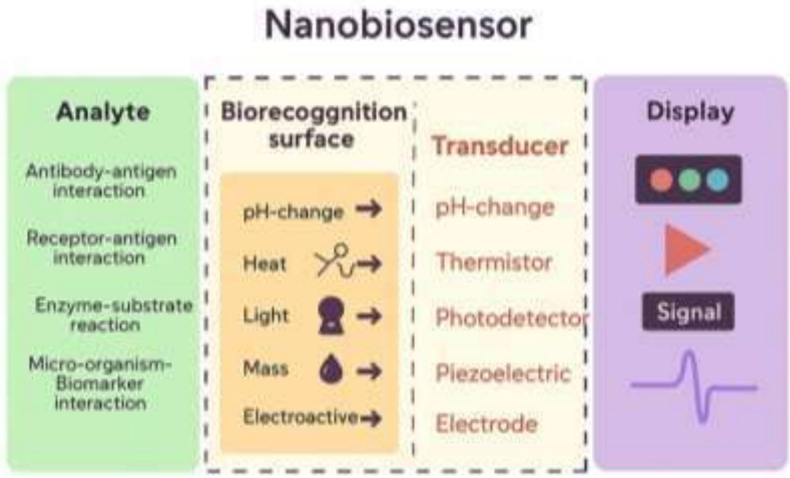

Fig.2: A schematic depiction of nanobiosensors, their interactions, and constituent parts.

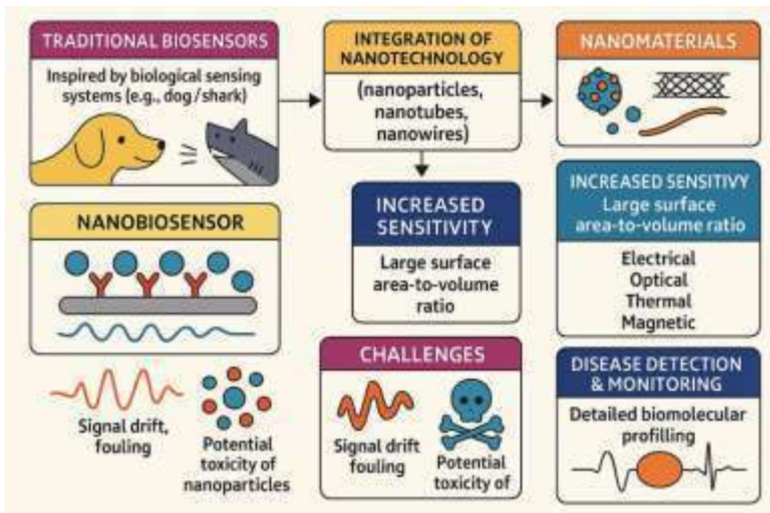

Fig.3: Advantages of Nanobiosensors Over Traditional Biosenssors

CAUSES AND EFFECT OF FOOD ADULTERATION

One of the primary reasons for food adulteration is the pursuit of economic gain by dishonest traders or manufacturers. Adulterating food with cheaper substances allows them to increase profits. As the food supply chain becomes more intricate, it becomes easier for adulteration to occur. With multiple intermediaries involved, there are more opportunities for adulteration to go undetected. Weak regulatory frameworks or inadequate enforcement of existing regulations can embolden unscrupulous individuals or companies to engage in food adulteration without fear of consequences. While technology has improved food production and processing, it has also provided opportunities for sophisticated adulteration techniques that are harder to detect. In some cases, consumer demand for certain foods or characteristics at low prices may indirectly encourage adulteration as suppliers seek to meet these demands at reduced costs [27].

Microorganisms vehiculated by food can be related to a variety of scenarios, including those benefiting health (e.g., stimulation of host antibodies, release of chemicals to stimulate the health of the overall system, or inhibition of pathogen development). Ready-to-eat (RTE) foods are foods and beverages consumed at the point of sale or at a later time without any further processing or treatment in such a way that may significantly reduce the microbial load and could be raw or cooked, hot or chilled [1]. RTE foods can be fruits and fruit products, meat and its products, eggs and the like.

RTE foods provide an important source of readily available and nutritious meals for consumers. Today, the increasing demand for RTE foods has led to an increase in the amount of food and different types of food that consumers can easily obtain. RTE foods are convenient meals for today's lifestyle because they do not require cooking or further preparation. In addition to its benefits, the incidence of foodborne diseases is increasing globally, involving a wide range of diseases caused by pathogenic organisms, and becoming a public health problem that requires urgent response [28]. Due to the negligence of regulatory agencies and weak law enforcement, which has affected food quality and led to the provision of unsafe food to consumers, the hygiene and safety practices of most food suppliers have not been supervised or monitored. A study found that between 1995 and 2011, a significant portion of food in Dhaka city was adulterated, with 40-54% of daily food items affected. It also revealed that while consumers prioritize freshness and expiry dates when buying food, very few check for regulatory approval, highlighting a need for better awareness and action against food adulteration [29].

