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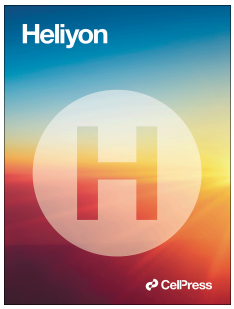

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PII: S2405-8440(24)17212-X

DOI: https://doi.org/10.1016/j.heliyon.2024.e41181

Reference: HLY 41181

To appear in: *HELIYON*

Received Date: 15 August 2024

Revised Date: 6 December 2024

Accepted Date: 11 December 2024

Please cite this article as: F.H. Awlqadr, A.B. Altemimi, S.A. Qadir, T.A. Hama Salih, Z.T. Alkanan, Q.H. AlKaisy, O.A. Mohammed, M.A. Hesarinejad, Emerging Trends in Nano-Sensors: A New Frontier in Food Safety and Quality Assurance, *HELIYON*, https://doi.org/10.1016/j.heliyon.2024.e41181.

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Emerging Trends in Nano-Sensors: A New Frontier in Food Safety and Quality Assurance

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Abstract

The rapid evolution of nanotechnology has catalyzed significant advancements in the design and application of nano-sensors, particularly within the food industry, where ensuring safety and quality is of paramount concern. This review explores the multifaceted role of nano-sensors constructed from diverse nanomaterials in detecting foodborne pathogens and toxins, offering a comprehensive analysis of their operational principles, sensitivity, and specificity. Nano-sensors leverage unique physical and chemical properties at the nanoscale to enhance the detection of microbial contamination, actively contributing to food safety protocols. With applications ranging from real-time monitoring of pathogenic bacteria, such as Escherichia coli and Salmonella, to assessing environmental factors affecting food quality, these innovative devices demonstrate unparalleled advantages over conventional detection methods. Recent research illustrates the integration of nano-sensors with biosensing techniques, enabling multiplex analysis and rapid detection. Furthermore, the review addresses current challenges in the commercialization and regulatory landscape of nano-sensor technology, emphasizing the need for ongoing research to optimize their performance and facilitate widespread adoption in food safety systems. Overall, the incorporation of nano-sensors represents a transformative approach to safeguarding public health by proactively managing food safety risks and enhancing the efficiency of food quality assurance processes.

Keywords: Bacteria; Biosensors; Foodborne; Nanotechnology; Nano-sensor; Pathogenic.

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1. INTRODUCTION

The field of nanodevices includes the study of their manipulation, development, application, and analysis techniques, as well as their operating modes. Nanotechnology is used extensively in producing nanocomposites and nano-sensors [1]. The nanomaterials used have diverse chemical, physical, and surface properties, but are limited in size to 100 nm. In the food sector, nanotechnology is applied for the development of nano sensors and nanoscale food products. Nanomaterials help improve the shelf life of food products by removing gas and moisture. Nano sensors are used for assessing the safety and quality of food during preparation and packaging. Nanotechnology has the potential to address concerns related to food safety, food processes, and food packaging [2]. Nanotechnology in food packaging is particularly interesting as it enhances the quality and safety of food products. Nanotechnology offers several advantages to the food packaging industry, including the ability to detect microbial contamination. Nano sensors have become a valuable tool in the food industry [3, 4].

Nano sensors convert physical or chemical quantities into easily detectable and analyzable signals. They are used to detect pesticides, food spoilage, toxins, foodborne pathogens, and undesirable tastes or smells. They are also used to monitor time, temperature, and oxygen levels [5]. Additionally, nano sensors play a crucial role in detecting foodborne pathogenic bacteria. The incidence of foodborne illnesses caused by contaminated products is increasing globally. Ingesting food tainted with bacteria, viruses, and parasites has been linked to approximately 250 separate illnesses [6]. Managing these interconnected illnesses places a significant burden on healthcare and socio-economic stability. According to the European Food Safety Authority (EFSA), the number of foodborne outbreaks, cases, hospitalizations, and deaths increased in 2022 compared to the previous year, with the main causes being *L. monocytogenes* and *Salmonella* [7]. Although most bacterial strains are benign, a subset of them possess pathogenic properties. Foodborne pathogens, such as (*Campylobacter jejuni, Escherichia coli* type O157H7, *salmonella subspecies*, *Clostridium perfringens*, *Vibrio species*, *Shigella species*, *Listeria monocytogenes* , and *Clostridium botulinum)*, are the primary causes of disease outbreaks [8, 9].

Regular examination for microbial contamination is essential to guarantee the quality and safety of food. Nanomaterials have been recently incorporated into biosensing systems to enable multiplex analysis of foodborne bacteria. This integration offers improved sensitivity and reduced

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detection time. Nanomaterials are typically combined with biomolecules such as enzyme, antibody, and nucleic acid in sensor applications to achieve the desired specificity. Nano sensors for foodborne pathogens and toxins have been created by utilizing the optical and electronic characteristics of nanomaterials [10].

The target or food compound binds to organic molecules, resulting in the formation of detectable outputs through biological signals. These signals are identified by a transformer, which can detect signals such as (electro-chemical, optical, electric, calorimetric, acoustic, and mechanical). The sensor's design depends on the reaction between a biological element and substratum. The development of nano sensors involves the utilization of confinement and fabrication techniques to integrate nanomaterials and nanoparticles with transducers. The nanotechnology recent researches are focusing on the development of nano sensors, which possess significant potential because of their high-rise sensitivity, small size, quick response, and streamlined research techniques. Additionally, biosensors offer the ability to perform bioanalytical methods [11].

The review focuses on recent advancements and concerns related to nano sensors based on nanomaterials. These sensors have shown significant potential in detecting foodborne pathogens with exceptional sensitivity and specificity, while also offering advantages such as reduced reagent volume and shorter detection times, thus improving food safety.

2. NANO-SENSOR

2.1 Definition

Nano-sensors are constructed using materials at the nanoscale level (10^{-9} m) or have the ability to detect material or food components at the nano range level (10^{-9}m) [12]. Nano-biosensors are analytical sensor devices capable of detecting biological agents at the nano range. These sensors are constructed using materials that are at least one nanometer in size to detect biological agents [13]. The quantification and detection of target pathogens have been achieved by utilizing the biochemical reactions triggered by the binding of bio-receptors such as enzymes, antibodies, and nucleic acid. When the bioreceptor forms a strong connection with the target pathogen, it induces alterations in optical, thermal, or electrical characteristics, which can be detected using biosensors [14]. Nano sensors can be categorized into three main types based on the signal they generate while interacting between the bio receptor and the pathogen, as well as their construction. The most

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exemplary types of nanoparticle-based nano sensors are those that utilize magnetic nanoparticles (MNPs), nanoparticles made of metals such as gold (Au) or silver (Ag), and silica nanoparticles [15]. These nano sensors utilize a sensor fabrication material at the nanoscale level. Optical nano sensors generate optical signals, while electrochemical nano sensors produce electrical signals when there is binding between bio receptors and target analytes.

2.2. Nano-sensors categorization

Nano-sensors can be classified into three categories according to the type of signal they detect: physical nano-sensors, chemical nano-sensors, and biological nano-sensors. Furthermore, they can be further categorised based on their applications, framework, and source of energy. Figure 1 provides a description for certain nano-sensors, enumerating different types. Mechanical nano-sensors have the capability to precisely quantify stress, strain, and pressure, making them crucial elements in the functioning of microelectronic nanodevices. They frequently exhibit superior performance in terms of accuracy and dependability when compared to optical and electromagnetic counterparts. The fluidic shear stress carbon nanotube and nanomechanical cantilever sensors are the most sophisticated options available. For instance, a specific research conducted an engineering nano-sensor to quantify the oscillation and elasticity of nanospheres [16].

Chemical nano-sensors, including gas nano-sensors, are utilized in diverse fields such as medical, ecological surveillance, food quality and safety, and national security. Pearton et al. have discovered chemical sensors that possess the capacity to analyze a broad range of environmental and biological gases and liquids, demonstrating their versatility. These sensors demonstrate exceptional sensitivity and have the ability to discern and detect specific analytes with precision [17]. Gas sensors, for example, measure gas volume by undergoing oxidation or reduction reactions and quantifying the resulting change in electric current. A sensor composed of zinc oxide (ZnO) nanobelts has the ability to accurately detect ammonia (NH_3) [18].

Optical nano-sensors are utilized to observe and analyze the chemical makeup of the surroundings. These sensors facilitate meticulous chemical analysis by quantifying the optical characteristics of materials. Optical nano-sensors find applications in the domains of biotechnology, environmental science, and chemistry. They utilize photovoltaics and a single binding component. Luminescence is frequently involved in their operation, as it arises from the absorption of light by a fluorophore

followed by its subsequent emission [19]. The initial optical nano-sensor, which utilized fluorescein, was employed specifically for pH measurement. Vo-Dinh et al. have conducted research on the innovative application of fiber optic sensors for highly effective in vivo monitoring of cells. The reaction between a target and receptor gives rise to physiochemical phenomena, which are subsequently converted into a measurable electrical signal [20].

In the study examined the reaction between AuNPs and H_2S gas molecule. [21]. They observed that the formation of a sulfide shell promotes the transfer of charge between two nanoparticles, a phenomenon referred to as hopping. This is depicted in Figure 2. In addition, magnetic nano-sensors, which comprise of magnetic nanoparticles such as iron oxide, engage with particular substances to create long-lasting nano assemblies. This interaction can lead to a modification of the spin–spin relaxation time, a phenomenon that can be observed through Magnetic resonance imaging (MRI) and is frequently working in the detection of biomolecules[22].

Biological nano-sensors, a type of chemical nano-sensor, have the ability to simultaneously detect entities such as cancer, specific DNA, and different diseases. Field-effect transistors are highly efficient biosensors as a result of their ability to be produced in large quantities, their inexpensive, and their exceptional sensitivity in detecting substances. The combination of biosensor and microfluidic technologies on chips has demonstrated durability and efficiency within the body, leading to their widespread use in diagnosis and signaling a novel approach to biosensing that merges chemical and biological elements [23]. Furthermore, optical nano-sensors commonly employ noble metal and metal oxide nanoparticles for material categorization. In addition to nanoparticles, semiconductor quantum dots (QDs) are utilized for the creation of sophisticated nano-sensors. In certain nano-sensors, nanoprobes containing dye are employed to suppress fluorescence when an analyte is present. A specific instance is a biomarker composed of Au nanoparticles that can identify protease diseases in humans [24]. Figure 3 illustrates the process of detecting these proteases. Carbon nanotubes (CNTs) possess high strength and lack reactivity, making them well-suited for chemical doping and functionalization. This enhances their capacity to selectively identify specific target analytes. A significant number of carbon nanotube (CNT) nano-sensors are designed as field-effect transistors. Chemo-resistive sensors composed of nanofibers and nanowires are highly skilled at diagnosing diseases [25]. They have the ability to detect volatile organic compounds present in breath released, as shown in Figure 4.

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Graphene nano-sensors are employed in biomedical and chemical sensing applications to identify particular gases by analyzing changes in the noise spectra of the graphene transistors. The utilization of high-conductivity three-dimensional graphene sheets has been observed in diverse industries, while graphene foams exhibit numerous promising applications [26]. Bulk nanostructured sensors offer certain advantages in certain cases. The nanoparticles' great range surface area enables them to coat biomaterials and immobilize molecules. Electrochemical nano-sensors derive advantages from the catalytic properties of nanoparticles, specifically platinum (Pt) nanoparticles combined with porous carbon, which exhibit exceptional effectiveness in gas diffusion electrodes [27]. Metal-organic frameworks (MOFs) are porous substances composed of cations of metallic elements and organic molecules known as "linkers". They are extensively utilized for gas sensing purposes due to their substantial surface area and hollow structure [28].

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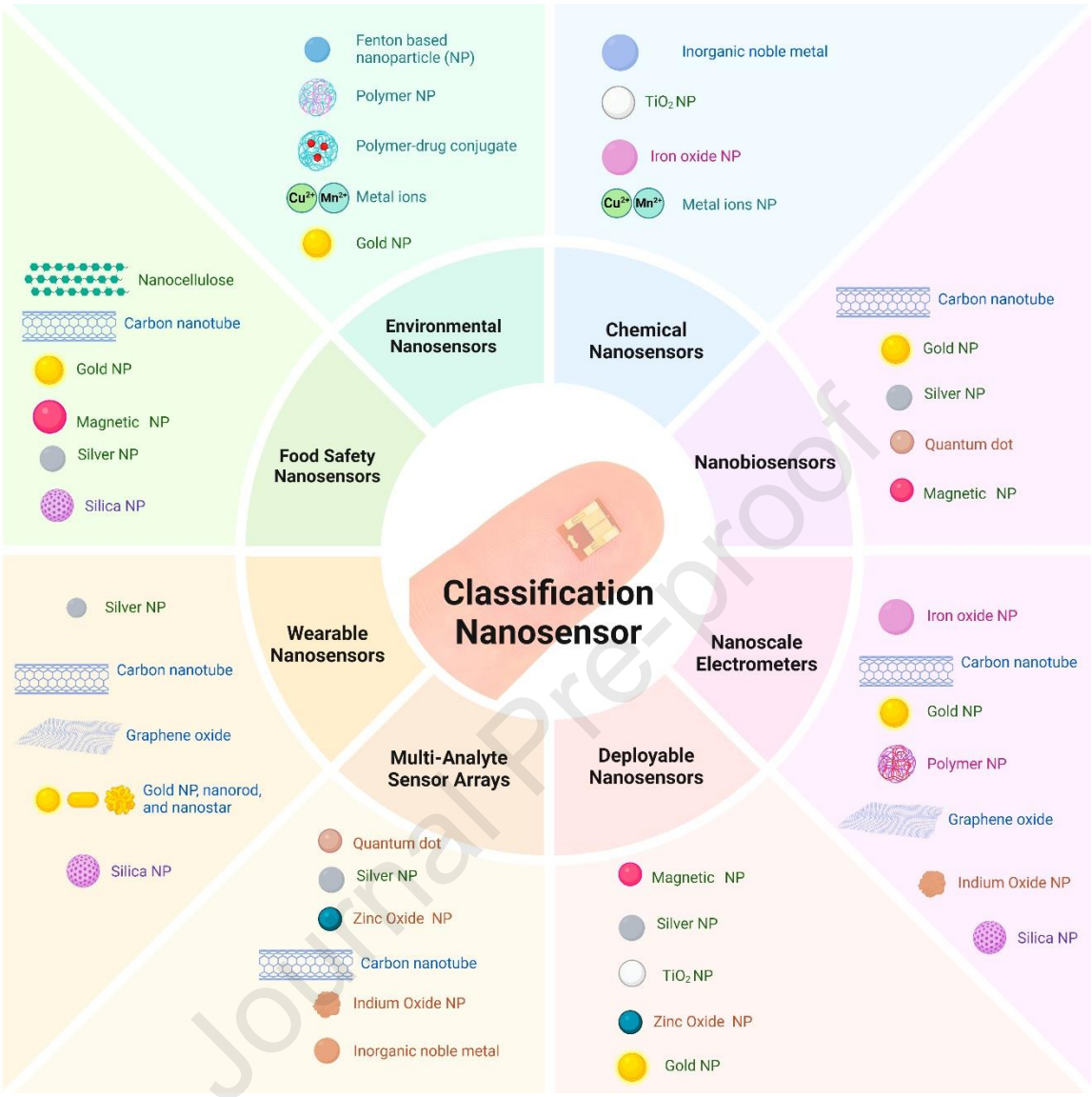
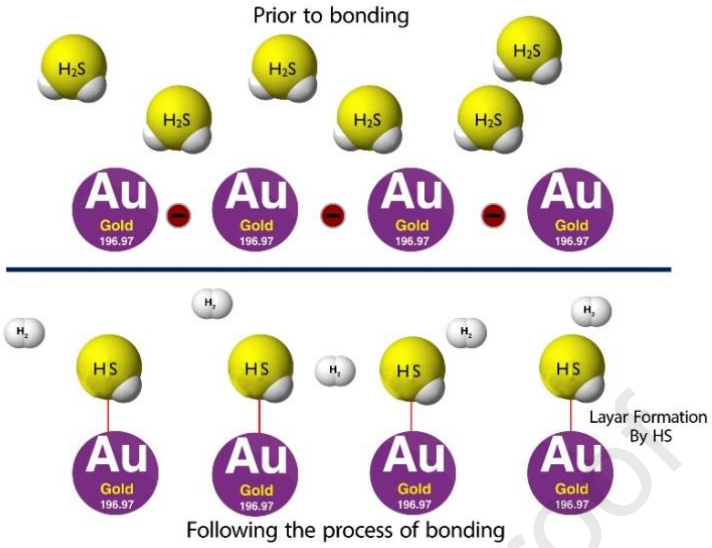


Figure 1 Functional Classification of Nanosensors



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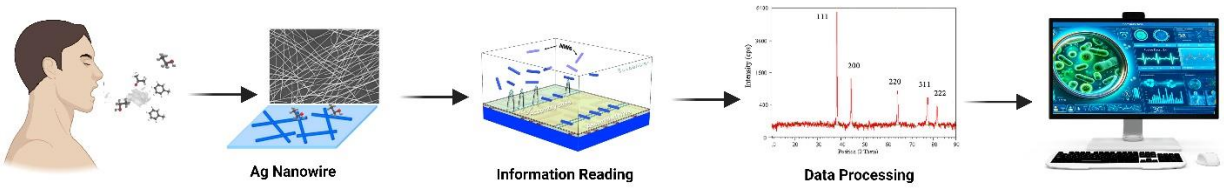
172 **Figure 2** Electron migration prior to bonding and following the process of bonding

173

174 **Figure 3** Casein-coated gold nanoparticles. Proteases degrade the protective casein barrier,
175 thereby exposing the surface of the gold nanoparticles.

