

# An Overview of the Relationships between the Food Industry and Nanotechnology

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## Abstract

**Background and Objective:** Due to the growth of the global population, food demands are increasing. Hence, the need to develop more efficient methods for producing better quality, safer, and more sustainable food seems essential. In the past decades, the use of nanoscale materials has increased greatly due to the unique chemical, physical, and biological characteristics of nanomaterials compared to bulk materials. This research presents nanotechnology role in improving sensorial properties (taste, appearance, and texture) and safety aspects as well as processing and packaging of foods. The use of nano-omics-based technologies and artificial intelligence-nanotechnology-based technologies in the food industry is also discussed.

**Results and Conclusion:** Linking food science and nanotechnology as a multidisciplinary scientific field can help safeguard food security, production, processing, storage, and quality control. Although nanotechnology has addressed the challenges in different sectors of food biotechnology, there are still various problems and opportunities to improve the current conditions as well as the complications and health risks caused by nanotechnology.

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## 1. Introduction

The food industry needs innovative and advanced technologies to improve safety and quality programs while developing fresh, genuine, and tasty food products. Nanotechnology is a powerful technology that provides the potential for fundamental advances in essential fields such as medicine, agriculture, and food systems. Nanotechnology is used to address various food issues by developing nano-filters, nano-biocatalysts, nanotechnology-derived food ingredients, nanocomposite films, edible coatings, nano-sensors, nano-tracers, and nano-delivery systems to improve

food processing, manufacturing, packaging, pathogen detection, monitoring, safety, security, and quality [1–3]. Protecting humans against pathogens in water, foods, and the environment and helping to maintain food security are issues that can be achieved through innovations in nanotechnology. Studies show that nanotechnology outperforms traditional food processing methods by extending the shelf life of food products, decreasing the risk of contamination and enhancing the overall quality of foods. The use of nanotechnology within food industries has



resulted in the generation of larger volumes of sustainable, safer, and healthier food products for human consumption, addressing the escalating demands of a burgeoning global population. Nanotechnology is expected to revolutionize the entire food industry, changing the methods of production, processing, packaging, transportation, and consumption. Foods undergo numerous transformations after harvesting and processing that may affect their biological and biochemical characteristics. Innovations in nanotechnology have the potential to help in this area [4, 5]. This review intends to provide an update on the possible uses and impacts of nanotechnology in food systems. It emphasizes the characteristics of food nanotechnology, as well as its current and emerging uses within the field of food science. In the following, the present review discusses the potential applications of nanotechnology in improving strategies related to the processing, packaging, as well as sensorial and nutritional quality of food. The use of nano-omics-based technologies and artificial intelligence (AI)-nanotechnology in the food industry has also been discussed.

## 2. Results and Discussion

### 2.1. Nanotechnology in food processing and production

#### 2.1.1. Nanofiltration technology

Nanofiltration is an emerging membrane technology with unique advantages in the separation of molecules based on size and charge. The pore size of nanofiltration membranes is typically between 0.1 and 1 nanometer, making them ideal for the separation of small solutes and larger ions [6]. Unlike reverse osmosis, nanofiltration allows salts and small molecules to pass through, providing a selective filtration mechanism. The food industry has recognized the potential of nanofiltration as it addresses a number of processing challenges while improving product quality, reducing waste and improving sustainability.

Nanofiltration as a pressure-driven process is similar to reverse osmosis but at lower pressures (5–40 bar), allowing selective permeability based on molecular weight cut-off and solute charge. Nanofiltration membranes, which are made from polymeric or ceramic materials, are defined by their pore size, charge characteristics and composition [7].

Key filtration mechanisms include size exclusion; by which, molecules larger than the pore size of the membrane are retained while smaller molecules pass through; Donnan exclusion, which enables separation of salts and charged molecules by repelling or attracting charged solutes; and solution diffusion; in which, solutes dissolve in the membrane and diffuse through under pressure. Due to its versatility, nanofiltration is used in various processes in the food industry, e.g., for demineralization, concentration and fractionation of food ingredients [8].