According to estimates by the World Health Organization, eating contaminated food can cause/spread more than 200 different types of disease, and sometimes they can cause long-term health problems, especially for vulnerable groups such as the elderly, pregnant women, and babies. Recently there has been an increase in knowledge on gut bacterial genera and species commonly affected by diet, as well as evidence suggesting that the intestinal microbiome plays an important role in modulating the risk of several chronic diseases (e.g., inflammatory bowel disease, obesity, type 2 diabetes, cardiovascular disease, and cancer) [30,31]. Nevertheless, comprehensive information about the types of diet that transmit bacteria implicated in those diseases, as well as environmental and host factors favoring their colonization, remains scarce. Food preparation usually involves multiple steps including processing, packaging, transportation and storage. Each step could be a potential source for POP invasion. Food could be contaminated by POPs through different paths. For example, raw materials may contain POPs that are transferred from the environment. Since POPs are resistant to degradation, they can stay in the environment for an extended period time. Previously released POPs in the environment are a major source of the POP contamination of food and feed supplies. Plant foliage uptake of POPs can effectively transfer POPs from air to plant and subsequently to food. Other sources of POPs are food preparation steps, during which POPs may artificially be introduced by humans. Ensuring food safety and quality has been one of the current challenges today due to an increasing number of food poisoning incidents according to the World Health Organization (WHO) with an estimated 600 million illnesses per year leading to 420,000 deaths annually. Foodborne diseases are related to unhygienic food handling, processing, and inadequate temperature storage conditions. The Food and Drug Administration (FDA) and European Food Safety Authority (EFSA) highlighted that consumption of biogenic amine-contaminated foods can lead to adverse health effects, including allergic reactions, migraines, and even life-threatening conditions at high concentrations [32,33].

Biogenic amines are naturally occurring organic compounds derived mainly from the decarboxylation of amino acids by microorganisms. They play important roles in biological processes such as neurotransmission, protein synthesis, and cell growth. However, their excessive accumulation in food, especially protein-rich items like meat, fish, cheese, and fermented products, can pose health risks including allergic reactions and food poisoning. The formation of biogenic amines is influenced by factors like microbial contamination, storage conditions, temperature, and pH. Monitoring and controlling these compounds through good hygiene, proper storage, and food processing techniques is essential for ensuring food safety and quality. Regulations often set limits for key amines like histamine to prevent toxic effects, highlighting the importance of managing biogenic amine levels in food production and consumption. Biogenic amines (BAs) such as histamine, putrescine, and cadaverine are nitrogenous molecules generated through the decarboxylation of amino acids in protein-rich foods during the extended storage time of food products. In this regard, BAs are considered to be a freshness and quality indicator as their concentration increases with food spoilage [34].

Foodborne illnesses often arise from contamination by bacteria, viruses, parasites, toxins, and chemical compounds such as biogenic amines. These amines, including histamine and tyramine, form primarily in fish and fermented foods when improper storage or processing allows microbial activity to thrive. Exposure to high levels of these compounds can cause symptoms that mimic allergic reactions, migraines, and hypertensive crises. Regulatory agencies in the US and EU have established limits on histamine levels in food to mitigate these health risks. Analytical techniques like high-performance liquid chromatography are essential for detecting and quantifying biogenic amines, as organoleptic methods are often insufficient. Effective control of biogenic amine formation through proper handling and storage is critical for ensuring food safety and public health.[35]

Bisphenol compounds are found throughout the contemporary world in the form of plastics that are used extensively by consumers for food storage. These polymers are also widely used in the packaging of baby formula, baby bottles, the lining of canned food and drink, dental implants, and sales receipts. Mainly though, these particular plastics enter the diet when people microwave food in plastic food containers or eat and drink from plastics that have been exposed to much wear or harsh chemicals that break down the monomers and release them into the food or drink. The use of bisphenols has been incredibly wide-spread and global for decades [8]. However, in 2007, the first indications were published that bisphenol polymers may leak monomers into food and drink and disrupt endocrine pathways by mimicking estrogen. Since then, BPA (bisphenol A) has become one of the most well-known EDCs (endocrine disrupting compounds) with pronounced effects on the reproductive system, child development, metabolic disorders, obesity, endocrine disorders, and the nervous system; as well as being implicated in causing DNA damage, oxidative stress, and breast cancer disorders, and the nervous system; as well as being implicated in causing DNA damage, oxidative stress, and breast cancer [9].

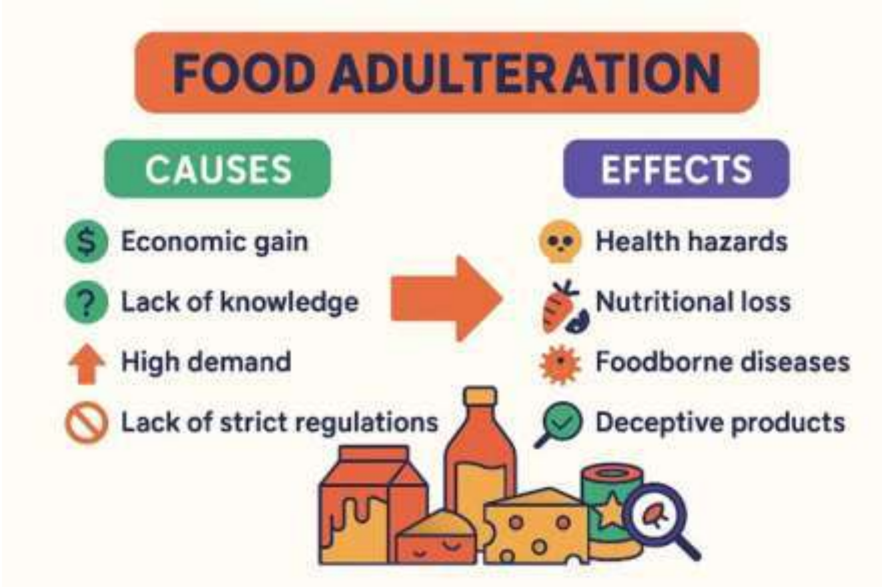

Fig.4: Causes and Effects of Food Adulteration

APPLICATION OF BIOSENSORS IN DETECTION

Biosensors offer exceptional sensitivity, specificity, and rapid response times, making them a vital tool for detection and measurement. Their applications have significantly advanced scientific and technological progress in various fields. Biosensors have a broad range of applications in detection, including:

- **Medical diagnostics**

Biosensors are versatile tools that can detect specific pathogens or antibodies in samples, aiding in the diagnosis of diseases like HIV, malaria, or tuberculosis. They can identify allergens in the body, help diagnose allergies and guide treatment plans, and measure hormone levels to assist in the diagnosis and management of conditions like thyroid disorders or hormonal imbalances. Additionally, biosensors can analyse DNA or RNA samples for genetic testing, paternity testing, or personalized medicine. They are capable of detecting cardiac troponin I, a protein biomarker released into the bloodstream following a heart attack, and can measure glucose levels in blood, urine, or saliva to help manage and treat diabetes. Furthermore, biosensors can detect cancer biomarkers, such as HER2, in DNA or bodily fluids, and monitor pH levels in wounds to indicate the presence of infection or inflammation. They are also used to create prosthetic limbs that respond to muscle signals, allowing for more natural movement and control [36,37].

- **Food safety**

Biosensors play a crucial role in ensuring food safety and public health by detecting harmful biotoxins in real time, preventing contamination, and ensuring consumer safety. They identify pesticide residues, promote sustainable food production and protect human health. Additionally, biosensors monitor antibiotic concentrations, enabling early intervention and minimizing harmful effects. They are also capable of identifying pathogenic bacteria, such as E. coli, to prevent foodborne illnesses, and detecting heavy metals, like lead, to ensure the safety of food products. These instruments provide a fast and effective means of identifying different contaminants. They also can be used to check whether fruits have ripened naturally and not artificially, which could be harmful. These instruments ensure that the food we buy is genuine and labelled correctly, which protects consumers from deception and misdescription. Lastly, biosensors find use in agriculture to detect disease in crops at an early stage, where farmers can act and avoid large losses. For most instances, biosensors are superior to conventional methods of testing, being quicker, cheaper, and even more precise [38].

Consider a system that is always monitoring your food from farm to plate. Biosensors can do it all, tracking things such as temperature and humidity during storage and transport to avoid spoilage. They can even detect the early warning signs of decay by identifying the gases emitted as food rots, allowing us to steer clear of consuming rotten items. In addition to safety, these innovative devices are also able to analyze the nutritional composition of our food, testing vitamin and mineral content to guarantee proper labelling and enable informed nutritional decisions. In the production of fermented foods, biosensors play the role of a vigilant overseer, monitoring the fermentation process with care to guarantee a uniform and safe end product [39].

Actinobacteria are a promising source for new pharmaceuticals, especially due to their ability to produce specialized biomolecules and synthesize nanoparticles. These microorganisms yield nanoparticles with unique physical, chemical, and biological properties, including potent antibacterial activities. Unlike conventional chemical methods, which are often hazardous and expensive, nano-biosynthesis using Actinobacteria offers a green technology approach that reduces metal salts through biological processes. This field focuses on the role of natural products, specifically Actinobacteria-derived nanoparticles, in discovering and developing new therapeutic agents. Actinobacteria are excellent producers of specialized biomolecules, and their genomes contain numerous biosynthetic pathways, representing an untapped source of novel antibacterial molecules. Nanoparticle bioproduction can occur through both intracellular and extracellular mechanisms, often as part of cellular detoxification processes against heavy metals. Controlling particle size and polydispersity is crucial for biotechnological applications. The antimicrobial properties of these biogenic nanoparticles are thought to be linked to their surface-reactive groups, which lead to the formation of reactive oxygen species, with smaller particles having increased surface area and more reactive sites. Various techniques are used to characterize these nanoparticles, including UV-vis spectrophotometry, transmission electron microscopy, scanning electron microscopy, atomic force microscopy, dynamic light scattering, X-ray powder diffraction, Fourier transform infrared spectroscopy, zeta potential measurement, particle size analysis, and energy dispersive X-ray spectroscopy [40].

- **Environmental monitoring**

Biosensors are highly effective in environmental monitoring, capable of detecting lead and mercury in water and soil, as well as pesticides, herbicides, and dioxins in water, air, and soil. They can also identify phenolic compounds and various toxins in these environments. Additionally, biosensors are used to detect pathogens in water and soil, ensuring the safety and health of ecosystems and human populations. These sophisticated sensors assist in the detection of irrigant water contaminants, presenting real-time information that allows farmers to take action and ensure crop health and yield maximization. Aside from ensuring water quality, biosensors also play a significant role in the monitoring of air pollution, ensuring that the identification of toxic emissions that might impact crops and livestock is done while promoting sustainable agricultural practices. Soil health is another key consideration, and biosensors help assess nutrient content and the presence of toxins, enabling farmers to make good fertilizer and soil amendment choices. Recent developments have also incorporated nanomaterials into biosensors, making them much more sensitive and capable of identifying even trace levels of contaminants. The information collected from these sensors is also useful for informing environmental policies and sustainable agriculture practices. In addition, coordinated efforts among government agencies, industries, and research institutions increase the strength of biosensor applications, enabling innovation and extensive use in the agricultural industry [33]. Nanobiosensors represent a significant advancement in environmental monitoring, offering superior capabilities compared to conventional sensors due to their nanoscale dimensions and unique properties. These devices are designed to detect and assess environmental contaminants by responding to specific chemical, biochemical, or physical stimuli. Their advantages include high sensitivity and selectivity, fast response times, portability, and the ability to operate with low energy consumption. They are particularly useful for detecting harmful substances in air, water, and soil, leveraging the distinct optical, electrochemical, mechanical, and magnetic properties of nanomaterials. The integration of nanotechnology with biotechnology has further enhanced the development of more efficient and selective nanobiosensors for various environmental applications, including the detection of pathogens, toxic gases, organic chemicals, and heavy metals [41].