176



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178 **Figure 4** Detect VOC present in breath released

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2.3. Current limitations of nano-sensors

The limitations of nano-sensors present significant challenges for their widespread adoption across industries, including food safety, healthcare, and environmental monitoring. High production and operational costs stand out among the major hurdles. Advanced materials such as noble metals, essential for high-performance sensors, require expensive fabrication methods like chemical vapor deposition and lithography, limiting scalability [29]. Furthermore, nano-sensors are highly susceptible to environmental conditions despite their promising sensitivity and selectivity. Temperature, humidity, or light exposure changes can degrade performance, impacting real-world applications [30].Another challenge involves scalability and standardization. As nano-sensors' production transitions from laboratory prototypes to industrial-scale manufacturing, ensuring consistency and reproducibility across batches remains difficult. Variability in material properties such as size and surface chemistry hampers standardization efforts, limiting broader commercialization [31]. The regulatory landscape further complicates the adoption of nano-sensors. As nanomaterials introduce uncertainties regarding long-term environmental and health impacts, regulatory bodies are cautious in approving these technologies, especially for food safety applications. This creates uncertainty for companies, slowing down investments and market adoption [32]. However, their efficient speed has led some companies to produce and put it at the service of society. Table 1 shows the types, manufacturers and characteristics. Fabrication methods also represent a bottleneck. Techniques like lithography and chemical etching are complex, time-consuming, and prone to defects. Achieving precision in sensor production at scale is difficult, requiring more efficient, cost-effective manufacturing methods [33]. Moreover, the lack of high-resolution sensor images and the need for innovative packaging solutions for lab-on-chip technologies underscore further challenges in design and integration [34].

Table 1 Types, Manufacturers, and Characteristics of Nano-Sensors Used in Food Safety

Type of Nano-Sensor	Manufacturer	Characteristics	Use Case
Optical Nano-Sensor	Tellspec Inc.	Provides rapid, non-invasive detection of food contaminants and allergens	Detection of allergens in packaged foods

Electrochemical Nano-Sensor	Biosensia Ltd.	Measures chemical and biological analytes with high sensitivity and specificity	Monitoring freshness and spoilage in perishable goods
Magnetic Nano Sensor	MagID	Utilizes magnetic nanoparticles to detect pathogens with minimal sample preparation	Identification of bacterial contamination in food samples
Carbon Nanotube Sensor	Nanomix Inc.	Highly sensitive and selective detection for gases and volatile organic compounds	Detection of spoilage gases in food packaging
Plasmonic Nano-Sensor	Plasmore Srl	Employs plasmonic resonance for enhanced sensitivity to chemical and biological substances	Detection of toxins and chemical residues
Lab-on-a-Chip Nano-Sensor	Microfluidic ChipShop	Integrates multiple sensors on a microchip for real-time analysis of food quality	Comprehensive testing for foodborne pathogens at point-of-care
Biosensing Nano-Coatings	NanoBioMatters	Enhances packaging surfaces to detect spoilage or harmful bacteria	Real-time spoilage detection in food packaging
Quantum Dot Nano-Sensor	QD Vision	Emits light signals for fast and highly accurate detection of contaminants	Detection of heavy metals in food and beverages
Nanopore Sensor	Oxford Nanopore	Performs single-molecule analysis of nucleic acids and proteins for microbial detection	Detection of pathogens through DNA sequencing

205

206 ***2.4. Manufacturing of Nano-sensors***

207 Nano-sensors are manufactured using various techniques, with the most prevalent methods being
208 top-down, bottom-up utilization, and self-assembled nano-structure. The fundamental distinction
209 between the top-down and bottom-up methods is illustrated in Figure 5 and depicts various
210 techniques employed in nano-sensor production.

211

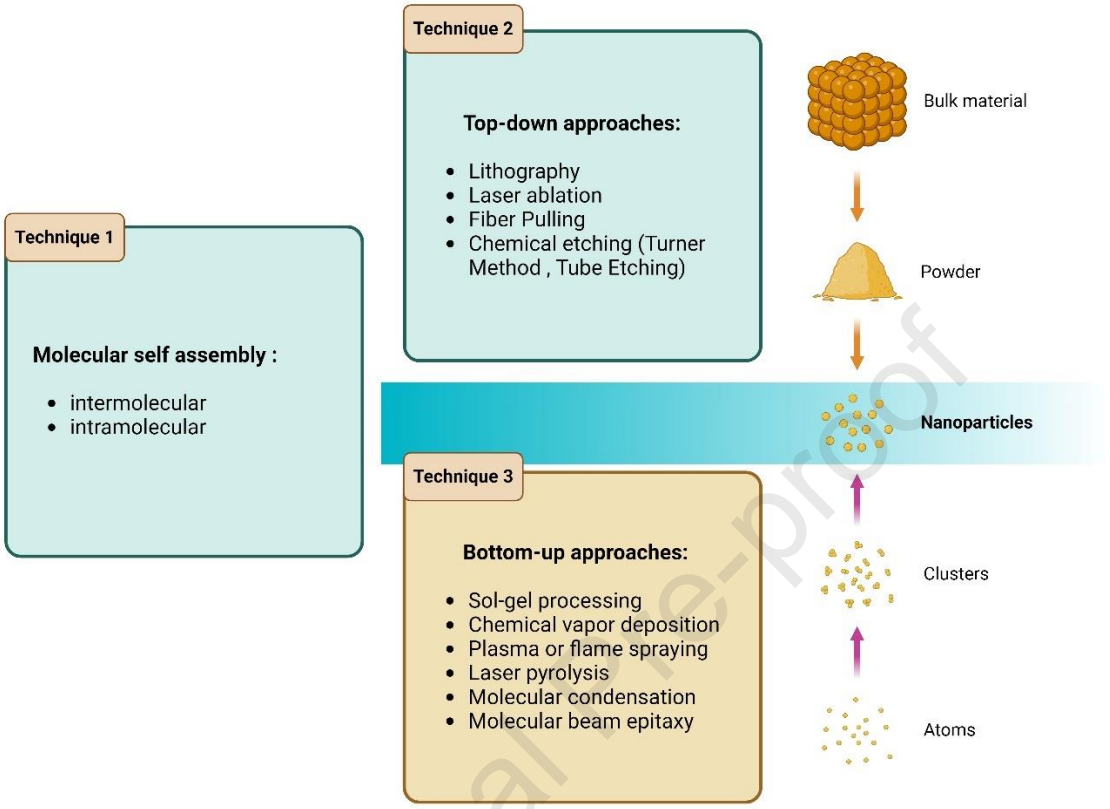

Figure 5 The key differentiation between top-down and bottom-up methodologies

2.4.1 Methods Top-down

The top-down method, common in microelectronics, involves creating nanoscale shapes by subtracting material from the original deposited material. This method can produce items a few tens of nanometers in size and is tightly controlled to ensure precise size and shape. The top-down nano-sensor production methods are described below [35]:

2.4.1.1 Lithography

Nano-sensors made via lithography can identify pollutants and quality markers at the molecular level, improving food safety. Nanoimprint lithography (NIL) Figure 6 (A-D) shows some types of fabrications Nanoimprint, soft lithography, and electron-beam lithography (EBL) all have

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advantages for generating sensitive and specialised sensors [35]. NIL combines pressure and heat to transfer nanoscale features onto a polymer layer using a mould, allowing for high-fidelity, low-cost structures. Paper-based plasmonic sensors that detect biogenic amines, food deterioration markers, use reversal nanoimprint lithography, a form of NIL. Nanoparticles are embedded onto flexible substrates. Because they are cheap, flexible, and eco-friendly, these sensors are perfect for disposable food monitoring systems [36]. Moreover, Soft-lithography Popular soft lithography creates reusable sensors that send real-time data, including NH_3 concentrations in food packaging, to cellphones for easy monitoring. The technology is suitable for rapid food safety detection due to its low cost and adaptability for flexible substrates [37]. In addition, Electron-beam lithography produces nanoscale designs with sub-10 nm feature sizes with unmatched precision EBL is essential for sensors that detect extremely low microbial or chemical contamination, but it is more expensive and time-consuming than NIL or soft lithography. Food safety biosensors and nanosensors with great specificity and stability are made with EBL, but its cost limits large-scale manufacture [38]. Finally, Food Safety Nano-Sensor Applications Lithographic technologies have enabled the development of various nano-sensors for food safety monitoring. NIL-based nanopillar arrays improve cell adhesion, allowing food samples to be tested for bacterial infections, reducing foodborne diseases [39]. NIL and EBL can also make sensitive polymer-based nanostructures that can detect chemical residues and pollutants in food, providing cost-effective and scalable food monitoring and safety solutions [40].

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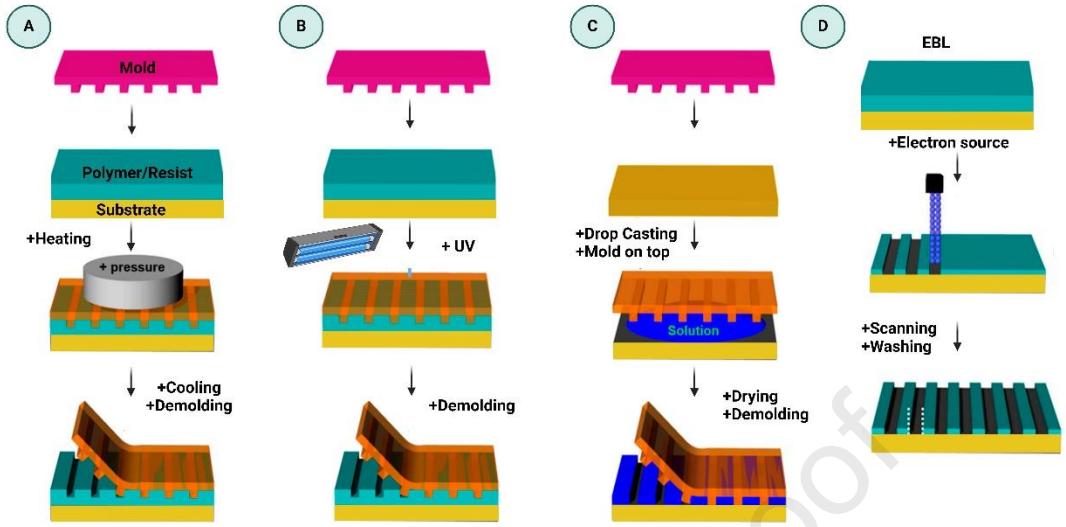


Figure 6 (A–C) Nanoimprint lithography (NIL) examples: thermal (TNIL), ultraviolet (UVNIL), and moulding in capillaries (MCNIL) (D) Electron-beam lithography (EBL).

2.4.1.2 Pulling fiber

The pulling fiber method, commonly utilized in the field of technology in fiber optics, involves exerting a tensile force on a fiber to achieve nanoscale dimensions along its main axis. To facilitate elongation, the fiber is heated [35]. Figure 7 graphically illustrates the thermal pulling process. Due to their great sensitivity and particular surface contacts, pulling fibre nano-sensors may detect pollutants, pathogens, and chemical residues at low concentrations. In particular, fibre optic-based sensors with nanofiber tapers may detect volatile organic compounds (VOCs), which indicate food spoilage. These nanofibers are ideal for real-time food quality monitoring due to their great transmission efficiency and sensitivity. Combining these fibres with functional coatings like metal oxides or carbon nanotubes can increase selectivity for certain analytes like ammonia in packaged goods, making them more useful for food freshness monitoring and spoiling prevention [41].

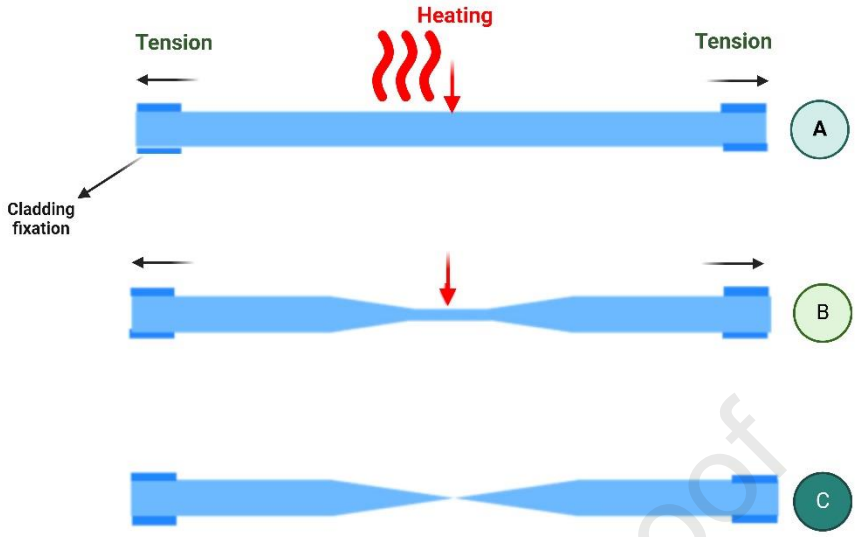
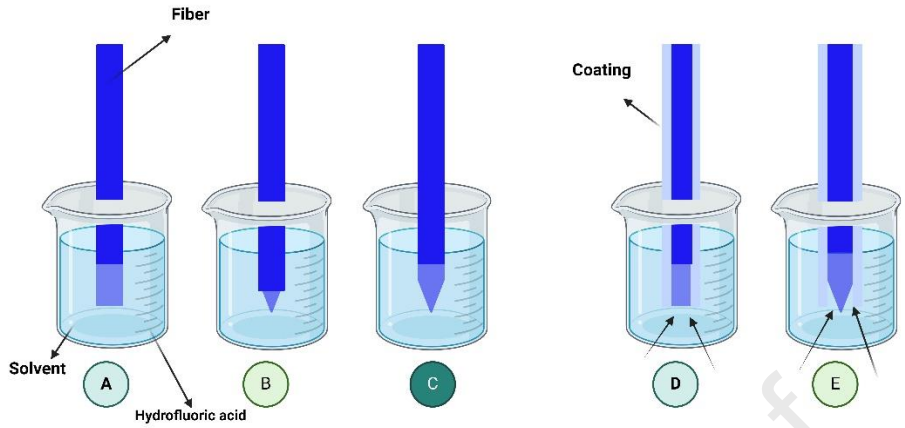


Figure 7 Schematic representation of the thermal pulling process (A). An input fibre component. Biconical taper featuring a central waist (B). Two optical fibre tips(C).