However, the most important approaches in nanofiltration include [7] a) Donnan exclusion, which distinguishes charged molecules based on their ionic characteristics, b) solution diffusion, which depends on the solubility of the solutes and their diffusion through the membrane under pressure, c) hydrophilic and hydrophobic interactions; by which, customized membrane materials improve separation performance and d) hybrid systems including integration of nanofiltration with additional technologies (e.g. ultrafiltration) to improve selectivity and throughput.

#### 2.1.2. Applications of nanofiltration in the food industry

The food industry has utilized nanofiltration for various intentions, focusing on improving product quality, increasing production efficiency, and promoting sustainability. The major applications of nanofiltration in various food sectors are as follows.

##### 2.1.2.1. Dairy industry

One of the most important uses of nanofiltration in the food industry is the processing of dairy products; where it is used for various purposes [8]. Nanofiltration plays a key role in whey protein concentration, a valuable byproduct of cheese production by removing water and solutes with low molecular weights (LMW) such as lactose and salts while leaving larger protein molecules behind [9]. This process leads to the production of whey protein concentrate, which is widely used in sports nutrition and food fortification. Nanofiltration is also used to reduce lactose through partial demineralization [9]. This selectively removes the lactose while retaining the protein content, making it an effective technique for the production of dairy products that are lactose-free or low-lactose, designed for lactose-intolerant consumers [10]. In addition, nanofiltration membranes are used in the processing of skimmed milk to remove excess water and minerals. The result includes a concentrated product with a higher protein content, which is particularly beneficial in the production of high-protein milk drinks and yogurts [11].

##### 2.1.2.2. Beverage Industry industry

Nanofiltration is used extensively in the beverage industry, particularly in the processing of fruit juices and wine. In the juice industry, nanofiltration is used to clarify fruit juices by removing suspended solids, pectins, and colloidal particles while preserving essential flavors, vitamins, and minerals; thereby, improving the shelf life, quality, and sensory characteristics of the juices [12]. Additionally, nanofiltration plays a role in sugar decrease by selectively removing monosaccharides without diluting natural flavors while preserving major polyphenols and flavors [13].



### 2.1.2.3. Water treatment

Water is a critical content in almost all food-processing operations and effective treatment of the process water is essential for food manufacturing. Nanofiltration is often used for water softening and desalination, as nanofiltration membranes efficiently delete divalent ions, including calcium ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ) that contribute to water hardness [14]. This improves water quality for food processing and increases the effectiveness of CIP (cleaning-in-place) systems [15]. In addition, nanofiltration plays an essential role in wastewater treatment by separating and concentrating valuable components such as proteins and sugars from wastewater streams [15]. These components can be recycled back into the production process, decreasing water consumption, minimizing waste, and decreasing the overall environmental effects of food production.

### 2.1.2.4. Edible oil processing

Nanofiltration has shown considerable potential in the edible oil industry, particularly in refining and purification processes. One of its main applications is degumming, where nanofiltration is used to remove phospholipids and other mucilage from crude vegetable oils [16]. The result includes cleaner more stable oils with a longer shelf life and improved product quality. Nanofiltration is used to recover solvents in oil extraction processes where organic solvents are used [17]. By recovering these solvents for reuse, nanofiltration not only decreases operating costs but also contributes to further sustainable and eco-friendly methods of oil production.

### 2.1.2.5. Sugar and sweetener production

The sugar industry has adopted nanofiltration for the refining of raw sugar and the production of sweeteners such as high fructose corn syrups [18]. Nanofiltration is used to remove colorants, organic acids, and other impurities from sugar solutions to improve the purity and whiteness of the final products. In high-fructose corn syrup production, nanofiltration plays a key role in removing impurities and concentrating the fructose content, resulting in a higher-quality sweetener [18]. In addition, nanofiltration is used in the processing of molasses, helping to fractionate by separating and concentrating valuable compounds such as betaine and other nutrients, adding value to what would otherwise be a waste stream [19].