- **Biodefense**

Biosensors stand at the nexus of contemporary biodefense. These devices allow users to determine that a biological risk exists quickly and accurately, thereby allowing them to control an outbreak prior to spreading. Researchers have prioritized biothreats in terms of toxicity to help them create a targeted detection prototype for biothreat determination. The influx of mobile units for biodefense led sensor engineers to develop compact, durable sensors capable of testing in the field so that users receive results where they want them and when they want them! Many techniques now target bacteria, viruses, and toxins, providing first responders with the applied technology to address the hazard. Unconventional nanoscale material additions such as graphene oxide, gold nanoparticles, or carbon nanotubes improved the performance of each biosensor by increasing sensitivity and selectivity. Since biosensor datasets are often massive, artificial intelligence has entered the field to systematically analyze the datasets, magnify the confidence of the readings, and remove background noise. With these new synergistic hardware and intelligent software capabilities, a fully developed biosensor now provides a clear differentiation or classification between harmful microbes from non-harmful microbes, thus meeting the operational demands for national defence applications [34].

- **Point-of-care testing**

Biosensors are transforming point-of-care (POC) testing by providing fast, accurate, and cost-effective solutions for medical diagnostics. Their ability to detect disease biomarkers at extremely low concentrations is essential for early diagnosis, enabling timely treatment and improved patient outcomes. They allow rapid detection of diseases like COVID-19 in clinical settings. One of their key advantages is delivering rapid test results, which is particularly crucial in emergencies where immediate medical decisions can save lives. Additionally, biosensors facilitate continuous health monitoring, making them invaluable for managing chronic conditions by tracking biomarker fluctuations in real time. The incorporation of carbon-based nanomaterials has significantly enhanced their sensitivity and specificity, ensuring precise detection even in complex biological samples while minimizing errors. Furthermore, biosensors are designed to be cost-effective, making advanced diagnostics more accessible, especially in low-resource settings where conventional lab testing is impractical. Electrochemical sensor technology, particularly those utilizing carbon nanocomposites, has proven highly effective in detecting a wide range of biomarkers, further strengthening the role of biosensors in modern healthcare. Beyond diagnostics, these advanced sensors hold potential applications in drug delivery and cancer therapy, demonstrating their versatility in both disease detection and treatment innovations [42].

- **Wearable devices**

Wearable biosensors are revolutionizing healthcare by enabling continuous monitoring of vital signs and biochemical markers, playing a crucial role in early disease detection. They enable continuous monitoring of vital signs like heart rate or blood glucose for health and wellness. These advanced devices track key health parameters such as heart rate and glucose levels, offering valuable insights into conditions like cardiovascular diseases and diabetes. For individuals managing chronic illnesses, wearable sensors provide real-time data, allowing for better control over health conditions through continuous monitoring and timely adjustments. In fitness and wellness applications, they help users keep track of their physical activity and overall health, promoting healthier lifestyles without requiring invasive procedures. One of the most significant benefits of these biosensors is their ability to provide instant health data, ensuring prompt medical attention in case of abnormal readings, such as sudden heart rate fluctuations. By facilitating continuous health tracking, these devices contribute to the early identification of potential health issues, allowing for timely medical intervention and improved patient outcomes while also reducing healthcare costs [36].

- **Drug detection**

Advancements in nanomaterials have enabled the seamless integration of biosensors with drug delivery systems, allowing for precise detection and targeted release of medications. This innovation enhances treatment effectiveness while reducing potential side effects. Additionally, biosensors play a critical role in monitoring drug levels within the body, ensuring that dosages remain within safe and effective ranges, particularly for medications that require precise administration. They help in identifying illegal drugs or monitoring drug levels in patients. They also assist in identifying possible drug interactions, helping healthcare professionals prevent adverse effects when multiple medications are prescribed. In therapeutic drug monitoring, these sensors provide real-time data on drug concentrations in the bloodstream, which is especially crucial for medications with narrow therapeutic windows. Beyond therapeutic applications, biosensors contribute to pharmaceutical safety by detecting contaminants or adulterants in medications, ensuring product quality and patient safety. Furthermore, their use in drug research and development accelerates the screening of new compounds by offering rapid and reliable data on drug efficacy and safety, ultimately expediting the development of novel treatments [43].

- **Bioprocess monitoring**

Enzymatic biosensors play a crucial role in continuously tracking key biomarkers such as glucose and lactate during fermentation, allowing for real-time optimization of microbial growth and product formation. This ensures that bioprocesses remain efficient and productive. They are involved in monitoring biomolecules in bioreactors for biotechnology applications. In pharmaceutical manufacturing, biosensors are essential for quality control, detecting specific metabolites or by-products to guarantee that final products meet stringent safety and efficacy standards. By providing immediate insights into the metabolic state of cultures, these sensors enable timely adjustments to process parameters, such as nutrient supply and environmental conditions, to maximize yield while reducing waste. Additionally, biosensors are instrumental in identifying contaminants, including unwanted microorganisms or toxic by-products, safeguarding the integrity of fermentation processes. Their integration into automated bioprocessing systems further enhances efficiency by enabling continuous monitoring and control, ensuring consistency and scalability in large-scale production [38].