2.4.1.3 Chemical Etching

The main chemical etching methods for nano-sensor fabrication include the Turner method and Tube etching. Tube etching utilizes hydrofluoric acid to corrode the optical fiber that is inserted within. This technique involves submerging the silica fiber, coated with an outer protective material, in hydrofluoric acid, which specifically corrodes the end of the fiber while leaving the cladding material unaffected. After the etching process, a conical shape with a smooth and gradual taper is created [42]. The Turner method involves accurately placing the fiber's tip at the boundary between hydrofluoric acid and the organic overlayer, resulting in the production of a significant taper angle and tip diameter. However, the etching process using the Turner method is highly susceptible to environmental influences [43]. Figure 8 (A-E) displays the preparation methods for etching. These sensors can identify trace levels of harmful compounds or pathogens, enabling rapid, on-site food quality assessments. The integration of these sensors into food packaging can offer continuous monitoring of freshness, extending shelf life and enhancing consumer safety.



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278 **Figure 8** Diagram of Turner etching. (A)Start of etching. (B) Etching is still in progress.
279 (C)Etching ending. Then the tube etching technique. (D)Start of the process. (E)Intermediate
280 process step, such as the creation of the tip.

281 ***2.4.2 Bottom-Up Methods***

282 The bottom-up process involves adding and rearranging atoms and molecules to shape the nano-
283 sensor. Atomic force microscopy is used to rearrange atoms and molecules, assembling smaller
284 components to give the nano-sensor its desired shape. There are two common bottom-up nano-
285 sensor manufacturing processes: gas-phase and liquid-phase synthesis. The possible techniques
286 for this method include wet synthesis or the decomposition of organic metals, chemical vapor
287 deposition (CVD), the sol-gel process (SGP), laser pyrolysis, plasma arcing (P.A), molecular beam
288 epitaxy (MBE), and self-assembly (MSA).

289 ***2.4.2.1* Plasma-arcing *(P.A)***

290 P.A is a prominent nanoparticle and nano-sensor formation process. Positive ions are deposited as
291 nanoparticles, which requires highly ionized gas atoms with high energy, causing electrons to leave
292 the material's valence shell and resulting in atoms carrying a positive charge. Electron detachment
293 from atoms is feasible due to a substantial potential difference. It utilizes an inert gas for heating,
294 and the formation of an arc between the electrodes is triggered by an electron avalanche. The ions
295 produced in these reactions possess significant amounts of kinetic energy, and the deposition of
296 nanoparticles at the cathode is facilitated by the voltage-driven movement of ions [43]. The plasma-
297 arcing method has shown promising results for creating nano-sensors that detect contaminants like

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pesticides, spoilage-related compounds, and pathogens. For instance, metal oxide nanoparticles synthesized via plasma deposition have been used in sensors for detecting chemical residues, enhancing food quality control processes[44]. Additionally, plasma-assisted techniques are valued for producing high-purity nanoparticles with controlled size distribution, essential for consistent sensor performance in food safety applications[45].

2.4.2.2 Chemical Vapor Deposition (CVD)

CVD uses substrates and volatile precursors. Precursors react with the substrate, breaking it down at high temperatures and depositing crystals. This method is frequently used in the semiconductor industry [46]. CVD deposits thin films of diverse materials on substrates by chemically reacting gaseous precursors. In a heated reaction chamber, these precursors react and disintegrate on a substrate to generate a solid layer during CVD. At high temperatures (750 °C), CVD may synthesise multiwalled carbon nanotubes (MWCNTs) from carbon-based precursors like ethanol and an inert carrier gas like argon. Uniform and controlled deposition is necessary for nano-sensor property repeatability [47]. In addition, Plasma enhancement (PECVD) lowers reaction temperature and allows the creation of more sensitive nanostructures with less energy. This version allows deposition at lower temperatures while preserving high-quality material growth, increasing adaptability and industrial scalability [48]. Moreover, CVD-fabricated nano-sensors are highly effective for food safety applications due to their sensitivity and specific surface interactions. For example, MWCNT-based thin films prepared via CVD have been utilized for CO2 detection, which can signal spoilage in food storage. The precise control over the growth conditions ensures the high surface area and uniformity required for detecting low concentrations of gases and volatile organic compounds (VOCs), key indicators of food quality[49].

2.4.2.3 Molecular Beam Epitaxy (MBE)

MBE is a physical evaporation method that does not include any chemical reactions. The procedure is conducted inside a low-temperature setting and involves vacuum evaporation, where atomic beams are directed onto a heated substrate under high vacuum conditions [50]. Molecular Beam Epitaxy (MBE) is a physical vapor deposition technique that allows for the precise formation of thin films and nanostructures at an atomic level without chemical reactions. The process is performed in an ultra-high vacuum (UHV) environment, typically in the range of 10^{-8} to 10^{-11}torr,

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to prevent contamination and ensure high purity. During MBE, atomic beams of source materials (such as metals or semiconductors) are evaporated and directed onto a heated substrate, where they condense and form an epitaxial layer. The temperature of the substrate is carefully controlled to facilitate crystal growth, resulting in highly uniform and well-defined nanostructures. This method allows for layer-by-layer construction with precise control over thickness and composition. In addition, MBE is ideal for nano-sensors that require clean, regulated materials. The method's ability to manufacture thin films with few faults makes it perfect for constructing sensors that detect low levels of pesticides or food deterioration indications. The sensitive photodetectors and gas sensors made from MBE-grown semiconductor films may identify substances produced by spoilt or tainted food [51].

2.4.2.4 Sol-Gel Process (SGP)

The sol-gel process involves the amalgamation of sol and gel. A sol consists of solid colloidal particles evenly scattered throughout a liquid, while a gel is a solid-like material formed by linked nanostructures in a liquid phase. This technique involves the blending of solid nanoparticles in a liquid media, resulting in the formation of a gel with a pore diameter in the nanoscale range. The characteristics of sol-gels are influenced by factors such as temperature, catalysts, pH, duration, and solvent type [52]. The procedure involves a series of operations including mixing, sol formation, aging, gelation, drying, dehydration, chemical stabilization, and densification [53].

2.4.3 Molecular Self-Assembly (MSA)

Molecular self-assembly (MSA) is a highly efficient method for producing nano-sensors. Molecular self-assembly is the process by which natural materials, such as DNA, are produced. This process involves the assembly of atoms and molecules to create a precisely defined nanostructure that is held together by noncovalent bonds. The resulting device has the capability to create nanostructures with dimensions ranging from 1 to 100 nanometers [54].

2.5. Inorganic Nano-sensors

2.5.1 Carbon based-nanomaterials

Carbon-based nanomaterials offer a means to expose a functional surface to analytes, making them highly effective for detecting foreign substances. These materials exhibit high stability, excellent

conductivity, and are easily amenable to surface functionalization. Graphene, carbon nanotubes (CNTs), and other materials are used in diverse electroanalytical applications. Figure 9 illustrates the various categories [55].

2.5.2 Nanomaterials composed of metal and noble metals

Metallic nanoparticles possess distinctive chemical and physical characteristics that render them suitable for diverse applications. Metals such as gold, platinum, silver, cobalt, copper, and rare earth metals exhibit significant potential due to their excellent selectivity and stability [56]. These nanomaterials, which are composed of metals, possess a significant surface/volume ratio, rendering them valuable for utilization in diverse domains such as medicine, catalysis, electrodes, fuel cells, and mechanical actuators. Here, we present an elaboration on certain nanomaterials that are based on metal [57].

2.6. Nano-sensors produced from biopolymers

2.6.1 Polymer Nanomaterials

Polymeric nanoparticles are commonly employed for the detection of hazardous and chemical pollutants in both gaseous and liquid forms, as well as for health-related applications. Nanocomposites composed of carbon nanotubes (CNT), graphene, metal nanoparticles, or a mixture of these materials exhibit improved electrochemical detection characteristics. The properties of the nanocomposites or nano-sensors are greatly influenced by the combination of filler material and matrix in these composites, impacting selectivity, sensitivity, and biocompatibility. Polymeric nanoparticles are widely utilized in various applications within the healthcare sector, such as medicinal coatings, prostheses, implants, and medical equipment [58].

2.6.2 Bionanomaterials

Biomolecules are structured into nanoparticles in the field of bionanomaterials. The incorporation of nanostructures into biomolecules enhances their analytical capabilities, making them suitable for application as nano-sensors. For example, in one study, multiwalled carbon nanotubes (MWNTs) were synthesized to detect capsaicin using electrochemical methods by employing a nano-bio-composite of L-phenylalanine ammonia-lyase enzyme [59]. Furthermore, in another study,

nano-sensors for the identification of Escherichia coli were fabricated through the creation of a self-assembled monolayer (SAM) [60].

2.6.3 Nanostructures Made of DNA

DNA, a nucleic acid molecule serving as a repository for genetic information, consists of a phosphate group, a sugar molecule, and a nucleobase containing nitrogen. Its double-stranded structure makes it advantageous for utilization in self-assembly procedures in nano-sensors [61]. DNA possesses significant attributes, functioning as an inflexible polymer when its size is below 50nm. Its molecules can be separated through a self-assembly mechanism, enabling manufacturing at the nanoscale [62]. Genetic information is encoded through chemical coding mechanisms, and intermolecular interactions between molecules can be readily programmed [63]. These features enable the utilization of DNA for constructing nanostructures in nanomaterials.

2.6.4 Dye-doped Nanoparticles

The encapsulation of dyes into nanoparticles is performed to produce nanomaterials that are sensitive to temperature. The precipitation method is used to synthesize temperature sensors at the nano-scale. A homogenous solution is created through the dissolution of a host substance and a probe in an organic solvent. An additional solvent, in which the host material and probe are insoluble, is introduced into the current solution. The probe is enclosed within a structure, and subsequently, the host material solidifies. This approach can be used with a wide range of temperature sensors [64].

2.6.5 Thermo-responsive Organic Gels

Certain organic gels have the ability to detect temperature within a living organism. Phase transition plays a crucial role in temperature detection. Thermo-responsive poly(N-isopropylacrylamide) undergoes a phase transition in an aqueous solution. Below a temperature of 305K, the polymer undergoes swelling. However, as the temperature increases, it undergoes a transformation, forming nanoparticles with a size of 100nm. The polymer has the capability to retain specific near-infrared (NIR) probes, enhancing its suitability for in vivo temperature sensing [65].

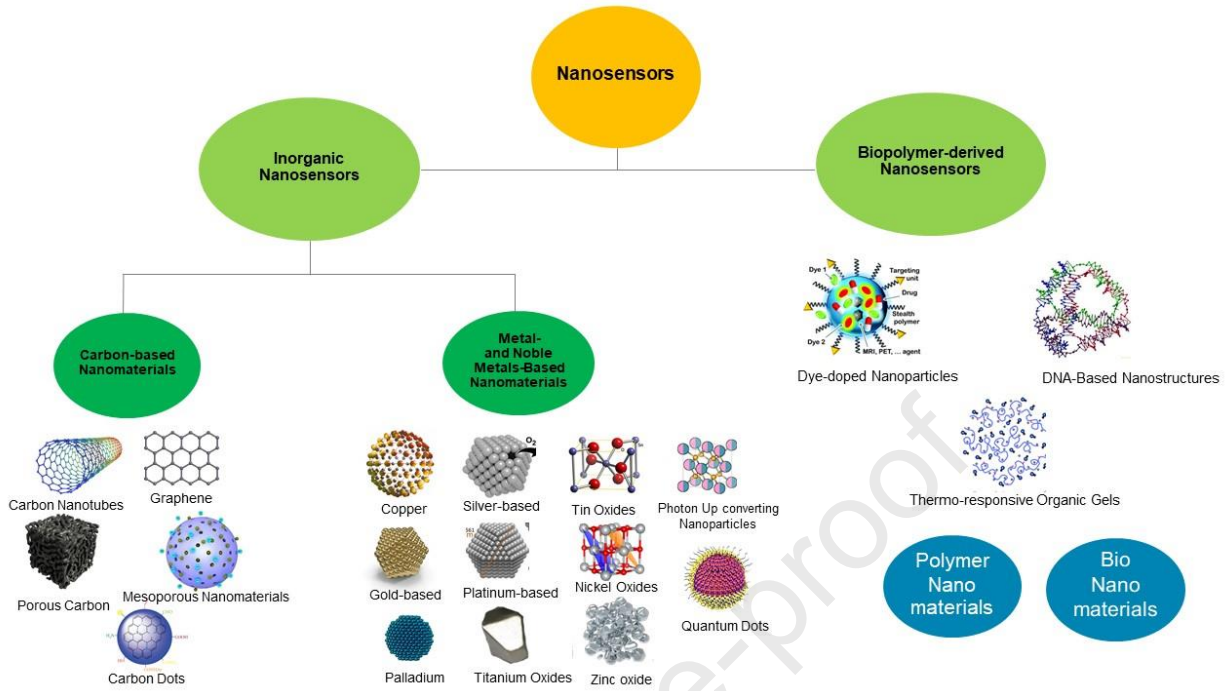

Figure 9 Nano-sensors can be fabricated from various types of nanomaterials.

2.7 Fabrication of Lab-on-Chip (LOC) Devices

Lab-on-chip (LOC) technology has become pivotal in advancing food safety and quality monitoring through its innovative fabrication methods and versatile applications. The fabrication of LOC devices typically involves techniques like soft lithography, photolithography, and 3D printing, which allow for the creation of microfluidic platforms capable of performing complex analyses on a compact scale. Soft lithography, for example, uses a polymer like polydimethylsiloxane (PDMS) cast on a master mold to create microchannels for fluid flow, making it an effective and cost-efficient method for LOC device production [66]. More recent advances include the use of 3D printing, particularly Fused Filament Fabrication (FFF), which supports rapid prototyping of customizable LOC devices, expanding their use in various food safety applications through cost-effective production and innovative design flexibility [67].LOC devices integrate essential functions such as sample preparation, detection, and analysis, enabling rapid, on-site testing that significantly reduces the time needed for traditional laboratory-based methods. For example, LOC systems have been shown to effectively detect pathogens like E. coli

and Listeria in food samples, combining processes such as cell capture, DNA lysis, and amplification on a single platform. This integrated approach can reduce detection time to mere hours compared to days required by conventional methods, enhancing the responsiveness of food safety protocols [68]. Additionally, LOC devices are increasingly used for detecting chemical residues and pesticides in food products. Hybrid paper-based LOC platforms, for instance, have been designed to screen for toxic substances like carbofuran in produce, demonstrating their practical application in routine safety checks [69].The ability to incorporate sensors capable of detecting pH changes and volatile compounds has made LOC systems essential for monitoring food quality. This capability is crucial for maintaining the freshness of perishable items during transport and storage, as these sensors provide real-time data that can alert supply chain managers to early signs of spoilage [70]. Overall, the portability, minimal sample requirement, and integration with digital devices for easy data analysis have made LOC technology an indispensable tool in modern food safety management, supporting a shift towards faster, more efficient, and decentralized testing approaches. Figure 10 shows fabrication method LOC.