Although conventional filtration also has the aforementioned applications, it should be noted that one of the advantages of nanofiltration is its ability to selectively remove impurities while allowing some dissolved substances to pass through. First, this helps preserve important nutrients and flavors. Second, it saves energy compared to reverse osmosis as it works at a lower pressure. Third, it includes positive effects on the environment as fewer harmful chemicals are used to soften and purify water.

Fourth, it preserves heat-sensitive ingredients as it operates at lower temperatures and protects sensitive food ingredients from heat damage [17]. Overall, nanofiltration is transforming the food industry by providing a versatile and efficient method of separating, concentrating and purifying foods. Its uses range from dairy processing and juice clarification to water treatment and edible oil refining. With the increasing demand for high-quality, sustainable, and cost-effective food processing technologies, nanofiltration will play an increasingly important role in the future horizon of food production. However, overcoming the challenges associated with fouling, costs, and durability of the membranes is critical to realizing their full potential.

### 2.1.3. Nanobiocatalysts in food systems

Enzymes, also known as biocatalysts, are tools that play important roles in food processing to improve production processes. The novel method of combining biotechnology and nanotechnology to achieve desired results in bioprocessing applications is known as nanobiocatalysis. These results consist of improved enzyme properties, including activity, stability, and capacity. Nanobiocatalysts have many applications in the food industry, including production and packaging, contaminant identification, purification, and clarification [20, 21]. Advances in nanobiotechnology have greatly contributed to the improvement of enzyme technology. The use of nanotechnology in enzyme-based food processing methods can increase cost-effectiveness and improve sustainable and multifunctional materials, as well as multicompartimentalized structures. These benefits are achieved by improving the catalytic efficiency of enzymes and providing optimal enzyme uses. Enzyme-nanostructure biocatalysts have several advantages such as enhanced activity, stability, and recyclability. Studies indicate that the use of nanomaterials as biocatalyst carriers will be of great importance in the food industry in the future [20].

### 2.2. Texture and quality of food

Texture serves as a key attribute for consumers in the determination of food qualities. The sense of food texture is developed when consumers feel the food in their mouths. Hence, food texture is a key factor in determining whether consumers enjoy a particular food item. The texture of a food results from its structure or microstructure [22]. The textural characteristics of food can be classified into three groups based on the sensation mechanisms, as described previously, including visual, acoustic, and tactile characteristics. The most common examples of visual texture characteristics include smoothness, glossiness, thinness, and viscosity. The visual texture is determined by the food's appearance and light reflection [23]. The most popular texture features related to hearing are crispness and crunchiness, which are associated with the noise created



when solid food is broken down. Such texture features are closely related to the other sensory stimuli identified by mechanoreceptors. Internal skull vibration has also been shown to be important to the sensation of these texture features [24]. Among all texture properties, tactile texture is likely the most prevalent and frequently serves as the primary emphasis in the study of texture. The perception of tactile texture characteristics occurs through the direct interaction of food with the human skin, including the hands and oral surfaces [25]. Advertising, pricing, and consumption environment can affect how the consumers perceive the eating quality of foods, but sensory factors often are centered in the field of food quality. The significance of appearance, aroma, and taste has garnered considerably more focus compared to that of texture. This can stem from limited comprehensions of the physiological mechanisms underlying texture perception. This concept has emerged as a refresh word in the sensory literature. An extra concern may include that poor texture, in contrast to appearance, flavor, and odor, does not serve as a reliable indicator of spoilage. Thus, a high-quality texture is frequently linked to superior food preparation [26].