- **Biothreat agent detection**

Detection of biothreat agents by using biosensors is a revolutionary technique for identifying dangerous biological substances like bacteria, viruses, or toxins that may be employed in bioterrorism or warfare. Such agents, e.g., Bacillus anthracis (anthrax), Clostridium botulinum (botulinum toxin), or ricin, are serious threats to national security and public health. Biosensors provide quick, sensitive, and on-site analysis of such agents with minimal sample preparation. By pairing a biological recognition element (such as nucleic acids or antibodies) with a signal transducer, biosensors can provide real-time notification, which allows for rapid response in military, environmental, and clinical applications. Their speed, portability, and specificity make them critical components of early warning systems and biothreat readiness. The integration of nanomaterials such as gold nanoparticles, quantum dots, carbon nanotubes, and magnetic nanoparticles has significantly enhanced the sensitivity, specificity, and portability of biosensors used in biothreat surveillance. These nanobiosensors enable the detection of extremely low concentrations of pathogens and toxins like *Bacillus anthracis*, *Brucella* spp., ricin, and botulinum toxin, often within minutes and with minimal sample requirements. The paper highlights how such platforms—using optical, electrochemical, or magnetic signal transduction—offer a promising alternative to conventional diagnostic methods, especially in field-based or point-of-care applications critical for biodefense [32].

- **Sepsis Marker Detection**

Detection of sepsis marker by biosensors is a modern diagnostic approach directed at detecting early indicators of sepsis—a life-threatening condition resulting from the body's overreaction to infection. Accurate and timely detection is essential since late diagnosis can cause organ failure and death. Biosensors are employed to rapidly detect certain biomarkers like procalcitonin (PCT), C-reactive protein (CRP), and interleukins in blood samples. These indicators show the extent and severity of infection and inflammation. In contrast to classical laboratory tests, biosensors provide rapid, real-time answers at the point of care, which can accelerate clinical decision-making and patient outcome improvement in emergency and intensive care. A paper-based plasmonic nanobiosensor has been developed for the rapid detection of interleukin-6 (IL-6), a key early marker of sepsis, directly from whole blood samples. The sensor employs gold nanoparticle immunoprobes and utilizes a smartphone-assisted colorimetric readout system, achieving a remarkably low detection limit of 0.1 pg/mL within just 17 minutes. This approach eliminates the need for complex laboratory equipment and allows for real-time, point-of-care assessment of sepsis risk. The integration of nanotechnology with portable diagnostic tools demonstrates significant potential for early sepsis detection, especially in resource-limited or emergency settings [33].

- **Mycotoxin Detection**

Mycotoxin analysis with biosensors is an important method for securing food and feed safety by detecting toxic substances synthesized by fungi, including aflatoxins, ochratoxins, and fumonisins. These mycotoxins can infect crops during growth, harvest, or storage, e.g., cereals, nuts, and spices, and produce severe health issues in humans and animals, such as cancer, liver damage, and suppression of the immune system. Conventional detection techniques are usually time-consuming and need advanced equipment. Compared to them, biosensors offer a fast, sensitive, and economical option for in-situ detection. With the use of biological components such as antibodies or aptamers to bind specifically to mycotoxins, biosensors allow monitoring in real-time and prevent contaminated materials from reaching the food chain. A paper-based nanobiosensor has been developed that enables rapid, sensitive detection of key mycotoxins—including ochratoxin A (OTA) and aflatoxin B_1 (AFB_1)—directly in rice samples. This colorimetric aptasensor leverages unmodified gold nanoparticles conjugated with target-specific aptamers; in the absence of toxins, the aptamer-coated nanoparticles remain dispersed and retain their red color, but upon binding to the mycotoxins, the aptamers detach and trigger nanoparticle aggregation and a visible color shift. The system achieves exceptionally low detection limits of approximately 0.005 ng/mL for OTA and 0.07 ng/mL for AFB_1, shows high specificity even in the presence of other contaminants, and delivers prompt results suitable for on-site analysis [34].

- **Heavy Metal Detection**

An inventive and effective method for detecting harmful metals like lead, mercury, cadmium, and arsenic in water, soil, food, and biological samples is heavy metal detection with biosensors. Even at trace amounts, these metals can build up in living things and lead to serious health problems like kidney damage, neurological disorders, and developmental problems. Traditional detection techniques frequently call for costly equipment and intricate lab work. However, by employing biological recognition components like enzymes, proteins, or DNA sequences that interact specifically with target metals, biosensors provide a quicker, more portable, and more affordable solution. This promotes improved public health and environmental protection by enabling real-time, on-site monitoring of industrial and environmental contamination. This review by Fakayode et al. (2023) underscores the significant advancements in electrochemical and colorimetric nanosensors for the rapid and cost-effective detection of heavy metal ions in environmental and biological samples [34]. The authors highlight that conventional analytical techniques, while highly sensitive and accurate, are often hindered by high costs, sophisticated instrumentation, and lack of portability, limiting their applicability for in situ, real-time monitoring. In contrast, recent developments in portable nanosensors—such as smartphone-operated screen-printed electrodes, microfluidic devices, and paper-based sensors—offer promising alternatives that are simple, affordable, and suitable for field deployment. The review emphasizes that these sensors utilize nanomaterials like graphene, carbon nanotubes, and metal nanoparticles to achieve high sensitivity and selectivity, enabling detection at trace levels. Additionally, the paper discusses the advantages of optical and electrochemical nanosensors in providing rapid visual or electronic signals, facilitating quick decision-making in environmental monitoring and food safety. The authors also explore current challenges and future directions, including improving specificity, reducing interference, and expanding the range of detectable ions, which are crucial for the widespread implementation of nanosensor technology in heavy metal monitoring [35].