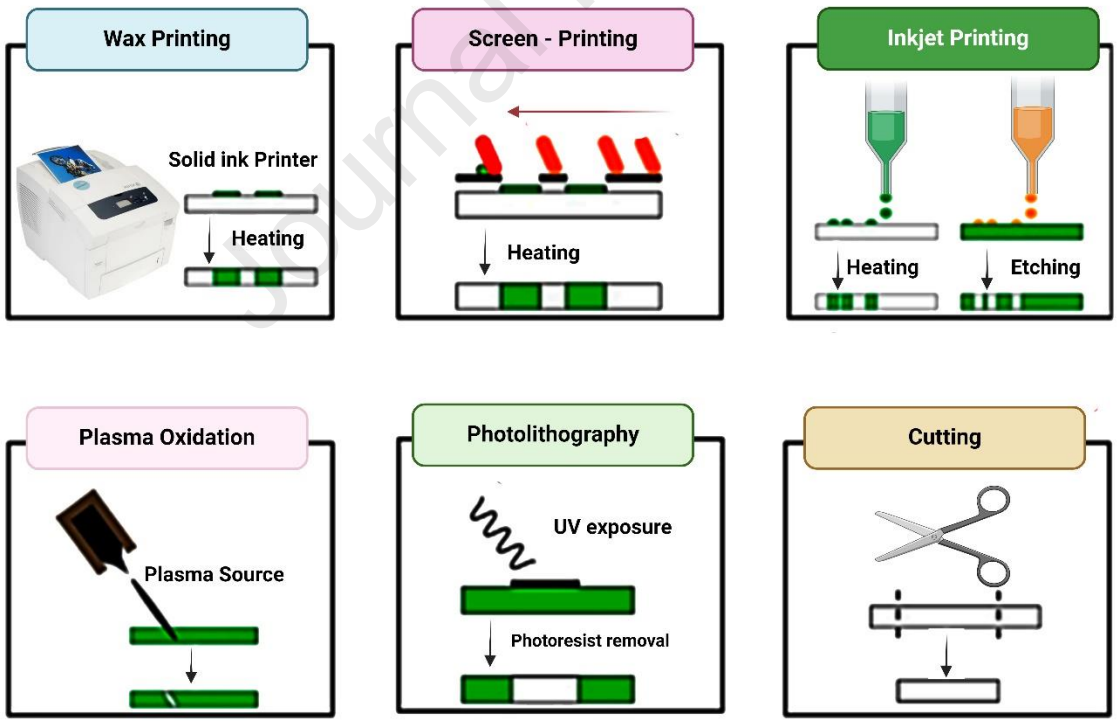

Figure 10 Methods of manufacturing for the construction of lab-on-chip devices

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2.8 Application Nano-sensors

The utilization of nano-sensors to identify harmful bacteria in the field of food safety and quality is rapidly advancing and has the potential to fundamentally transform methods for ensuring food and beverage safety. Nano-sensors, known for their exceptional sensitivity and specificity, are being employed to detect and identify bacterial pathogens in different food matrices, averting foodborne diseases and outbreaks. These advanced instruments can identify infections at extremely low levels, well in advance of them posing a threat to public health [71].

Nano-sensors employ several processes to detect pathogens, such as optical, electrochemical, and mass-sensitive methods. For instance, some nano-sensors use gold nanoparticles or quantum dots within a biosensor system to visually detect the existence of infections by means of color alterations. Others utilize carbon nanotubes or graphene-based materials to identify bacterial DNA or specific proteins, providing quick and precise detection capacities [72].

The incorporation of nanotechnology in pathogen detection is especially advantageous for the food industry, where it is crucial to guarantee the sterility and quality of products [72]. Nano-sensors have the capability to be employed in food production facilities, packaging, and even integrated into smart packaging to consistently monitor the existence of detrimental bacteria including *Salmonella*, *Listeria*, and *E. coli*. This not only aids in preserving the quality and prolonging the shelf life of food goods but also substantially diminishes the likelihood of foodborne illnesses [73].

2.8.1 Detection of Pathogens Bacteria in Foods

2.8.1.1 E coli (Escherichia coli)

Escherichia coli-O157H7 is the most significant strain among all *E. coli* strains due to its ability to produce toxins that can damage the intestines, leading to symptoms such as stomach ache, bloody diarrhea, and Haemolytic–uraemic syndrome (HUS). Even a small amount of 100 cells can cause infection [74]. Human transmission can occur through the consumption of raw or undercooked minced beef and unpasteurized milk. Foods identified as sources of *E. coli* outbreaks include raw hamburger, salami, contaminated apple cider, yogurt, and cheese made from unpasteurized milk.

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Contamination of meat, vegetables, water, and fruit with fecal matter also contributes to outbreaks [74, 75].

In the study developed a DNA sensor based on a quartz crystal microbalance (QCM) for mass enhancers to increase the frequency change using streptavidin-conjugated with MNPs. This sensor is used for the detect of *Escherichia coli-O157H7* by utilizing nanoparticles.[76]. A DNA probe, which has been chemically altered with thiol groups, was affixed to the QCM sensor. This probe specifically targets the eae-A gene of *Escherichia coli- O157H7*. Hybridization was initiated by subjecting the single-stranded DNA probe with the complementary target DNA. The process of amplification was carried out using asymmetric PCR, utilizing primers that were labeled with biotin. This is caused to a change in mass, as well as a simultaneous alteration in the frequency of the QCM, which was used to detect *Escherichia coli- O157H7*. The detection limit reached was 267 colony forming units (CFU/mL) within the linear working range of 267 - 267 × 10^4 CFU/mL [76]. A circulating-flow (PEB) piezo electric biosensor was created to detect *E.coli- O157H7* utilizing a Gold Nano Particles-conjugated thiolated probe as a mass intensifier and sequence verifier, following a similar technique[77]. A thiolated probe specific to the eae-A gene of *Escherichia coli*-O157H7, conjugated to piezoelectric biosensor (PEB), was used to detect a gene fragment of *Escherichia coli* amplified by PCR. The resulting change in mass was evaluated as a frequency shift of piezoelectric biosensor. The detection limit achieved was 120 CFU/mL within the linear working range of 100-1,000,000 CFU/mL[77]. A disposable immune-sensing strip was created for *Escherichia coli-O157H7* detection in milk. This strip utilizes a double antibody system for an indirect sandwich enzyme-linked immunoassay. To build the strip, 13-nm gold nanoparticles (GNPs) were attached to screen printe carbon electrodes (SPCEs) [78]. The electrode was connected to the first *Escherichia coli-O157H7* specific antibody, *Escherichia coli -O157H7* intact cells, and the second *Escherichia coli-O157H7* specific antibody that was linked to horseradish. The substrate employed was hydrogen peroxide, while the mediator used was ferrocedicarboxylic acid (FeDC). The use of gold nanoparticles (GNPs) and iron dextran-coated (FeDC) particles significantly increased the current responsiveness by a factor of 13.1. This improvement enabled the detection of 6 colony-forming units (CFU) per strip in buffer solution and 50 CFU per strip in milk. This amperometric approach is capable of detecting bacterial various levels of concentration from 102 - 107 CFU/mL. Cho et al [79]. Fabricated an electrochemical immunosensor by depositing peptide nanotubes on screen-printed carbon electrodes (PNseSPCE).

The immobilized anti- *Escherichia coli-O157H7* antibody on PNeSPCE effectively adsorbed *Escherichia coli-O157H7* from samples by means of antigene-antibody interaction. Additional *E. coli* strains were identified with the use of sensors that integrated nanomaterials, including MNPs [80], SNPs [81], GNPs [82], and carbon nanotubes (CNTs). In the study devised a technique to identify *E. coli* cells at a concentration of 10^4 cells/mL using D-mannose-functionalized magnetic nanoparticles (MNPs). The process involved the modified MNPs incubation with fluorescein-labeled concanavalin A at a temperature of 4 °C for a duration of 12 hours. Subsequently, the MNPs were further incubated with *Escherichia coli-O157H7* cells in a (PBS) phosphate buffer saline. The magnetic field was then employed to separate the MNPs, which were subsequently stained with a fluorescent dye and examined using epifluorescent microscopy[80]. In a comparable investigation, Kalele et al employed rabbit immunoglobulin-G (IgG) antibody-conjugated silver nanoshells to swiftly and extremely selectively identify E. coli within the range of 5-10^9 cells. This was achieved by observing the alteration in the shift of the surface plasmon resonance (SPR) band in the presence of *E. coli* cells[81]. Furthermore, a swift electrochemical method for detecting *E. coli* was disclosed, utilizing core-shell Cu@GNPs as sensors specifically designed to target *E. coli* Maurer et al [82]. Despite this, with the help of polyethyleneimine (PEI) coated golden tungsten wire, bionano-sensor single-walled carbon nanotubes (SWCNTs) was developed. The bionano-sensor was able to detection *Escherichia coli* through the activity that occurred at the junction of the golden tungsten and SWCNT wires. The streptavidin and *Escherichia coli*-specific antibody were used to functionalize this junction, and the electrical current change was measured while the material containing *Escherichia coli* was being introduced into the junction. The use of the golden tungsten wire coupled with the SWCNT resulted in an electrical current change of 290.90 near 291 nanoampere, whereas the use of the Single-walled carbon nanotubes SWCNT alone resulted in a change of 33.13 nanoampere in the electrical current. For the developed SWCNT coupled bionano-sensor, the total amount of time required for the detection of *Escherichia coli* was five minutes, and the detection limit was 102 colony-forming units per milliliter [83]. Shen et al devised a technique known as functional nanoparticle-enhanced ELISA to detect *Escherichia coli-O157H7* in food samples. The magnetic nanoparticles, coated with antibodies specific to *Escherichia coli-O157H7*, were employed to gather and then isolated from the target bacteria using a magnetic separator. Subsequently, polyclonal anti-*Escherichia coli-O157H7* antibodies were applied to Beacon gold nanoparticles (B-GNPs) and then added to the isolated *Escherichia coli-O157H7*

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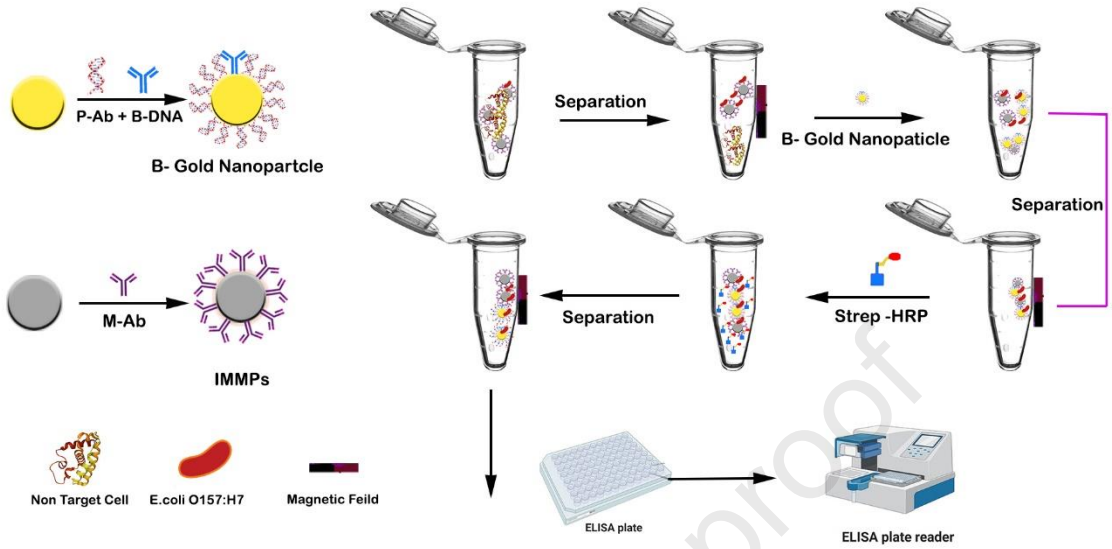
complex. This facilitated the occurrence of an immunoreaction. The unbound B-GNPs were subsequently extracted from the complex using a magnetic separator. Afterwards, Strep-HRP was added to the solution to interact with the pre-existing polyclonal anti-*Escherichia coli-O157H7*. Subsequently, any unattached Strep-HRP particles were removed using a magnetic separation technique. The color change, caused by *Escherichia coli-O157H7,* was checked by ELISA test. This is shown in Figure 11 [84]. A separate investigation demonstrated the use of single-walled carbon nanotubes (SWCNTs) in a nano-sensor, employing the potentiometric approach, can detect 6 coliform units per milliliter in milk and 26 coliform units per milliliter in apple juice within a timeframe of one to two minutes[85]. The specific strain of *Escherichia coli* known as O157H7. On the other hand, Phage-type M13 KE phage nano-sensors, specifically designed for water, orange juice, and skim milk samples, use a fluorescent solution method to detect *Escherichia coli-K12*. These nano-sensors were able to detect 50 coliform units per milliliter in water and 5 coliform units per milliliter in orange juice and skim milk within a time frame of less than 4 hours[86]. It has recently fabricated innovative nano-biosensor platforms by attaching RNA-coated GNPs to CNTs. This platform is specifically designed for determination of *Escherichia coli*. Finally, the development of nano-sensors for the detection of *Escherichia coli,* is in progress and nanoscale will reduce the risks of this bacterium. In addition for lab on chip, Guo et al. employed electrochemical impedance spectroscopy to identify *E. coli*, achieving a detection limit of 102 CFU/mL. Once more, these detection limits remain subpar (or the test duration is excessively prolonged) compared to those of "labelled" ELISA lab-on-a-chips[87].



552

553 **Figure 11** illustrates the process of preparing IMMPs and B-GNPs, as well as the steps involved
554 in separating and conducting immunoreactions with E. coli O157H7 using IMMPs, B-GNPs, and
555 Strep-HRP. E. coli O157H7 detection via the enzyme-linked immunosensor

556

557 ***2.8.1.2 Salmonella***

558 *Salmonellosis* is a significant bacterial disease mostly caused by *Salmonella species*, including *S.*
559 Enteritidis and *S.* Typhimurium [88]. According to WHO estimates, there are around tens of millions
560 of new instances of human infection each year, resulting in 100,000 fatalities. Symptoms of this
561 infection include Pyrexia, Abdominal discomfort, gastroenteritis, vomiting, and nausea [74]. In the
562 study demonstrated a highly sensitive electrochemical immune-assay for detecting *Salmonella*
563 Typhimurium. They immobilized mono-clonal antibodies on polystyrene to capture the bacteria.
564 Subsequently, a polyclonal antibody-GNPs conjugate was introduced to facilitate the binding of
565 the bacteria, in the presence of a Cu or Cu-enhancer solution and ascorbic acid. The Cu generated
566 during the reduction process was selectively accumulated onto gold nano particles in order to
567 directly quantify the concentration of *S.* Typhimurium through anodic stripping voltammetry. This
568 method detection limit was 98.9 CFU/mL, and the anodic current showed a linear relationship with
569 the *Salmonella* Typhimurium concentration within the range of 1.30×10^2 to 2.6×10^3 CFU/mL[89].