One further explanation for the comparatively limited focus on texture can include inherent complexity involved in the perception of texture. Tactile feedback from the fingers plays a significant role as it serves as a quality indicator when selecting fruits and vegetables. Use of utensils such as knives, forks and spoons to serve foods provides an additional type of tactile information. These tools serve as sources of textural details before the food is consumed [27]. In the mouth, the act of biting involves a sophisticated sequence of shearing and crushing movements, which serve to decrease the whole food into smaller fragments. Tongue and palate assume a progressively significant function during this process, skillfully manipulating and compressing the food until the textural characteristics of the bolus render it appropriate for swallowing [28]. Therefore, assessment of the texture can only be effectively carried out with the involvement of human subjects. Of the most important tools for the assessment of texture is quantitative descriptive analysis, which assesses all sensory characteristics of foods that are typically selected by the panelists during round-table discussions. A high-fructose corn syrup panel is normally trained to establish terminology specific to a product type and assigns scores reflecting the intensity of its attributes. While various forms of high-fructose corn syrup have become popular in the industry, use of trained panels can often be excessively time-consuming and costly [29]. Due to the challenges associated with sensory methods, significant efforts have been directed to use instrumental assessments to assess the physical characteristics of foods. Hence, varieties of empirical instruments have been created

for particular uses. Typically, these devices are quite straightforward, frequently portable and provide a restricted scope of semi-quantitative information.

### 2.2.1. Nanotechnology-derived food ingredients

Nanotechnology involves the manipulation of nanomaterials for various uses, significantly affecting the food and agriculture industries. This helps in enhancing crop yields, improves the quality and safety of food, and promotes human health via innovative and novel methods [30]. Nanoparticles, including silver (Ag), gold (Au), zinc oxide (ZnO), titanium dioxide (TiO<sub>2</sub>), and carbon, find uses in air filtration systems, food storage solutions, deodorizing products, medical bandages, toothpaste formulations, paints, and various household items [31, 32]. Moreover, nanoparticles are repeatedly used as food additives to safeguard against contaminations; thereby, extending the shelf life of the food products. It can serve to identify food pathogens, functioning as indices of food quality and safety. The nanomaterial is divided as organic and nonorganic-based, as well as a mixture of the two [33]. The use of inorganic nanomaterials as antimicrobial agents in food packaging is extensive. Supplying of inorganic nanoparticles can be achieved via various methods, including sol-gel techniques, mechano-chemical processing, and physical vapor synthesis, which are determined by the specific type of inorganic nanoparticles that are produced [34]. Nanostructured materials consist of microstructures formed from nanoscale components or structures, with dimensions typically ranging 1–10 nm. These materials occupy a size range that bridges the nanoscale and microscale, allowing for the development of various forms [35].

Nanostructured materials primarily comprise nanorods, nanoparticles, nanowires, and similar entities, which typically assemble into layered films, wires, and atomic configurations. Nanostructured materials are classified into three distinct classes of (i) zero-dimensional for nanoparticles, (ii) one-dimensional for nanorods or nanotubes, and (iii) two-dimensional for thin films, with three-dimensional for nanocomposites and dendrimers. These classifications are determined by the dimensions of the structural elements [35]. Food-grade ingredients are used in creating nanostructures through a straightforward layer-by-layer method and a cost-effective method. A comprehensive understanding of the biological and physical processes occurring within food systems is necessary to understand distinct physical, chemical, and biological characteristics of these nanostructures and nanoparticles [35]. Various techniques, including milling, homogenization, ultrasound emulsification, and microfluidization, are used for the generation of nanoparticles [36]. Milling is a traditional method primarily