- **Cosmetics Safety Testing**

Biosensor-based cosmetics safety testing is a contemporary method that guarantees cosmetics are non-toxic, safe, and devoid of dangerous or prohibited ingredients before they are distributed to customers. Long laboratory processes and animal testing are common in traditional cosmetics testing methods, which present ethical and legal issues. By identifying allergens, microbial contaminants, heavy metals, or endocrine-disrupting chemicals in products like creams, shampoos, and makeup, biosensors provide a quicker, more moral, and more economical option. Biosensors can provide quick and precise analysis by utilizing biological recognition elements like enzymes, antibodies, or cells. This helps manufacturers meet safety regulations while safeguarding the health of consumers. [37] Nanomaterials function at an extremely small scale, which grants them distinct physical and chemical properties that differ significantly from their larger-scale versions. These unique characteristics are being harnessed to develop innovative cosmetic products, such as formulations with enhanced delivery mechanisms and improved stability. However, the small size and reactivity of nanomaterials also raise safety concerns, particularly regarding their potential to penetrate biological barriers and interact with cellular systems. To evaluate these safety issues effectively, advanced diagnostic tools like nanobiosensors are being developed to monitor and assess the health impacts of nanomaterials.

- **Neurotransmitter detection**

The identification of neurotransmitters is also an important area of study and diagnosis of neurological diseases since these chemical messengers control key brain functions like mood, cognition, motor functions, and memory. Classical detection systems are usually slow, non-specific, or lacking in sensitivity to be employed in real-time analysis in complex biological systems. Nanobiosensors have been a highly effective alternative option, providing greater sensitivity, quick response, and capability for detection of neurotransmitters at very low concentration levels. Incorporating nanomaterials such as carbon nanotubes, graphene, and metal nanoparticles with biorecognition entities such as enzymes or aptamers, nanobiosensors provide precise measurement of neurotransmitters such as dopamine, serotonin, acetylcholine, and glutamate. This development is not only of clinical diagnostic and therapeutic monitoring value but also critically important to neuroscience research, pharmaceutical development, and the investigation of brain disease and disorders like Parkinson's disease, Alzheimer's disease, and depression [38]. Nanobiosensors represent a significant advancement in the detection of neurotransmitters, overcoming the sensitivity and selectivity limitations often encountered with traditional electrochemical biosensors. By integrating nanomaterials and nanotechnologies, these biosensors achieve enhanced performance due to properties such as large surface areas, excellent templating capabilities, and improved electron transfer. This allows for highly sensitive and selective detection of neurotransmitters like dopamine and serotonin, even at nanomolar concentrations. These advancements are crucial for various applications, including the early diagnosis and treatment of neurological disorders, real-time monitoring of neural processes, and the development of neural stem cell therapies.

- **Cardiac marker detection**

Cardiac markers are biomolecules that are released into the blood when there is an injury or stress to the heart, such that their identification is critical in the early diagnosis and treatment of cardiovascular conditions like myocardial infarction (heart attack), heart failure, and ischemia. Traditional diagnostic methods are effective but time consuming and often lack the sensitivity needed for detection at an early stage. Nanobiosensors provide a rapid, highly specific and sensitive alternative for sensing important cardiac biomarkers such as troponin I and T, creatine kinase-MB (CK-MB), myoglobin, and B-type natriuretic peptide (BNP). The nanobiosensors use nanomaterials including gold nanoparticles, quantum dots, and carbon nanotubes to enhance the sensitivity and detection limits. Their capability of delivering real-time point-of-care analysis renders them extremely useful in the emergency environment and continuous cardiac monitoring, leading to quicker clinical decision-making and better outcomes for the patient [39]. Nanobiosensors, specifically those utilizing single nanofibers derived from multi-walled carbon nanotubes (MWCNTs) embedded in SU-8 photoresist, offer an ultrasensitive, label-free platform for detecting cardiac biomarkers, which is crucial for early diagnosis of acute myocardial infarction (AMI). These chemiresistive biosensors operate by measuring changes in electrical conductance of functionalized nanofibers upon target antigen binding. The nanofibers are functionalized with specific monoclonal antibodies, and antigen binding induces a surface stress that increases charge carrier mobility within the MWCNTs, leading to a measurable conductance change. This direct detection method eliminates the need for time-consuming external labeling procedures, making it suitable for point-of-care diagnostics. The platform has successfully detected myoglobin (Myo), cardiac Troponin I (cTn I), and Creatine Kinase-MB (CK-MB) with experimental minimum detection limits of 6 fg/mL for Myo, 20 fg/mL for CK-MB, and 50 fg/mL for cTn I, which are significantly lower than clinical requirements. The nanobiosensor demonstrates excellent specificity, showing no response to non-specific proteins, and offers a rapid response time of less than a minute, high sensitivity, and good specificity. Its durability has also been confirmed over several months.

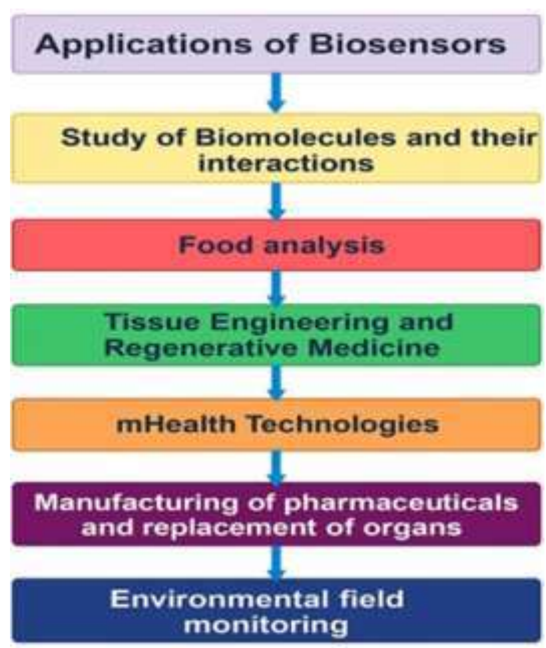

Fig.5: Various Applications of Biosensors Across Different Fields

ROLE OF NANOTECHNOLOGY IN BIOSENSORS AND ITS VARIOUS APPLICATIONS.