A further investigation developed a reusable capacitive immunosensor that utilized ethylene-di-amine and gold nanoparticles attached to a glassy carbon electrodes (GCEs). This immune-sensor was designed for *Salmonella sp*. detection in some pork samples [90]. The direct measurement of the interaction between monoclonal *Salmonella species* with antibody GNPs conjugated, can be achieved by using Electrochemical impedance spectroscopy (EIS) with the detection limit 1×10^2 (CFU/mL). Joo et al for *Salmonella* detection in milk, devised a simple and highly sensitive technique by employing optical nanocrystal probes and Magnetic nanoparticles (MNPs). The milk bacteria were trapped by MNPs-linked antibodies. The bacteria-MNP complexes were separated from the solution by using a magnetic field. Next, the complexes were exposed to TiO_2 nanocrystals that were immobilized with antibodies, allowing them to absorb UV light. Finally, the MNP-*Salmonellae*-TiO2 complexes were magnetically separated from the solution in order to analyze the TiO2 nanocrystals that were not bound using a UV-visible spectrometer. Although, the Salmonella detection limit in milk was 100 CFU/mL [91]. Jain et al tried to optimize the efficacy of an electrochemical biosensor by integrating carbon nanotubes (CNTs). The researchers fixed carbon nanotubes (CNTs) that had been modified with monoclonal antibodies onto a glassy carbon electrode. The aforementioned configuration was employed to determine *S.* Typhimurium by examining alterations in charge transfer resistance and impedance via electrochemical impedance spectroscopy. The detection method exhibited a linear response range spanning from 10^{-1} to 10^{-6} of an overnight bacterial culture's serial dilution value. The detection limit was determined to be 1.6×10^4 CFU/mL.[92]. Quantum dots (QDs) are becoming more commonly used as fluorescent markers, making them a novel and promising type of fluorescent biosensors. Yang and Li conducted a study to identify *S.* Typhimurium in the wash water of chicken carcasses. The bacteria were separated from the wash water by employing magnetic beads that were coated with antibodies specific to Salmonella. Afterwards, an additional biotin-labeled antibody specific to Salmonella was added, allowing for the interaction between biotin and quantum dots coated with streptavidin. This interaction facilitated the quantification of the intensity of fluorescence. An association was observed between the logarithm of bacterial cell number and the intensity of fluorescence between 10^3-10^7 CFU/mL [93]. The lowest detectable concentration was determined to be 103 CFU/mL. Prior to the aforementioned method, Weeks et al, *Salmonella enterica* cells detected at concentrations as low as 25 CFU/mL by (SNC) silicon nitride cantilevers, this was achieved by monitoring the surface bending of the cantilever, which was directly correlated with the quantity of bacteria

attached to it [94].On the other hand, Peroxidase-gold nanoparticles have been employed to create aptamer-based sensors, for rapid determination of *Salmonella enterica serovar* in milk samples. This detection method utilizes optical techniques and can get results within 3 hours, with a sensitivity of 1×10^3 CFU/mL coliform unit per milliliter[95]. Moreover, an integrated lab-on-a-chip (LoC) platform and process were developed by Tsougeni et al. for quick pathogen analysis in food samples. An oxygen plasma nanotextured polymeric chip in a cohesive microfluidic chamber captures bacteria by immunoaffinity, chemical lysis, and isothermal DNA amplification. The analytical time from sample to result was under 4.5 hours, a fivefold improvement over standard procedures. Without labels, *Salmonella, B. cereus, Listeria, and E. coli* can be detected in milk with minimal off-chip processing and fast analysis[96]. Table 2 displays various designed nanoparticles for *Salmonella* germs detection.

Table 2 Creation of nano-sensors designed to detect *Salmonella* germs

Serotype	Nano-sensor Type	Application	Limit of detection	Time
S. Typhimurium	Gold nanoparticles–urease	Chicken- duck	102 CFU/mL	120 min
S. Typhimurium	nickel nanowires	Chicken	80 CFU/mL	120 min
S. Typhimurium	(MWCNT)s	Chicken	80 CFU/mL	10 min
S. Typhimurium S. Enteritidis	AuNRs	Buffer	23 - 108 CFU/mL	<1 min
S. Typhimurium	Apt/AuNPs@AuNDs	Milk	35 CFU/mL	60 min
S. Typhimurium	Melittin/Fe3O4/ SPIDE/Abd	Apple juice and potable water	10 CFU/mL	25 min
Salmonella	Lab on chip (LOC) Base Immunomagnetic beads	Pork	50 cells per test	40 min
Salmonella	Lab on chip (LOC) Base Magnetic bead	MILK	10 cells for each kind of pathogen	15 min
S. Typhimurium	Lab on chip type Microfluidic chips	Fresh cut salad	6.1 × 101 CFU/mL	45 min
S. Typhimurium	Lab on chip Finger-actuated microfluidic Biosensor	Chicken	14 CFU/Ml	60 min

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615 ***2.8.1.3 Mycobacterium avium***

616 The paratuberculosis sub-species *Mycobacterium avium* is a pathogen which responsible for
617 Johne's disease in cattle. The main challenge in limiting the transmission of this illness is the
618 difficulty in quickly identifying this germ at low concentrations. Advancements in the
619 development of nano-sensors offer appealing alternatives for rapid, sensitive, and efficient
620 analysis. Kaittanis et al. devised a single-step technique for detecting bacteria in milk and blood
621 using superparamagnetic iron oxide nanoparticles (SPIONs), which takes advantage of the
622 magnetic relaxation characteristic of these nanoparticles. The method of magnetic nano-sensors is
623 based on their capacity to transition between scattered and clustered states when interacting with
624 a target. This transition leads to a simultaneous alteration in the relaxation period of spine spins.
625 To detect MAP, the SPIONs were linked to anti-MAP antibodies via protein G. The nano-sensors
626 demonstrated a dose-dependent response when MAP was added, with the most effective results
627 observed at a nanoparticle concentration of 2 microgram Fe per microlitre. As a result, the mean
628 arterial pressure (MAP) increased in whole milk that was mixed with 2 micrograms of iron per
629 microlitre. The MAP nano-sensor detected a change in T2, it was inversely proportional to the
630 MAP concentration. The accurate measurement was achieved within the range of 15.5-775 coli
631 form unit per milliliter after a 30 minutes incubation at 25 ^{0}C. Nevertheless, at a temperature of 37
632 degrees Celsius, the identification and measurement of MAP could be accomplished with great
633 accuracy in 2% milk. An additional benefit is that exposing the sample to a (30 min) incubation at
634 37 ^{0}C did not impact the ability to detect another bacteria, such as (*Escherichia coli, Staphylococcus aureus, Enterococcus faecali, Proteus vulgaris, Pseudomonas aeruginosa, and S.marcescens)*. However, extending the incubation time to 45 minutes resulted in an increase in
635 the minimum detectable concentration from 15.5 Colony forming units to 38.8 Colony forming
636 units. In addition, this assay has the capability to ascertain the MAP status (positive or negative)
637 of blood samples from an individual in a single step[94, 97]. In a separate investigation, Yakes et al
638 devised a sandwich immunoassay to swiftly and accurately detect Mycobacterium avium subsp.
639 paratuberculosis (MAP) at low concentrations. This method utilized (SERS) surface enhanced
640 Raman scattering and involved two crucial elements: the immobilization of 13E1, monoclonal
641 antibody, to target the MAP2121c which is a surface protein on the microorganism, and the
642 creation of extrinsic Raman labels using 60 nano meter gold nanoparticles to selectively bind the
643 captured proteins and generate strong SERS signals. Li and Church have conducted a review on
644
645

the utilization of Raman spectroscopy for the examination of nanomaterials in the fields of food and pharmaceuticals[98].The creation of the Raman label relied on the natural absorption of sulfur compounds onto gold nanoparticles, followed by the construction of a 5,50-dithiobis(succinimidyl-2 nitrobenzoate) (DSNB) adlayer on the nanoparticle's surface. This adlayer can then attach antibodies, leading to the generation of a biospecific label. The detection relied on measuring the intensity of the powerful ns(NO2) of the DSNB-derived monolayer. The Raman label-incorporated surface-enhanced Raman scattering (SERS)-based immunoassay successfully detected *Mycobacterium avium* subsp. paratuberculosis (MAP) within 24 hours. The test achieved a detection limit of 100 nanogram/mL in phosphate-buffered saline (PBS) and 200 nanogram/mL in pasteurized whole milk. This was achieved by using a recognition element 13E1 in the SERS platform. The high reproducibility seen in this process can be attributed to the creation of homogenous nanoparticles and the optimization of Raman labels during manufacture[99].

2.8.1.4 Listeria monocytogenes

Listeria monocytogenes, Gram-positive bacteria, is the source of the infectious disease listeriosis. Of all the bacterial infections spread through food, it is the most aggressive and the third most deadly. By employing a high-transition temperature superconducting quantum interference device (SQUID) to measure the rate at which antibody-bound magnetic nanoparticles adhere to bacteria, Grossman et al. developed an inventive method for detecting L. monocytogenes. A 50 nm-sized sample of superparamagnetic nanoparticles coated with antibodies was mixed with the Listeria monocytogenes sample. The magnetic dipole moments were then oriented using a pulsed magnetic field.SQUID can be used to measure the slow release of magnetic flux caused by Neel relaxation in nanoparticles attached to Listeria monocytogenes, as opposed to the rapid randomization of unattached nanoparticles caused by Brownian rotation. In a 20 mL sample volume, the detection limit for Listeria monocytogenes was found to be 560 cells. In addition, 230 cells of Listeria monocytogenes were detected in a 1 nL sample volume. [100]. The upper section describes the use of a comparable magnetic relaxation technique for the detection of mycobacterial species. Table 3 shown summarize nanosensors application in food and detection listeria monocytogenes.

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Table 3 Nano-sensors designed to detect *Listeria monocytogenes* in different types of food

Type of Food	Nano-sensor Type	Detection Limit	Reference
Whole milk, ground meat	Magnetic nanoparticle-based colorimetric assay	2.17×10^2 CFU/mL	[101]
Lettuce, milk, ground beef	Impedance immunosensor with magnetic nanoparticles and microfluidic chip	10^3 CFU/mL	[102]
Spiked food samples	Multicolorimetric assay based on etching of gold nanorods	10 CFU/mL	[103]
Lettuce homogenate	Single-walled carbon nanotubes-based electrochemical impedance immunosensor	10^3 CFU/mL	[104]
Spiked food samples	Nanohybrid quantum dot complex	5.19×10^3 CFU/mL	[105]
Artificial contaminated food	Gold nanoparticle-based colorimetric detection with hyperbranching rolling circle amplification (HRCA)	75 copies	[106]
Lettuce, tomato, ground beef	Magnetic nano-beads based separation combined with propidium monoazide treatment and multiplex PCR	5.4×10^2 CFU/g	[107]
Meat samples	Optical label-free biosensor	Not specified	[108]
Ready-to-eat meat samples	Multiplex fiber optic biosensor	10^3 CFU/mL	[109]
Spiked food samples	Nanoporous sensor with aptamer	100 CFU/mL	[110]

2.8.1.5 Pseudomonas aeruginosa

Pseudomonas aeruginosa, a ubiquitous Gram-negative bacterium, is renowned for its capacity to induce inflammation and sepsis. Importantly, the invasion of specific organs such as lungs, urinary system, and kidney can result in life-threatening outcomes. Moreover, it is accountable for nosocomial infections in healthcare facilities and medical apparatus, such as catheters. Norman et al. showed a study on the targeted elimination of *Pseudomonas aeruginosa* using gold nanorods. The gold nanorods, which have amine terminations, were covalently attached to carboxylic acids obtained from primary antibodies against *P. aeruginosa.* This attachment was achieved using 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide, a compound commonly used in a chemical process called carbodiimide chemistry. Subsequently, the mixture consisting of antibodies, nanorods, and

686 bacteria was subjected to near-infrared (NIR) light with a wavelength of 785 nm and a power of
687 50 mW for a period of 10 minutes. Afterwards, the suspension was dyed with vital (green) and
688 non-vital (red) dyes, and the quantity of living and non-living cells was assessed. The cell viability
689 of P.aeruginosa cells coated with nanorods and exposed to NIR radiation decreased by 75%,
690 compared to the 80% cell viability observed in both NIR-exposed cells with and without nanorods
691 that were not exposed to NIR[111].on the other hand A study was conducted using Au-N triangles
692 nanoparticles to detect the presence of P. aeruginosa bacteria in water samples. This was achieved
693 by utilizing the localized surface plasmon resonance signal. The figure 12 below shows the
694 imaging of a single bacterial cell using scanning electron microscopy (SEM)[112].

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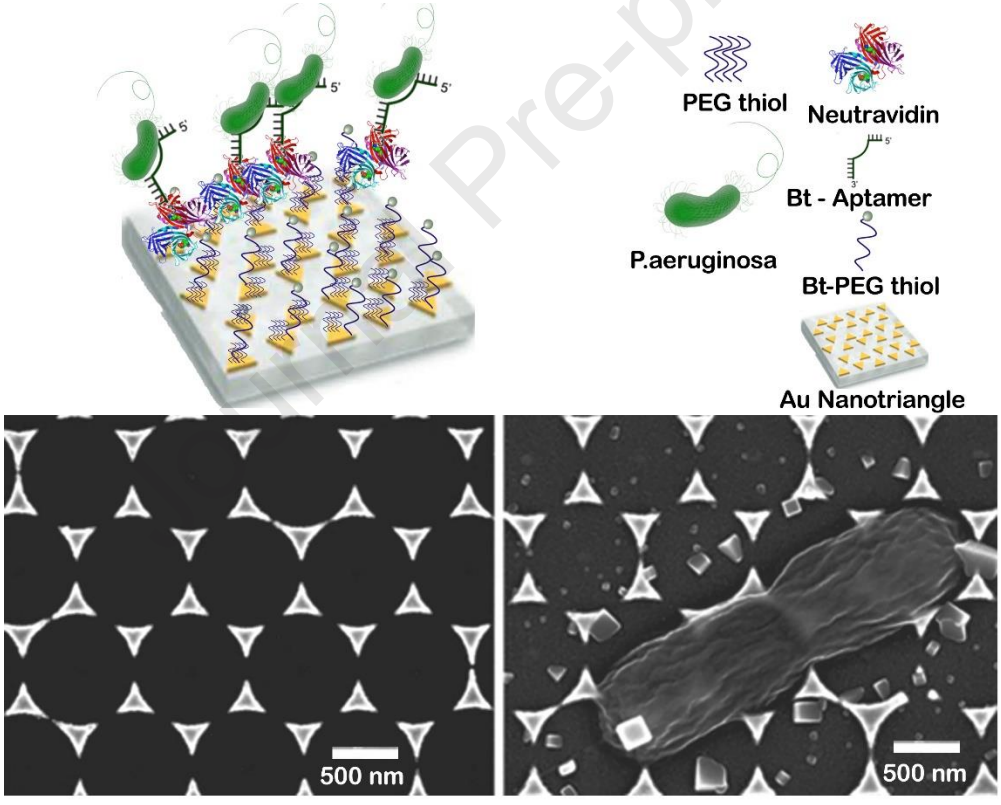


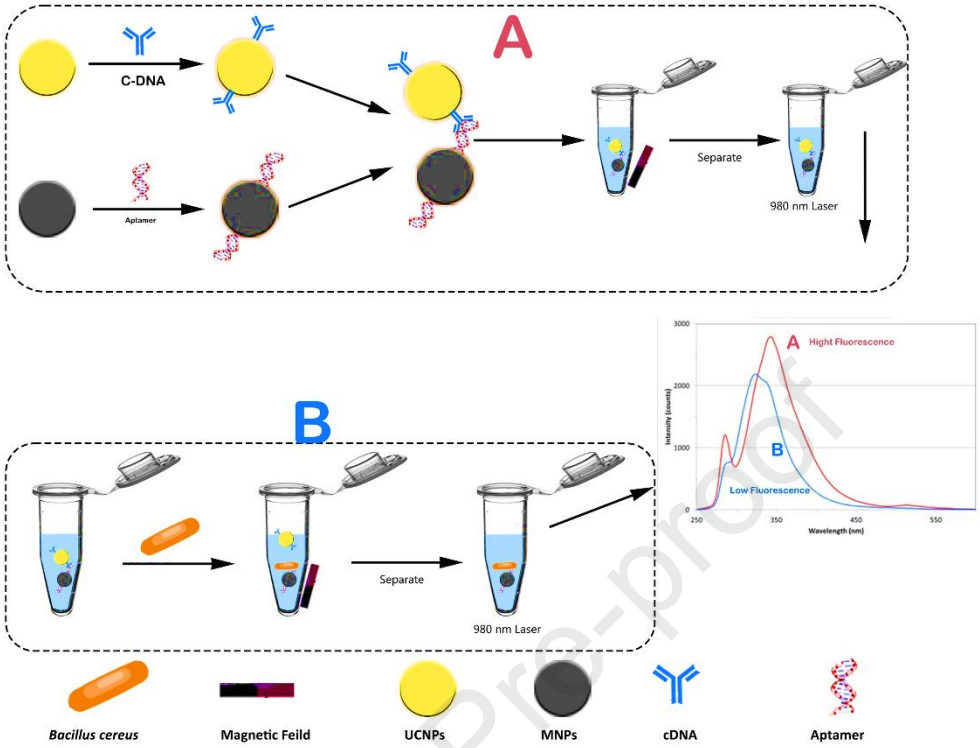
696

697 **Figure 12** illustrates the operational mechanism and detection process of *Pseudomonas* bacteria
698 for the nanosensor.