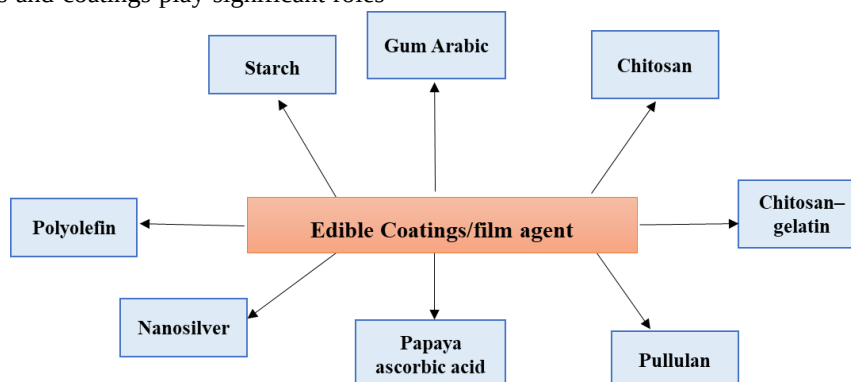
used for grinding materials to achieve flour at the nanoscale through mechanical energy. Production of fine wheat flour and green tea powder, which enhance water binding capacity and antioxidative characteristics, include important uses.

Homogenization, a long-established technique, is used to decrease fat globules in milks; thereby, stabilizing emulsions. In contrast, high-pressure homogenization is further effective in creating highly fine emulsions using significant stresses [37]. Microfluidization not only facilitates size decrease and formation of emulsions but also improves texture and mouthfeel. This technique is used in the production of various products (e.g. yoghurts, syrups, creams, malted beverages, flavored oils, icing and fillings, and salad dressings) [38]. Numerous food ingredients are included in their natural state at the nanoscale such as milk proteins and casein, and distinct from synthetic nanomaterials. A majority of proteins are globular in shape, typically ranging 10–100 nm, while polysaccharides and lipids are generally smaller than 1 nm. The most important nanostructures in food systems include nanostructured proteins, nanoemulsions, nanocomposites, and liposomes, as they enhance bioavailability, safeguard bioactive components, and facilitate controlled releases [39].

### 2.2.2. Nanocomposite films and edible coatings

Nanocomposite food packaging, characterized by its affordability and high functionality, represents a superior alternative to traditional packaging substances such as papers, glasses and metals. Polymer matrices are enhanced with nanofillers such as nano-oxides, nanoclays, cellulose microfibrils, and nanotubes based on carbon to create nanocomposites. In these materials, at least one dimension of the phase is smaller than 100 nm [38]. Natural materials (e.g. cellulose, chitosan and carrageenan) and synthetic materials (e.g. nylon, polystyrene, polyamides, and polyolefins) are used in packaging processes [41, 42]. One of the important reasons in international trade includes protection of fresh horticultural products. Thus, prolonged shipping times and extended distribution durations may increase the risk of significant losses. In this regard, bionanocomposite films and coatings play significant roles

in minimizing weight loss by serving as barriers against moisture evaporation. In addition, edible coatings can make the texture better, enhance the visual appeal of the products, and extend food shelf life by forming semi-permeable barriers that regulate gas exchanges. Edible coatings and packaging can be developed from various biological sources to enhance preservation of fruits, vegetables, and cheeses. This film effectiveness is determined by the specific materials and their natural characteristics, which can affect their barrier, microbial, mechanical, and optical characteristics [43]. Packaging needs change depending on the food type, as maturation rates, mechanical stability, and water content depend on their compositions [44]. Additionally, numerous disadvantages are linked to the use of biopolymers in food packaging. To moderate these issues, composite or multicomponent films are developed, which consist of a combination of various materials that possess beneficial characteristics. For example, nanosilver-coated fruits and vegetables maintain their activities throughout transportation and storage due to modifications in their respiration processes [45]. Studies are currently carried out on heavy-metal nanoparticles as components of edible coatings to enhance nutrient uptake and bioavailability. The development of self-cleaning nanomaterials is popular as a promising area of research, owing to the innovative self-cleaning characteristics provided by nanocomposites under specific storage conditions. By using thinner hybrid edible films with a thickness of less than 100  $\mu\text{m}$ , moisture,  $\text{CO}_2$ , water, and oxygen barrier characteristics can be enhanced, which in turn can improve the shelf life and sensory attributes of the food products [46]. Figure 1 presents a diagram that summarizes edible coating in the food industry. Nanocomposite films are emerging as an additional packaging solution, consisting of a reinforcement of the biological polymer matrix with nanocrystals that improve their strength, thermal stability, and barrier characteristics. This process remains in a nascent stage and is essential for the design and development of progressed processing technologies.