Traditional biosensors were inspired by natural biological sensing systems, such as the olfactory abilities of dogs or the electrosensitivity of sharks, and typically relied on in vitro techniques to replicate these mechanisms. Over the last few decades, there has been a major shift towards integrating nanotechnology into biosensor design. This shift is driven by the ability to create nanoscale materials, such as nanoparticles, nanotubes, and nanowires, that exhibit unique physical and chemical properties. These nanomaterials allow biosensors to directly interact with biomolecules, significantly enhancing their functionality. Nanobiosensors offer several advantages, including increased sensitivity due to their large surface area-to-volume ratio, which enables more efficient capture and analysis of target biomolecules. This enhanced sensitivity leads to improved detection of specific analytes and a more accurate localization of biomolecular changes associated with diseases. Additionally, nanobiosensors can employ a wide variety of transduction mechanisms, such as electrical, optical, thermal, and magnetic techniques, providing versatility across different fields of application. This versatility has also advanced disease detection and monitoring, allowing for more detailed biomolecular profiling, which aids in therapeutic assessments and tracking disease progression. Despite these advantages, there are still challenges that need to be addressed. These include issues like signal drift, fouling, and non-specific interactions, which can lead to unreliable transduction signals and complicate the interpretation of results. Furthermore, the release of nanoparticles into the environment raises concerns about their potential toxicity, which could pose risks to both human health and the environment [28].

Nanomaterials have revolutionized biosensor technology by enhancing sensitivity, specificity, and detection capabilities across various applications list in Table 1. Among these, different types of nanomaterials, including metal-based, carbon-based, and semiconductor nanoparticles, play a crucial role in advancing biosensing techniques [28].

Table 1: Nanomaterials and their various applications in Biosensors [28,29,30]

S.No.	Nanoparticle Used	Applications
1	Graphene	Graphene consists of a single layer of carbon atoms organized in a two-dimensional hexagonal structure. Its outstanding electrical conductivity, combined with an extensive surface area, makes it highly suitable for biosensing applications. This material has the ability to interact efficiently with various biomolecules, thereby improving the sensitivity and selectivity of biosensors[28].
2	Gold Nanomaterials	Gold nanoparticles play a crucial role in biosensor technology due to their distinct optical and electronic characteristics. Their strong affinity for biomolecular interactions makes them particularly useful in colorimetric detection methods, where visible color shifts indicate the presence of target analytes. Additionally, their biocompatibility and ease of surface modification make them a preferred choice for diverse biosensing applications[29]
3	Silver Nanoparticles	Similar to gold nanoparticles, silver nanoparticles exhibit plasmonic properties that make them highly effective in biosensing applications. They are particularly useful in Surface-Enhanced Raman Spectroscopy (SERS)-based biosensors, enabling improved signal detection. Additionally, their role in colorimetric sensing allows for visual identification of target analytes through distinct color changes.[30]

4	Prussian Blue Nanoparticles	These nanoparticles are specifically utilized in lateral flow assay (LFA) biosensors for detecting clenbuterol. Their strong affinity for target antibodies facilitates precise recognition, producing visible colorimetric changes that indicate the presence of the target substance.[30]
5	Magnetic Nanoparticles	Magnetic nanoparticles can be functionalized with biocompatible coatings, making them suitable for targeted delivery and biosensing applications. Their ability to respond to external magnetic fields allows for precise control over biosensing targets, while also enhancing signal detection in electrochemical sensors, improving overall sensitivity and performance.[30]
6	Carbon-Based Nanomaterials	This category includes nanomaterials such as graphene and carbon nanotubes, both of which possess excellent conductivity, high surface area, and biocompatibility. These properties make them ideal for immobilizing biomolecules and facilitating efficient electron transfer, leading to improved biosensor sensitivity and performance.[30]
	Transition-Metal Dichalcogenides	Two-dimensional materials like molybdenum disulfide (MoS_2) have garnered attention in biosensor development due to their distinctive electrical characteristics. Their semi-conducting nature and wide bandgap provide advantages over traditional carbon-based materials in certain applications, making them highly effective for next-generation biosensing technologies.[30]
	Upconverting Nanoparticles	Renowned for their luminescent capabilities, upconverting nanoparticles are particularly valuable in optical biosensors. They possess the unique ability to convert near-infrared light into visible light, enhancing detection in low-light conditions, which is crucial for highly sensitive biosensing applications.[30]
	Quantum Dots	Quantum dots are semiconductor nanomaterials that exhibit remarkable optical properties, including fluorescence emission. Their tunable light-emitting characteristics make them highly suitable for a wide range of biosensing applications, particularly in fluorescence-based detection systems where high sensitivity and specificity are required.[30]

INNOVATIONS AND IMPROVEMENTS IN NANOBASED BIOSENSORS

Building upon the diverse range of nanomaterials used in biosensors, their unique properties play a crucial role in enhancing signal transduction, surface functionalization, and amplification strategies, further improving the sensitivity and efficiency of detection systems.