699

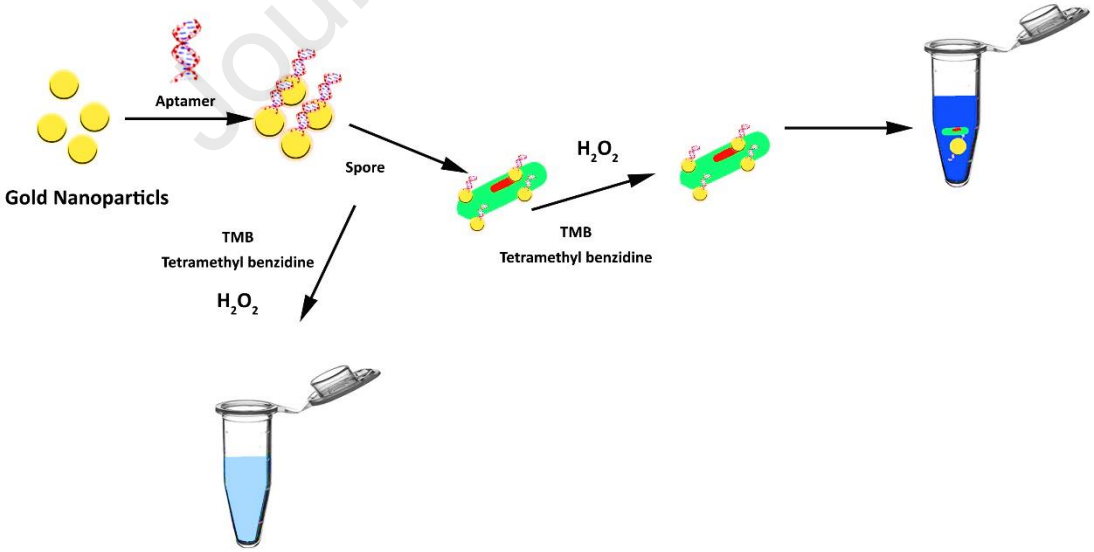
2.8.1.6 Bacillus cereus

Bacillus cereus, a gram-positive bacterium that forms spores, is widely recognized as the primary culprit behind foodborne illnesses. This bacterium is mostly found in soil and is commonly found in plant-based foods. However, because to its widespread presence and the ability of its endospores to withstand harsh physical conditions, it can also be found in other forms of food such as meat, eggs, dairy products, and processed foods. Furthermore, the emetic form is triggered by the ingestion of food contaminated with cereulide toxin, which is synthesized by bacteria. As a result, individuals experience symptoms of emesis and queasiness. The second type is caused by enterotoxins produced by B. cereus in the small intestine, leading to symptoms such as diarrhea and abdominal pain[113]. A study was conducted to assess the ability of Bacillus to cause disease. In this study, aptamers (Apt) were attached to the surface of magnetic nanoparticles (MNPs) to create Apt-MNPs capture probes. The results of the study demonstrated that this method has a strong ability to accurately quantify B. cereus within a range of 48–49×10^6 CFU/mL, under optimal conditions. The detection limit of this method was found to be 22 CFU/mL. Furthermore, the proposed detection method also demonstrates a high level of specificity. Figure 13 depicts the sequential steps involved in detecting the presence of *bacillus* [114]. In addition, the suggested detection method also exhibits a notable degree of specificity. In addition, GNPs were utilised in a distinct investigation to detect *bacillus* infections in water, milk, and cooked potatoes. The experiment was assessed through both visual observation and quantitative analysis using a spectrophotometer. The BAS6R@MPs aptasensor, when used with BAS6R@AuNPs, demonstrated exceptional sensitivity, enabling the detection of bacterial concentrations as low as 10^2 CFU/mL in water and milk, and 10^4 CFU/mL in mashed potatoes, visible to the naked eye. Furthermore, the researchers effectively differentiated between spores of *Bacillus cytotoxicus* and *Bacillus subtilis*, as well as bacterial vegetative cells, in contaminated food samples. This demonstrates a significant degree of selectivity. Figure 14 illustrates the sequential process of identifying the existence of bacillus [115].



727

728 **Figure 13** steps involved in detecting the presence of *bacillus*



729

730 **Figure 14** The colorimetric assay scheme is designed to detect *B.cytotoxicus* spores by utilizing
731 the spore-enhanced peroxidase-like catalytic activity of gold nanoparticles.

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732

733 ***2.8.1.7 Shigella***

734 *Shigella* is a collection of bacteria that possess specific traits: they are Gram-negative, capable of
735 surviving with or without oxygen, do not form spores, lack the ability to move, and have a
736 cylindrical shape. Furthermore, *Shigella* is genetically closely associated with *Escherichia*. The
737 medical term "shigellosis" is commonly used interchangeably with the term "bacillary dysentery."
738 The onset of diarrhea, which may manifest as either watery or bloody stools, along with fever and
739 abdominal cramps, usually takes place within a period of 1 to 2 days following the ingestion of the
740 bacteria. This condition typically resolves within a period of 5 to 7 days. In study presents a new
741 nanoplatform consisting of biofunctionalized magnetic nanoparticles (MNPs) that have been
742 modified with upconversion nanoparticles (UCNPs). The primary objective of this nanoplatform
743 is to rapidly and precisely identify the existence of *Shigella*. The MNPs@UCNPs fluorescence
744 biosensor effectively identified the existence of *Shigella* within a 1-hour period, with a minimum
745 detectable concentration of 32 colony-forming units per millilitre (CFU/mL). The study showcased
746 a rapid and specific sensing platform that produced outstanding results during the analysis of
747 chicken samples[116]. *Shigella* bacteria were detected in milk and chicken breast samples during a
748 separate investigation. A composite material was created by combining the Raman active 4-MBA
749 ligand of the Eu-complex with citrate-stabilized Au nanoparticles (cit-Au NPs). This material had
750 two functions, acting as both a reactive base and a Raman indicator. Specific aptamers that
751 selectively bind to *S. Sonnei* were immobilised onto the surface of this material with dual
752 functionality. The *Shigella species*, such as *S. dysenteriae, S. flexneri, and S. boydii*, exhibited a
753 remarkable level of specificity. Through the implementation of experiments on authentic samples,
754 the developed technique exhibits significant promise in producing a diverse array of aptasensors
755 capable of efficiently and conveniently detecting various food hazards [117].

756 ***2.6.1.8 Staphylococcus aureus***

757 *Staphylococcus aureus* is a coccus-shaped bacterium that is Gram-positive and classified within
758 the *Bacillota phylum*. It is frequently present in the body's microbiota, specifically in the upper
759 respiratory tract and on the skin. Common symptoms include the abrupt onset of vomiting and
760 stomach discomfort. A novel colorimetric test for detecting *S.aureus* has been developed

employing gold nanoparticles and aptamers, combined with TSA for enhanced identification. The devised approach has a detection sensitivity of 9 colony-forming units per milliliter (CFU/mL) and a wide linear range from 10 to 10^6 CFU/mL[118]. Furthermore, this established technique was effectively employed for the analysis of milk samples. Nano-sensors have been created to detect *Staphylococcus aureus* in food [119]. A nanobiosensor was developed using paper and DNA-Au/Pt bimetallic nanoclusters. This nanobiosensor has a detection limit of 80 CFU/mL[120]. Designed a PDMS microfluidic impedance-based immunoassay sensor with a high sensitivity of 10^2 CFU/mL. In Sung's study conducted in 2013, antibody/AuNPs/magnetic nanoparticle nanocomposites were employed for immunomagnetic separation and colorimetric detection. The detection limits for *S. aureus* in PBS and milk samples were determined to be 1.5×10^3 and 1.5×10^5 CFU, respectively[121]. In a recent study, examined the application of aptasensors in detecting *S. aureus*. The author emphasized the promising prospects of integrating aptasensors with nanomaterials. These studies collectively show that nano-sensors have the ability to quickly and accurately detect S. aureus in food[122]. Another method involves an aptamer-quantum dot and teicoplanin-gold nanoparticle-based fluorescence resonance energy transfer (FRET) sensor. This sensor offers a detection limit of 2 CFU/mL for S. aureus in buffer solutions and 100 CFU/mL in food samples like milk and orange juice, demonstrating high specificity and sensitivity [123].A dual electrochemical/colorimetric magnetic nanoparticle/peptide-based platform has also been developed. This sensor uses magnetic nanoparticles linked with specific peptides that, upon cleavage by S. aureus protease, reveal a color change detectable by the naked eye and an electrochemical signal proportional to the bacterial concentration. This platform can detect *S. aureus* at levels as low as 3 CFU/mL within one minute [124].Moreover, a novel approach using upconversion nanoprobes regulated by horseradish peroxidase for dual-mode detection has been created. This method combines aptamer-labeled magnetic nanoparticles and horseradish peroxidase-functionalized upconversion nanoparticles, achieving detection limits of 22 CFU/mL for fluorescence and 20 CFU/mL for colorimetry in meat samples [125].

2.9.2 Detection of Toxic Bacteria in Foods

2.9.2.1 Cholera toxin (CT)

Bacterium *Vibrio cholera* released a complex protein named Cholera toxin, which is responsible for watery diarrhea in individuals infected with cholera. The structure of this complex is

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oligomeric, specifically defined as AB5, and consists of six protein subunits one A, five B subunits) [74, 126]. Viswanathan et al utilized recent advancements in nanoparticle technology to create a highly sensitive method for detecting CT. They developed sensor that employed liposomal magnification and poly(3,4 ethylene-di-oxy-thiophene) coated on a Nafion-supported (MWCNTs) film on a glassy carbon electrode linked with anti-Cholera T-B subunit monoclonal antibody. The detection method relied on electronic transducers used sandwich-type assay. In this assay, the toxin is initially attached to the anti-cholera Toxin antibody and then with conjugated ganglioside-functionalized liposome. The inorganic compound ($C_6FeK_4N_6$) Potassium ferrocyanide molecules liberated from liposomes and linked to the electrode were quantified by adsorptive wave square stripping voltammetry. The limit of detection and the linear range of cholera toxin were 10^{-16} g/ml - 10^{-14} - 10^{-7}g/ml [127], respectively. In a separate investigation, gold nanoparticles (GNPs) were attached to a lipid bilayer that contained gangliosides in order to detect CT[128]. This approach offers a significant enhancement in sensitivity, with a 100-fold improvement compared to other standard fluorescent immune-assays (5nM). The detection limit is 10-100pM and the linear dynamic range spans from 10pM to 100nM. Schofield et al. devised a colorimetric bioassay where a thiolated-lactose derivative formed self-assembled structures on 16 nm gold nanoparticles (GNPs) [128]. These structures aggregated when they bound to the CT-B subunit, resulting in a color change from red to purple, which served as the basis for detection. The estimated limit of detection was 3 mg/mL[129].

2.9.2.2 Staphylococcal enterotoxin

Staphylococcal enterotoxins, a significant group of twenty-one thermally stable toxins produced by *Staphylococcus aureus*, are associated with foodborne illnesses caused by consuming spoiled foods.Exposure to Staphylococcal enterotoxins, even at a low concentration of 20-100 nanograms per person, causes anorexia, nausea, vomiting, and diarrhoea, which are indicative of food poisoning [130]. Moreover, SEs have been associated with the emergence of conditions such as atopic eczema, rheumatoid arthritis, and toxic shock syndrome [131, 132]. Although ELISA and other immunological assays are known for their speed and high throughput, they do not possess sufficient sensitivity for specific applications. To overcome this constraint, Yang et al. developed an optical immunosensor that employs carbon nanotubes (CNTs) for the detection of Staphylococcal enterotoxins. This is accomplished by interacting the carbon nanotubes (CNTs) with a fixed anti-SE primary antibody, and then attaching a secondary antibody labelled with

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horseradish peroxidase (HRP). Subsequently, the fluorescence of horseradish peroxidase is employed for the purpose of identifying the existence of Staphylococcal enterotoxins. The sandwich immunosensor-based assay provides a signal that is six to eight times greater than the standard immunosensor. The detection limit of this is 0.1 ng/mL and it has a linear dynamic range of 0.1-100 ng/mL. However, when applying this test to real food samples such as apple juice, soy milk, meat, and baby food, an additional purification step was required using carboxymethyl cellulose chromatography [131]. Afterwards, the research team conducted a study to identify and detect harmful substances in food, specifically focusing on SEs. Then employed gold nanoparticles (GNPs). The gold nanoparticle surface was attached to an anti-SE primary antibody through physical adsorption, and the antibody-GNPs conjugate was attached to a polycarbonate surface. The sandwich ELISA assay was implemented using a secondary antibody (HRP-conjugated antirabbit IgG) to improve chemiluminescence detection. Subsequently, the efficacy of the enhanced chemiluminescence (ECL) immunosensor was evaluated [131]. The approach's limit of detection was determined to be 0.01 ng/mL, which is tenfold more sensitive than both the classic ELISA method and the previously disclosed CNT-based immunosensor test. Gold nanoparticles are not only less poisonous than carbon nanotube, but they also do not require shortening and acid functionalization. As a result, the fabrication of an immunosensor based on GNPs is significantly simplified[131, 132]. In addition for Lab on chip Yang et al. integrated carbon nanotubes, increased chemiluminescence, and a cooled charge-coupled device (CCD) detector to augment the detection of *Staphylococcal enterotoxin* B (SEB) in food. Anti-SEB primary antibodies were affixed to the CNT surface, and the antibody-nanotube composite was adhered to a polycarbonate surface. SEB was then identified using an ELISA assay on the CNT-polycarbonate surface, coupled with an improved chemiluminescence assay. SEB in buffer, soy milk, apple juice, and meat infant food was analysed with a detection limit of 0.01 ng/mL utilising the CCD detector, which exhibited more sensitivity than the traditional ELISA. They also created a lab-on-a-chip utilising this CNT-ECL immunoassay to identify SEB[133].

2.9.2.3 Shiga toxin

Shiga-like toxins, which are part of the alike family as the Cholera T toxin, are synthesized by *Escherichia coli* bacteria, particularly the foodborne pathogen *Escherichia coli-O157H7*. The

subunit B of shiga same toxin produced by *Escherichia coli-O157H7* has a specific affinity for the globotriose (P^k) blood group antigen. This antigen consists of the trisaccharide α-Gal(1→4)β-Gal(1→4)β-Glc. Each of the 5 B subunits of the toxin has 3 binding sites that can interact with the P^k antigen[126, 134]. Chien and colleagues utilized this phenomena to create an SPR competition assay. They achieved this by self-assembling two variants of P^k onto glyconanoparticles of varying sizes four nanometer, thirteen nano meter, and twenty nano meter made of GNPs. Increasing the length of the chain was found to improve the binding strength of the P^k moiety, leading to increased flexibility of the P^k ligand to attach to several places on the toxin surface. Similarly, the P^keg old variants made with larger diameter GNPs exhibited a higher binding affinity, which can be attributed to the reduced curvature of the GNPs. A chip-based assay was designed by including glyconanoparticles, based on the results obtained[134]. Nagy et colleagues conducted a subsequent investigation where they enhanced a chromatic sensor using (Gal-α1,4-Gal) glycol-polydiacetylene nanoparticles to specifically detect Shiga toxin-producing *Escherichia coli-O157H7*. The plates containing shiga toxin producing *Escherichia coli-O157H7* exhibited a color transformation from purple to brown within a span of 5 minutes. In contrast, the non-Shiga toxin generating *Escherichia coli* solution maintained its purple hue after the addition of glycol-polydiacetylene nanoparticles. This approach demonstrated great selectivity, speed, and sensitivity, with a limit of detect of 1200 U/ml a linear range changed of 1200-7200 U/ml [135].