**Figure 1.** Edible coatings in the food industry.

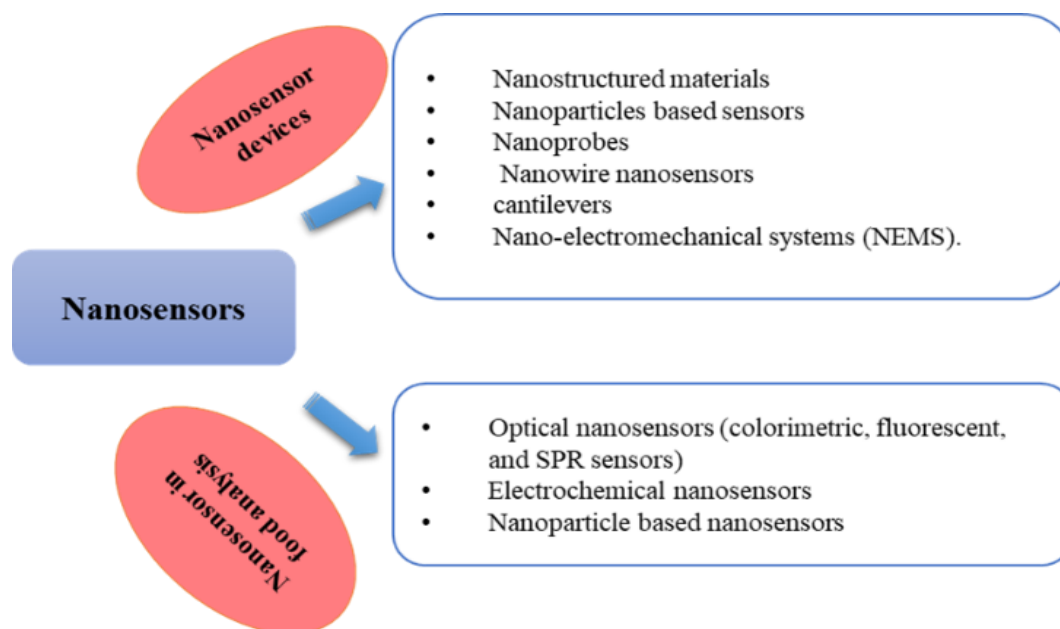


### 2.3. Food safety assessment and storage

Human health and life are directly affected by food safety, making it a major public health concern. Health risks linked to food safety are exacerbated by unhygienic conditions, incorrect storage, mishandling of foods, and contaminated food products, potentially causing several serious food-driven diseases [47]. For example, ranges of potentially harmful substances are reported that may occur in various food categories at every stage of food processing. These dangerous pollutants include heavy metals, toxic substances, pharmaceuticals, pesticides, prohibited additives, fungi, and bacteria [48]. Traditional strategies such as high-performance liquid chromatography (HPLC), mass spectrometry (MS), liquid chromatography-MS (LC-MS), gas chromatography-MS (GC-MS), and polymerase chain reaction (PCR) are well-established methods for assessing food quality, safety and detecting a wide range of chemical and biological components [49]. Despite their high sensitivity, accuracy, and stability, these methods typically involve slow and laborious processes that potentially delay the timely detection of hazards, thereby threatening consumer health. Nanotechnology, particularly nanobiosensors, has emerged as a promising solution for researchers and scientists to overcome these challenges.