➢ Signal Transduction [29]

Nanomaterials play a crucial role in enhancing signal generation and transmission within biosensors through multiple mechanisms:

- Enhanced Electrical Properties: Materials like graphene, carbon nanotubes, and metallic nanoparticles exhibit remarkable electrical conductivity, facilitating efficient charge transfer between the biosensor interface and target biomolecules. This results in stronger and more reliable signal output during detection.
- Expanded Surface Area: Due to their nanoscale structure, these materials provide an extensive surface area, promoting increased interactions with biological molecules. This heightened interaction significantly improves the conversion of biological events into quantifiable signals, thereby boosting sensor sensitivity.
- Innovative Signal Conversion Mechanisms: Nanostructured materials introduce novel transduction approaches, such as electrochemical and optical techniques, that are unattainable with bulk materials. For

instance, quantum dots enhance fluorescence signals, enabling the detection of trace amounts of analytes with high precision.

- **Surface Functionalization [29]**

Optimizing the surface of nanomaterials is essential for enhancing their biocompatibility and target specificity in biosensor applications:

- Biomolecule Attachment: Covalent or non-covalent binding of biomolecules such as antibodies, enzymes, or nucleic acids to nanomaterial surfaces improves their selectivity for specific analytes. This targeted interaction minimizes potential interference from other substances present in the sample.
- Customized Functional Groups: Modifications with chemical groups like carboxyl, amine, or thiol promote selective interactions with biological molecules, enabling stable and efficient molecular recognition. Such tailored surface modifications enhance the accuracy and reliability of biosensors.
- Improved Biocompatibility: Functionalized nanomaterials exhibit reduced cytotoxicity and increased stability, making them suitable for biomedical applications. This ensures prolonged sensor performance, particularly in clinical and diagnostic settings.

- **Signal Amplification Strategies [29]**

Nanotechnology-based biosensors utilize various techniques to amplify detection signals for greater sensitivity:

- Enzymatic Signal Enhancement: The incorporation of enzyme-based amplification mechanisms allows for increased signal output. Enzyme-linked probes catalyze reactions that produce detectable byproducts, strengthening the overall biosensor response.
- Nanoparticle Aggregation: Clustering nanoparticles on the sensor surface generates localized electromagnetic field enhancements, significantly boosting detection sensitivity in methods like surface-enhanced Raman scattering (SERS).
- Multiple Signal Pathways: Integrating diverse nanomaterials in a single biosensor enables the combination of different detection methods, such as electrochemical and optical techniques, ensuring cross-validation and greater signal reliability.
- Molecular Probe Integration: Functional probes that exhibit fluorescence or electrochemical responses upon binding to target molecules enhance signal intensity, making even trace-level contaminants or biomarkers detectable with high accuracy.

The integration of nanotechnology into biosensors has significantly enhanced their capabilities, offering improved sensitivity, versatility, and precision, while opening up new avenues for applications in disease detection, environmental monitoring, and beyond as given in Table 2.

Table 2. Technological developments in Nanobiosensors [31]

Sr. No.	Characteristic	Advantages
1	Rapid Detection	Nanobiosensors provide fast results, enabling immediate action in case of contamination or food safety risks.
2	High Sensitivity	They can detect even trace amounts of pathogens, allergens, toxins, and chemical contaminants, ensuring better food safety monitoring.
3	Real-Time Monitoring	These sensors enable continuous tracking of food safety throughout the supply chain, allowing timely interventions when necessary.

4	Adaptability	Nanobiosensors can be customized to detect a wide range of contaminants, making them suitable for diverse food safety applications.
5	Proven Effectiveness	Many successful applications have demonstrated the ability of nanobiosensors to accurately detect food adulterants and hazards.
6	Improved Safety Measures	Advances in nanotechnology have addressed previous concerns regarding nanoparticle migration and toxicity, making modern nanobiosensors more reliable.
7	Future Potential	Ongoing innovations, including AI integration and advanced nanomaterials, continue to enhance the effectiveness of nanobiosensors in food safety.

However, continued research and development are crucial to overcoming existing challenges and unlocking the full potential of nanobiosensors for widespread use. There are concerns about the long-term effects of nanoparticles if they leach into food, posing possible health risks to consumers. If not properly designed, nanoparticles may detach from sensors and contaminate food products, leading to unintended exposure. Without proper knowledge of their application and risks, nanobiosensors could be misused or relied upon incorrectly, compromising food safety. The adoption of nanobiosensors faces regulatory hurdles due to the lack of standardised guidelines governing their safe use in food monitoring. The development and implementation of nanobiosensor technology can be expensive, making it difficult for smaller food producers to adopt them.

CONCLUSION

The present review has emphasized the promising function of nanomaterials and their potential in food analysis. Guaranteeing the safety and quality of processed and raw agricultural food products is a considerable undertaking. The application of traditional detection methods in the food industry has raised concerns over their safety and cost-effectiveness. Nanosensor technology in the food business can enhance food quality and safety. Recent technical breakthroughs have rendered nanosensors more accessible in the food processing sector. The principal role of these nanosensors is to maintain food freshness and detect adulterants. Nanomaterial-based sensors facilitate the binding or response of biological components with target species, ultimately converting these interactions into detectable signals, thus allowing for the swift identification of food pollutants and ensuring food safety for timely preventive measures. Furthermore, they offer the benefits of speedy, sensitive, and user-friendly detection, facilitating mobility for field applications. Nonetheless, various challenges such as interference in real-sample analysis, repeatability, and the toxicity of nanomaterials persist and require resolution. Notwithstanding the benefits of nanomaterials such as quantum dots, carbon nanotubes, metal oxide/metal nanoparticles, nanowires, and nanorods in biosensors, their practicality regarding availability, synthesis, toxicity, cost, and sustainability requires assessment in the development of nanosensors for potential applications in food analysis. Concurrently, the urgent challenges can be efficiently addressed by establishing scientific proficiency in collaboration with industrial alliances, and by facilitating funding opportunities for researchers. Moreover, the integration of traditional methods with contemporary nanosensor technology in food processing can offer further solutions to these issues.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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