3. Challenges and Future Strategies for Nano-Sensors

Nano-sensors represent a promising technology for advancing food safety, environmental monitoring, and healthcare, but significant challenges remain that must be addressed to realize their full potential. The cost of production and scalability issues hinder their widespread deployment. Sophisticated materials like gold nanoparticles and carbon nanotubes are essential for performance but increase production costs, limiting accessibility in resource-constrained environments [17]. To mitigate these challenges, research into cost-effective alternatives and additive manufacturing methods can reduce material consumption and simplify fabrication processes [136]. Furthermore, environmental sensitivity is a double-edged sword; while it allows for high precision, it also exposes these sensors to potential degradation under varying conditions such as humidity or temperature. Future strategies should focus on developing more robust coatings and packaging solutions that maintain sensor stability without compromising performance in diverse

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environments [137].Additionally, regulatory challenges create barriers to commercial adoption, as nano-sensors involve materials with uncertain long-term environmental and health impacts. Many countries lack clear guidelines for approving nanotechnology products, which discourages investment and slows market entry. Developing internationally harmonized regulatory frameworks will be essential for fostering innovation and enabling companies to invest confidently in nano-sensor technologies [138]. Moreover, scalability remains a pressing issue. Current fabrication techniques, such as chemical vapor deposition and lithography, are not easily adaptable for mass production. To address this, research into new manufacturing technologies, such as printed electronics and nanomaterial-based additive manufacturing, will be crucial in achieving industrial scalability and maintaining reproducibility [139].Furthermore, the development of lab-on-chip platforms and integrated sensing systems offers promising solutions for addressing some of these challenges by combining different sensing technologies into compact, multi-functional devices . Such systems can provide enhanced detection capabilities while reducing overall costs through miniaturization. Future research should focus on modular designs that facilitate easy customization for various applications, from point-of-care diagnostics to real-time environmental monitoring. Collaborative efforts between industry and academia will also play a pivotal role in accelerating the adoption of nano-sensors. Establishing partnerships can bridge the gap between laboratory innovation and market-ready products, ensuring that future developments are aligned with both regulatory standards and commercial needs. Finally, research into eco-friendly materials and sustainable production methods will be essential for aligning nano-sensors with the growing demand for green technologies and minimizing their environmental footprint. With targeted advancements in these areas, nano-sensors can overcome their current limitations and become indispensable tools for the future of smart monitoring and quality assurance across industries

4. Conclusion

In summary, the development of nano-sensor technology represents a significant advancement in the battle against foodborne pathogens. This analysis highlights the exceptional sensitivity, specificity, and rapid detection capabilities of nano-sensors, distinguishing them from traditional detection methods. Their incorporation into food safety protocols offers the potential to greatly improve our ability to monitor and manage foodborne pathogens, ultimately reducing the

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occurrence of food-related illnesses. Nevertheless, there are still challenges to be addressed, such as refining the technology, ensuring cost-effectiveness, and meeting regulatory requirements. Future research should concentrate on overcoming these obstacles and advancing nano-sensor technology to its maximum potential. The implications of these advancements go beyond food safety, offering broader benefits for public health and environmental monitoring. The ongoing innovation in nano-sensor technology is crucial for creating a safer and healthier future for food consumption.

Consent for publication

All authors approved the manuscript for publication.

Availability of data and material

All data relevant to the study are included in the article.

Funding

Not applicable.

Ethical approval

This article does not contain any studies with human or animal subjects.

CRediT authorship contribution statement

All authors**:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

We declare no conflict of interest.

References

1. Pengsomjit U, Alabdo F, Karuwan C, et al. Innovative Graphene-Based Nanocomposites for Improvement of Electrochemical Sensors: Synthesis, Characterization, and Applications. Critical reviews in analytical chemistry 2024:1-19.

Journal Pre-proof

2. Ghosh T, Raj GVSB, Dash KK. A COMPREHENSIVE REVIEW ON NANOTECHNOLOGY BASED SENSORS FOR MONITORING QUALITY AND SHELF LIFE OF FOOD PRODUCTS. Measurement: Food 2022.
3. de Sousa MS, Schlogl AE, Estanislau FR, et al. Nanotechnology in Packaging for Food Industry: Past, Present, and Future. Coatings 2023.
4. Grumezescu AM, Holban AM. Impact of nanoscience in the food industry: Academic Press, 2018.
5. Kumar V, Guleria P, Mehta SK. Nanosensors for food quality and safety assessment. Environmental Chemistry Letters 2017;15:165-177.
6. Control CfD, Prevention. Foodborne germs and illnesses. Centers for Disease Control and Prevention. https://www. cdc. gov/foodsafety/foodborne-germs. html 2016.
7. Authority EFS, Prevention ECfD, Control. The European Union One Health 2022 Zoonoses Report. EFSA Journal 2023;21:e8442.
8. Panwar S, Duggirala KS, Yadav P, et al. Advanced diagnostic methods for identification of bacterial foodborne pathogens: contemporary and upcoming challenges. Critical Reviews in Biotechnology 2022;43:982 - 1000.
9. Labbé RG, García S. Guide to foodborne pathogens: Wiley Online Library, 2013.
10. Zheng L, Jin W, Xiong K, et al. Nanomaterial-based biosensors for the detection of foodborne bacteria: a review. The Analyst 2023.
11. Vijayakumar G, Venkatesan SA, Kannan VA, Perumal S. Detection of food toxins, pathogens, and microorganisms using nanotechnology-based sensors. Nanotechnology Applications for Food Safety and Quality Monitoring: Elsevier, 2023:155-170.
12. Mahmoud ZH, Salman HK, Hussein HH, et al. Organic chemical Nano sensors: synthesis, properties, and applications. Brazilian journal of biology = Revista brasleira de biologia 2023;84:e268893.
13. Sreejith S, Ajayan J, Radhika JM, et al. Recent advances in nano biosensors: An overview. Measurement 2024.
14. Valenzuela-Amaro HM, Aguayo-Acosta A, Meléndez-Sánchez ER, et al. Emerging Applications of Nanobiosensors in Pathogen Detection in Water and Food. Biosensors 2023;13.
15. Li L, Wang T, Zhong Y, et al. A review of nanomaterials for biosensing applications. Journal of materials chemistry. B 2024.
16. Wu L, Yuan X, Tang Y, et al. MXene sensors based on optical and electrical sensing signals: from biological, chemical, and physical sensing to emerging intelligent and bionic devices. PhotoniX 2023;4:1-56.
17. Hu H, Wang N, Liao J, Tovar-Lopez FJ. Recent Progress in Micro- and Nanotechnology-Enabled Sensors for Biomedical and Environmental Challenges. Sensors (Basel, Switzerland) 2023;23.
18. Hsueh TJ, Ding R-Y. A Room Temperature ZnO-NPs/MEMS Ammonia Gas Sensor. Nanomaterials 2022;12.
19. Krishnamoorthy K, Manivannan G, Kim SJ, et al. Antibacterial activity of MgO nanoparticles based on lipid peroxidation by oxygen vacancy. Journal of Nanoparticle Research 2012;14:1-10.
20. Karimiyan A, Najafzadeh H, Ghorbanpour M, Hekmati-Moghaddam SH. Antifungal effect of magnesium oxide, zinc oxide, silicon oxide and copper oxide nanoparticles against Candida albicans. Zahedan Journal of Research in Medical Sciences 2015;17.
21. Sierra-Fernandez A, De la Rosa-García S, Gomez-Villalba LS, et al. Synthesis, photocatalytic, and antifungal properties of MgO, ZnO and Zn/Mg oxide nanoparticles for the protection of calcareous stone heritage. ACS applied materials & interfaces 2017;9:24873-24886.
22. Bafghi AF, Daghighi M, Daliri K, Jebali A. Magnesium oxide nanoparticles coated with glucose can silence important genes of Leishmania major at sub-toxic concentrations. Colloids and Surfaces B: Biointerfaces 2015;136:300-304.
23. Borthakur P, Hussain N, Darabdhara G, et al. Adhesion of gram-negative bacteria onto α-Al2O3 nanoparticles: A study of surface behaviour and interaction mechanism. Journal of environmental chemical engineering 2018;6:3933-3941.
24. Baysal A, Saygin H. PHYSICO-CHEMICAL AND TOXICOLOGICAL BEHAVIOUR OF Al2O3 NANOPARTICLES IN FINE PARTICULATE MATTER. Environmental Engineering & Management Journal (EEMJ) 2019;18.
25. Manikandan V, Jayanthi P, Priyadharsan A, et al. Green synthesis of pH-responsive Al2O3 nanoparticles: Application to rapid removal of nitrate ions with enhanced antibacterial activity. Journal of Photochemistry and Photobiology A: Chemistry 2019;371:205-215.

26. Jalal M, Ansari MA, Shukla AK, et al. Green synthesis and antifungal activity of Al 2 O 3 NPs against fluconazole-resistant Candida spp isolated from a tertiary care hospital. RSC advances 2016;6:107577-107590.
27. Raghunath A, Perumal E. Metal oxide nanoparticles as antimicrobial agents: a promise for the future. International journal of antimicrobial agents 2017;49:137-152.
28. Alfei S, Schito AM. Positively charged polymers as promising devices against multidrug resistant gram-negative bacteria: A Review. Polymers 2020;12:1195.
29. Nazemi H, Joseph A, Park J, Emadi A. Advanced Micro- and Nano-Gas Sensor Technology: A Review. Sensors (Basel, Switzerland) 2019;19.
30. Sui X, Downing JR, Hersam MC, Chen J. Additive manufacturing and applications of nanomaterial-based sensors. Materials Today 2021.
31. Meng Z, Stolz RM, Mendecki L, Mirica KA. Electrically-Transduced Chemical Sensors Based on Two-Dimensional Nanomaterials. Chemical reviews 2019;119 1:478-598.
32. Mustafa F, Andreescu S. Nanotechnology-based approaches for food sensing and packaging applications. RSC Advances 2020;10:19309 - 19336.
33. Zhang S, Zhao Y, Du X, et al. Gas Sensors Based on Nano/Microstructured Organic Field-Effect Transistors. Small 2019;15 12:e1805196.
34. Xue L, Yamazaki H, Ren R, et al. Solid-state nanopore sensors. Nature Reviews Materials 2020;5:931 - 951.
35. Visakh P. Nanomaterials and Nanotechnology in Medicine: Wiley Online Library, 2022.
36. Unno N, Mäkelä T. Thermal Nanoimprint Lithography—A Review of the Process, Mold Fabrication, and Material. Nanomaterials 2023;13.
37. Tang N, Zhou C, Xu L, et al. A Fully Integrated Wireless Flexible Ammonia Sensor Fabricated by Soft Nano-Lithography. ACS sensors 2019;4 3:726-732.
38. Stokes K, Clark KR, Odetade D, et al. Advances in lithographic techniques for precision nanostructure fabrication in biomedical applications. Discover Nano 2023;18.
39. Choudhary R, Rathore N, Parihar K, et al. Unveiling the Nano World: Expanding Food Safety Monitoring Through Nano-biosensor Technology. Journal of Food Chemistry & Nanotechnology 2024.
40. Nam NN, Do HDK, Trinh KTL, Lee NY. Recent Progress in Nanotechnology-Based Approaches for Food Monitoring. Nanomaterials 2022;12.
41. Shruti A, Bage N, Kar PK. Nanomaterials based sensors for analysis of food safety. Food chemistry 2023;433:137284.
42. Beveridge TJ. Structures of gram-negative cell walls and their derived membrane vesicles. Journal of bacteriology 1999;181:4725-4733.
43. Ren E, Zhang C, Li D, et al. Leveraging metal oxide nanoparticles for bacteria tracing and eradicating. View 2020;1:20200052.
44. Bülbül G, Hayat A, Andreescu S. Portable Nanoparticle-Based Sensors for Food Safety Assessment. Sensors (Basel, Switzerland) 2015;15:30736 - 30758.
45. Sonawane A, Mujawar MA, Bhansali S. Plasma Assisted Control of Nanoparticle Distribution for Enhancing the Electrochemical Activity of Electrodes, 2020.
46. Gold K, Slay B, Knackstedt M, Gaharwar AK. Antimicrobial activity of metal and metal-oxide based nanoparticles. Advanced Therapeutics 2018;1:1700033.
47. Abd IK, Shano AM, Khodair ZT. MWCNT Thin Films by CVD Method and Some Applications. Journal of Nano- and Electronic Physics 2022.
48. Yi K, Liu D, Chen X, et al. Plasma-Enhanced Chemical Vapor Deposition of Two-Dimensional Materials for Applications. Accounts of chemical research 2021.
49. Najjar R, Nalbach JR, Xue W. Chapter 9:Carbon Nanotube Sensing in Food Safety and Quality Analysis, 2017.
50. Fu PP, Xia Q, Hwang H-M, et al. Mechanisms of nanotoxicity: generation of reactive oxygen species. Journal of food and drug analysis 2014;22:64-75.
51. Wawrzyniak J. Advancements in Improving Selectivity of Metal Oxide Semiconductor Gas Sensors Opening New Perspectives for Their Application in Food Industry. Sensors (Basel, Switzerland) 2023;23.
52. Parashar M, Shukla VK, Singh R. Metal oxides nanoparticles via sol–gel method: a review on synthesis, characterization and applications. Journal of Materials Science: Materials in Electronics 2020;31:3729-3749.
53. Baino F, Fiume E, Miola M, Verné E. Bioactive sol-gel glasses: processing, properties, and applications. International Journal of Applied Ceramic Technology 2018;15:841-860.

54. Karakoti AS, Hench LL, Seal S. The potential toxicity of nanomaterials—the role of surfaces. Jom 2006;58:77-82.
55. Mauter MS, Elimelech M. Environmental applications of carbon-based nanomaterials. Environmental science & technology 2008;42:5843-5859.
56. Geonmonond RS, Silva AGD, Camargo PH. Controlled synthesis of noble metal nanomaterials: motivation, principles, and opportunities in nanocatalysis. Anais da Academia Brasileira de Ciências 2018;90:719-744.
57. Guo S, Wang E. Noble metal nanomaterials: controllable synthesis and application in fuel cells and analytical sensors. Nano today 2011;6:240-264.
58. Gaikwad S, Ingle A, Gade A, et al. Antiviral activity of mycosynthesized silver nanoparticles against herpes simplex virus and human parainfluenza virus type 3. International journal of nanomedicine 2013:4303-4314.
59. Morris D, Ansar M, Speshock J, et al. Antiviral and immunomodulatory activity of silver nanoparticles in experimental RSV infection. Viruses 2019;11:732.
60. Rogers JV, Parkinson CV, Choi YW, et al. A preliminary assessment of silver nanoparticle inhibition of monkeypox virus plaque formation. Nanoscale Research Letters 2008;3:129-133.
61. Abu-Salah KM, Zourob MM, Mouffouk F, et al. DNA-based nanobiosensors as an emerging platform for detection of disease. Sensors 2015;15:14539-14568.
62. Brenneman KL, Poduri S, Stroscio MA, Dutta M. Optical detection of lead (II) ions using DNA-based nanosensor. IEEE Sensors Journal 2013;13:1783-1786.
63. Liu Y, Kumar S, Taylor RE. Mix-and-match nanobiosensor design: Logical and spatial programming of biosensors using self-assembled DNA nanostructures. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology 2018;10:e1518.
64. Yan J, Estévez MC, Smith JE, et al. Dye-doped nanoparticles for bioanalysis. Nano today 2007;2:44-50.
65. Mohammed OT, Abdulkhaliq RJ, Mohammed ST. The effects of Fusarium graminarum silver nanoparticles on leishmania tropica, In Journal of Physics: Conference Series, IOP Publishing, 2019.
66. SruthiP. S. Review on Lab on Chip Fabrication and its Application in Food Safety Sensing. Current Journal of Applied Science and Technology 2023.
67. Mitrogiannopoulou A-M, Tselepi V, Ellinas K. Polymeric and Paper-Based Lab-on-a-Chip Devices in Food Safety: A Review. Micromachines 2023;14.
68. Tsougeni K, Kaprou GD, Loukas CM, et al. Lab-on-Chip platform and protocol for rapid foodborne pathogen detection comprising on-chip cell capture, lysis, DNA amplification and surface-acoustic-wave detection. Sensors and Actuators B-chemical 2020;320:128345.
69. Umapathi R, Ghoreishian SM, Rani GM, et al. Review—Emerging Trends in the Development of Electrochemical Devices for the On-Site Detection of Food Contaminants. ECS Sensors Plus 2022;1.
70. Ma M, Yang X, Ying X, et al. Applications of Gas Sensing in Food Quality Detection: A Review. Foods 2023;12.
71. Rahmati F, Hosseini SS, Mahuti Safai S, et al. New insights into the role of nanotechnology in microbial food safety. 3 Biotech 2020;10:1-15.
72. Sharma P, Pandey V, Sharma MMM, et al. A review on biosensors and nanosensors application in agroecosystems. Nanoscale research letters 2021;16:1-24.
73. Singh R, Dutt S, Sharma P, et al. Future of nanotechnology in food industry: Challenges in processing, packaging, and food safety. Global Challenges 2023;7:2200209.
74. Sonawane SK, Arya SS, LeBlanc JG, Jha N. Use of nanomaterials in the detection of food contaminants. European Journal of Food Research & Review 2014;4:301.
75. Nanomaterials based biosensors for food analysis applications. Trends in Food Science & Technology 2011:625-639.
76. A nanoparticle amplification based quartz crystal microbalance DNA sensor for detection of Escherichia coli O157:H7. Biosensors and Bioelectronics 2006:1178-1185.
77. Chen S-H, Wu VC, Chuang Y-C, Lin C-S. Using oligonucleotide-functionalized Au nanoparticles to rapidly detect foodborne pathogens on a piezoelectric biosensor. Journal of Microbiological Methods 2008;73:7-17.
78. Lin Y-H, Chen S-H, Chuang Y-C, et al. Disposable amperometric immunosensing strips fabricated by Au nanoparticles-modified screen-printed carbon electrodes for the detection of foodborne pathogen Escherichia coli O157: H7. Biosensors and Bioelectronics 2008;23:1832-1837.
79. Cho EC, Choi J-W, Lee M, Koo K-K. Fabrication of an electrochemical immunosensor with self-assembled peptide nanotubes. Colloids and Surfaces A: Physicochemical and Engineering Aspects 2008;313:95-99.