#### 2.3.1. Nanosensors for food safety

Nanosensors are tools used to assess and ensure the quality of food samples, water, and other environmental factors. The use of nanomaterials and biological recognition elements by these sensors allows researchers to analyze certain biological and chemical components in foods. A sensor is a complicated system capable of reacting to a target in a qualitative or quantitative manner [50]. Nanosensors have a similar structure to conventional sensors, but their manufacture includes nanoscales. In addition to advantages such as high speed and immediate monitoring, high sensitivity, and detection of contaminants and pathogens in foods, these can be used in portable handheld devices [51]. The distribution of biosensors based on nanosensor devices and their uses in food analysis are shown in Figure 2. Nanobiosensors operate by using various methods that involve the use of nanomaterials and biological components to identify and assess specific analytes. Nanosensors can be categorized into three primary classes based on the physical phenomena used to interpret outputs of the interactions between the targets and analytes, including mechanical, electrochemical, and optical nanosensors.



**Figure 2.** The current nanosensor devices and their uses in food analysis. SPR, surface plasmon resonance.

### 2.3.1.1. Optical nanosensors

Optical sensors include extensive uses of quantum dots, gold, silver, up-conversion nanoparticles, and metal oxide-based, and organic fluorescent molecular-based nanomaterials to enhance performance. This section highlights colorimetric biosensors, fluorescent, and surface plasmon resonance (SPR) biosensors for the analysis of foods, depending on the type of signal outputs.

#### - Colorimetric biosensors for the food safety analysis

Colorimetric sensors have attracted increased attentions due to their simplicity as sensing methods, compared to various optical techniques. Using colorimetric method, color shifts can quickly be observed with the bare eyes, eliminating needs of complicated and expensive tools [52]. Major used nanomaterials are gold and silver, especially gold nanoparticles in various forms such as spheres, hollow spheres, nanorods, and nanotubes. Gold nanoparticles are extensively used in creating colorimetric assay sensors for detecting food contaminants within various nanomaterials, owing to their distinctive optical characteristics, straightforward synthesis process, excellent stability, and effortless modification [53]. Colorimetric sensors using gold nanoparticles are typically fabricated based on changes in the distance of the gold nanoparticles. Gold nanoparticles dispersed typically display a red hue, with their peak absorption wavelength approximately at 520 nm. Nevertheless, gold nanoparticles undergo polymerization, the solution color shifts to a navy blue or purple hue, indicating a surface plasmon band that transits from a visible spectrum into a near-infrared one [54].

A colorimetric approach with gold nanoparticles is used for the detection of food contaminants, including pesticide residues, heavy metals, veterinary pharmaceuticals, infectious agents, and toxins. For example, a colorimetric aptasensor for aflatoxins and ochratoxin A (OTA) detections was established, relying on the hybridization process between the capture DNA modified with amino groups and an OTA-specific amine-modified aptamer [55]. In another study, Luan and colleagues established a label-free detection method for OTA, using aptamers in addition to gold nanoparticles and the polymer poly diallyldimethylammonium chloride [56]. Colorimetric nanobiosensors based on aptamers are used for the recognition of infectious microorganisms present in food items. Yuan et al. presented an aptasensor for *Staphylococcus aureus* using gold nanoparticles [57]. Surface of the microplate for this aptasensor was altered by incorporating a biotin aptamer specific to *S. aureus* via the avidin-biotin interaction [57]. Colorimetric nanobiosensors based on antibodies are sensing methods for the identification of pathogenic agents in food products.