80. El-Boubbou K, Gruden C, Huang X. Magnetic glyco-nanoparticles: a unique tool for rapid pathogen detection, decontamination, and strain differentiation. Journal of the American Chemical Society 2007;129:13392-13393.
81. Kalele SA, Kundu AA, Gosavi SW, et al. Rapid detection of Escherichia coli by using antibody-conjugated silver nanoshells. Small 2006;2:335-338.
82. Zhang X, Geng P, Liu H, et al. Development of an electrochemical immunoassay for rapid detection of E. coli using anodic stripping voltammetry based on Cu@ Au nanoparticles as antibody labels. Biosensors and Bioelectronics 2009;24:2155-2159.
83. Yamada K, Kim C-T, Kim J-H, et al. Single walled carbon nanotube-based junction biosensor for detection of Escherichia coli. PLoS One 2014;9:e105767.
84. Shen Z, Hou N, Jin M, et al. A novel enzyme-linked immunosorbent assay for detection of Escherichia coli O157: H7 using immunomagnetic and beacon gold nanoparticles. Gut pathogens 2014;6:1-8.
85. Zelada-Guillén GA, Bhosale SV, Riu J, Rius FX. Real-time potentiometric detection of bacteria in complex samples. Analytical chemistry 2010;82:9254-9260.
86. Derda R, Lockett MR, Tang SK, et al. Filter-based assay for Escherichia coli in aqueous samples using bacteriophage-based amplification. Analytical chemistry 2013;85:7213-7220.
87. Guo X, Kulkarni AA, Doepke A, et al. Carbohydrate-based label-free detection of Escherichia coli ORN 178 using electrochemical impedance spectroscopy. Analytical chemistry 2012;84 1:241-6.
88. Pérez-López B, Merkoçi A. Nanomaterials based biosensors for food analysis applications. Trends in Food Science & Technology 2011;22:625-639.
89. Dungchai W, Siangproh W, Chaicumpa W, et al. Salmonella typhi determination using voltammetric amplification of nanoparticles: a highly sensitive strategy for metalloimmunoassay based on a copper-enhanced gold label. Talanta 2008;77:727-732.
90. Yang G-J, Huang J-L, Meng W-J, et al. A reusable capacitive immunosensor for detection of Salmonella spp. based on grafted ethylene diamine and self-assembled gold nanoparticle monolayers. Analytica Chimica Acta 2009;647:159-166.
91. HuiáShin H, JoonáCha H. A facile and sensitive detection of pathogenic bacteria using magnetic nanoparticles and optical nanocrystal probes. Analyst 2012;137:3609-3612.
92. Jain S, Singh SR, Horn DW, et al. Development of an antibody functionalized carbon nanotube biosensor for foodborne bacterial pathogens. J Biosens Bioelectron 2012;11:002.
93. Yang L, Li Y. Quantum dots as fluorescent labels for quantitative detection of Salmonella Typhimurium in chicken carcass wash water. Journal of Food Protection 2005;68:1241-1245.
94. Weeks BL, Camarero J, Noy A, et al. A microcantilever-based pathogen detector. Scanning: The Journal of Scanning Microscopies 2003;25:297-299.
95. Wu W, Li J, Pan D, et al. Gold nanoparticle-based enzyme-linked antibody-aptamer sandwich assay for detection of Salmonella Typhimurium. ACS applied materials & interfaces 2014;6:16974-16981.
96. Guo X, Kulkarni A, Doepke A, et al. Carbohydrate-based label-free detection of Escherichia coli ORN 178 using electrochemical impedance spectroscopy. Analytical chemistry 2012;84:241-246.
97. Kaittanis C, Naser SA, Perez JM. One-step, nanoparticle-mediated bacterial detection with magnetic relaxation. Nano Letters 2007;7:380-383.
98. Li Y-S, Church JS. Raman spectroscopy in the analysis of food and pharmaceutical nanomaterials. Journal of food and drug analysis 2014;22:29-48.
99. Yakes BJ, Lipert RJ, Bannantine JP, Porter MD. Detection of Mycobacterium avium subsp. paratuberculosis by a sonicate immunoassay based on surface-enhanced Raman scattering. Clinical and Vaccine Immunology 2008;15:227-234.
100. Grossman H, Myers W, Vreeland V, et al. Detection of bacteria in suspension by using a superconducting quantum interference device. Proceedings of the National Academy of Sciences 2004;101:129-134.
101. Alhogail S, Suaifan GARY, Zourob MM. Rapid colorimetric sensing platform for the detection of Listeria monocytogenes foodborne pathogen. Biosensors & bioelectronics 2016;86:1061-1066.
102. Kanayeva D, Wang R, Rhoads DD, et al. Efficient separation and sensitive detection of Listeria monocytogenes using an impedance immunosensor based on magnetic nanoparticles, a microfluidic chip, and an interdigitated microelectrode. Journal of food protection 2012;75 11:1951-9.
103. Liu Y, Wang J, Zhao C, et al. A multicolorimetric assay for rapid detection of Listeria monocytogenes based on the etching of gold nanorods. Analytica chimica acta 2019;1048:154-160.
104. Lee BE, Kang T, Jenkins D, et al. A single-walled carbon nanotubes-based electrochemical impedance immunosensor for on-site detection of Listeria monocytogenes. Journal of food science 2021.

105. Donoso W, Castro RI, Guzmán L, et al. Fast detection of Listeria monocytogenes through a nanohybrid quantum dot complex. Analytical and Bioanalytical Chemistry 2017;409:5359-5371.
106. Fu Z, Zhou X, Xing D. Sensitive colorimetric detection of Listeria monocytogenes based on isothermal gene amplification and unmodified gold nanoparticles. Methods 2013;64 3:260-6.
107. Yang Y, Xu F, Xu H, et al. Magnetic nano-beads based separation combined with propidium monoazide treatment and multiplex PCR assay for simultaneous detection of viable Salmonella Typhimurium, Escherichia coli O157:H7 and Listeria monocytogenes in food products. Food microbiology 2013;34 2:418-24.
108. Blanco AF, Pérez MH, Trigos YM, García-Hernández J. Development of Optical Label-Free Biosensor Method in Detection of Listeria monocytogenes from Food. Sensors (Basel, Switzerland) 2023;23.
109. Ohk SH, Bhunia AK. Multiplex fiber optic biosensor for detection of Listeria monocytogenes, Escherichia coli O157:H7 and Salmonella enterica from ready-to-eat meat samples. Food microbiology 2013;33 2:166-71.
110. Zhou C, Mo R, Chen Z-M, et al. Quantitative Label-Free Listeria Analysis Based On Aptamer Modified Nanoporous Sensor. ACS Sensors 2016;1:965-969.
111. Norman RS, Stone JW, Gole A, et al. Targeted photothermal lysis of the pathogenic bacteria, Pseudomonas aeruginosa, with gold nanorods. Nano letters 2008;8:302-306.
112. Hu J, Fu K, Bohn PW. Whole-cell Pseudomonas aeruginosa localized surface plasmon resonance aptasensor. Analytical chemistry 2018;90:2326-2332.
113. Jessberger N, Dietrich R, Granum PE, Märtlbauer E. The Bacillus cereus food infection as multifactorial process. Toxins 2020;12:701.
114. Zheng H, Sheng R, Li H, Chen Q. Rapid and selective detection of Bacillus cereus in food using cDNA-based up-conversion fluorescence spectrum copy and aptamer modified magnetic separation. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 2022;267:120618.
115. Rizzotto F, Marin M, Péchoux C, et al. Colorimetric aptasensor for detection of Bacillus cytotoxicus spores in milk and ready-to-use food. Heliyon 2023.
116. Song Y, Chen M, Yan Z, et al. A Novel Nanoplatform Based on Biofunctionalized MNPs@ UCNPs for Sensitive and Rapid Detection of Shigella. Chemosensors 2023;11:309.
117. Wu S, Duan N, He C, et al. Surface-enhanced Raman spectroscopic–based aptasensor for Shigella sonnei using a dual-functional metal complex-ligated gold nanoparticles dimer. Colloids and Surfaces B: Biointerfaces 2020;190:110940.
118. Yuan J, Wu S, Duan N, et al. A sensitive gold nanoparticle-based colorimetric aptasensor for Staphylococcus aureus. Talanta 2014;127:163-168.
119. Pebdeni AB, Hosseini M, Ganjali MR. Fluorescent turn-on aptasensor of Staphylococcus aureus based on the FRET between green carbon quantum dot and gold nanoparticle. Food Analytical Methods 2020;13:2070-2079.
120. Tan F, Leung PH, Liu Z-b, et al. A PDMS microfluidic impedance immunosensor for E. coli O157: H7 and Staphylococcus aureus detection via antibody-immobilized nanoporous membrane. Sensors and Actuators B: Chemical 2011;159:328-335.
121. Sung YJ, Suk H-J, Sung HY, et al. Novel antibody/gold nanoparticle/magnetic nanoparticle nanocomposites for immunomagnetic separation and rapid colorimetric detection of Staphylococcus aureus in milk. Biosensors and Bioelectronics 2013;43:432-439.
122. Huang Z, Yu X, Yang Q, et al. Aptasensors for Staphylococcus aureus risk assessment in food. Frontiers in Microbiology 2021;12:714265.
123. Tao X, Liao Z, Zhang Y, et al. Aptamer-quantum dots and teicoplanin-gold nanoparticles constructed FRET sensor for sensitive detection of Staphylococcus aureus. Chinese Chemical Letters 2020.
124. Eissa S, Zourob MM. A dual electrochemical/colorimetric magnetic nanoparticle/peptide-based platform for the detection of Staphylococcus aureus. The Analyst 2020.
125. Ouyang Q, Wang L, Ahmad W, et al. Upconversion Nanoprobes Based on a Horseradish Peroxidase-Regulated Dual-Mode Strategy for the Ultrasensitive Detection of Staphylococcus aureus in Meat. Journal of agricultural and food chemistry 2021.
126. Kaittanis C, Santra S, Perez JM. Emerging nanotechnology-based strategies for the identification of microbial pathogenesis. Advanced drug delivery reviews 2010;62:408-423.
127. Zhao X, Hilliard LR, Mechery SJ, et al. A rapid bioassay for single bacterial cell quantitation using bioconjugated nanoparticles. Proceedings of the National Academy of Sciences 2004;101:15027-15032.

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128. Minke WE, Roach C, Hol WG, Verlinde CL. Structure-based exploration of the ganglioside GM1 binding sites of Escherichia coli heat-labile enterotoxin and cholera toxin for the discovery of receptor antagonists. Biochemistry 1999;38:5684-5692.
129. Schofield CL, Field RA, Russell DA. Glyconanoparticles for the colorimetric detection of cholera toxin. Analytical chemistry 2007;79:1356-1361.
130. Inbaraj BS, Chen B. Nanomaterial-based sensors for detection of foodborne bacterial pathogens and toxins as well as pork adulteration in meat products. journal of food and drug analysis 2016;24:15-28.
131. Yang M, Kostov Y, Bruck HA, Rasooly A. Gold nanoparticle-based enhanced chemiluminescence immunosensor for detection of Staphylococcal Enterotoxin B (SEB) in food. International journal of food microbiology 2009;133:265-271.
132. Yang M, Kostov Y, Rasooly A. Carbon nanotubes based optical immunodetection of Staphylococcal Enterotoxin B (SEB) in food. International journal of food microbiology 2008;127:78-83.
133. Yang M, Kostov Y, Bruck HA, Rasooly A. Carbon nanotubes with enhanced chemiluminescence immunoassay for CCD-based detection of Staphylococcal enterotoxin B in food. Analytical chemistry 2008;80:8532-8537.
134. Chien YY, Jan MD, Adak AK, et al. Globotriose-functionalized gold nanoparticles as multivalent probes for Shiga-like toxin. ChemBioChem 2008;9:1100-1109.
135. Nagy JO, Zhang Y, Yi W, et al. Glycopolydiacetylene nanoparticles as a chromatic biosensor to detect Shiga-like toxin producing Escherichia coli O157: H7. Bioorganic & medicinal chemistry letters 2008;18:700-703.
136. Jung S, Kara LB, Nie Z, et al. Is Additive Manufacturing an Environmentally and Economically Preferred Alternative for Mass Production? Environmental Science & Technology 2023;57:6373 - 6386.
137. Vermeulen A, Lopes P, Devlieghere F, et al. Optimized Packaging and Storage Strategies to Improve Immunosensors' Shelf-Life. IEEE Sensors Journal 2024;24:13122-13128.
138. Bowman DM, Gatof J. Reviewing the regulatory barriers for nanomedicine: global questions and challenges. Nanomedicine 2015;10 21:3275-86.
139. Zikulnig J, Chang S, Bito J, et al. Printed Electronics Technologies for Additive Manufacturing of Hybrid Electronic Sensor Systems. Advanced Sensor Research 2023;2.

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Highlights

1. Nanotechnology enhances food safety and shelf life by detecting and monitoring microbial contamination.

2. Nano sensors can detect pathogens like *E. coli* and *Salmonella* with exceptional sensitivity.

3. Nano sensors are categorized as physical, chemical, or biological, each serving specific detection purposes.

4. Various nanomaterials and manufacturing techniques enable the creation of highly sensitive nano sensors.

5. Nano sensors play a crucial role in detecting various foodborne pathogens with exceptional sensitivity and specificity.

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Declaration of interests

☒ 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.

☐ The author is an Editorial Board Member/Editor-in-Chief/Associate Editor/Guest Editor for *[Journal name]* and was not involved in the editorial review or the decision to publish this article.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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