#### - Fluorescence biosensors for the food safety analysis

Compared to the colorimetric method, fluorescence phenomena include several advantages over subjective colorimetric methods in food detection. These offer a lower background, increased sensitivity, enhanced objectivity, lower detection limits and improved repeatability. Xu et al., [58] discovered carbonate quantum dots, the fluorescence emission characteristics of these dots have made them valuable as sensing probes for analyzing foods. Other nanomaterials without fluorescent characteristics can produce fluorescence effects for food analysis when combined with fluorescent biomolecules. Several conventional fluorescent probes include a chromophore that generates strong fluorescence when it is in a separated state; however, aggregation-caused quenching can prevent these molecules from emitting energy at a lot concentrations or when concentrated. With detection of the aggregation-induced emission effect (AIE) phenomenon, limitations of the aggregation-caused quenching have largely been overcome, and AIE can be used for high fluorescence concentrations. Detection mechanisms for AIE luminescence (e.g. AIEgens) typically encompass the following elements of interactions involving electrostatic and hydrogen bonds, alterations in the solubility of AIEgens, disruptions in the quenching of AIE luminescence, fabrications of AIE at the nanoscale, and target-induced disaggregation of AIEgens. Fluorescent nanobiosensors based on antibody and aptamer are used for the discovery of infections and chemical contaminants in food processing. To detect *Salmonella typhimurium*, Hu et al. prepared a multisignal immunoassay platform for *S. typhimurium* recognition [59]. The method uses colorimetric fluorescent magnetic nanospheres as labeling agents and two formats of quantitation. To assessment efficiency of the prepared assay, it was used for the recognition of *S. typhimurium* in samples such as milk, and tap water. Results showed that the fabricated platform was appropriate for the recognition of *S. typhimurium* [59].

#### - Surface plasmon resonance for the food safety analysis

The other optical nanosensors is SPR sensor, which is a specific optical technique that recognizes alterations in the refractive index because of the connections between ligands and molecules present on the sensor surface within a sample. The SPR technique includes advantages, compared to other conventional optical techniques. In general, SPR is composed of a light source, an optical arrangement, a sensing component, and a detection mechanism. Currently, there are four distinct types of SPR biosensor platforms, including 1) FOSPR, fiber optic surface plasmon resonance, 2) LSPR, localized surface plasmon resonance, 3) SPRI, surface plasmon resonance imaging, and 4) TSPR, transmission surface plasmon resonance. Nanoparticle-based SPR technology is extensively used for identifying contaminants in foods. Park et al. introduced an aptasensor



based on LSPR for the identification of OTA [60]. This method allowed for the quantitative detection of OTA at concentrations below 1 nM. Findings of this study demonstrated that the aptamer-functionalized gold nanorods (GNR) possessed significant efficacy, as it could be regenerated for reuses of more than seven times through heating in methanol at 70 °C to eliminate OTA. The suggested biosensor system demonstrated significant selectivity for OTA, compared to other mycotoxins [60].

### 2.3.1.2. Electrochemical nanobiosensors

One of the most commonly used techniques for ensuring food safety is the electrochemical detection approach. Because of their low cost, user-friendliness, natural sensitivity, rapid sensing capability, and ability to work with transportable systems, electrochemical biosensors are now the most swiftly expanding types of sensors. Traditional mercury-based electrodes have increasingly been substituted with modified electrodes using various appropriate nanomaterials, including biocompatible and highly conductive carbon nanomaterials, stable nanozymes with adjustable catalytic characteristics, and metal-organic frame-works known for their greater numbers of active sites and high porosity [61]. Electrochemical biosensors are categorized into three types based on the distinct conduction mechanisms of impedance, which are derived from the interactions between the target analytes and the detection elements located on the biosensor surface, including potentiometric, electrochemical, and impedance sensors [62].

#### - Antibody-based electrochemical nanobiosensors for the food safety analysis

Antibody-based biosensors are designed based on the principle of antibody-antigen interactions. Antibody-driven electrochemical systems facilitate fast and continuous monitoring of binding interactions without the necessity of extra reagents or washing/separation steps [63]. Electrochemical immunosensors are characterized by their simple construction, economical tools, low power demands, ability for mass production, quick response, high sensitivity, and adaptability for miniaturization. By miniaturizing the components and situating the signal detection elements close to the biocomponent, immunoelectrochemical sensors can convert centralized quantitative immunoassays into convenient portable biosensors [63]. In 2015, Xiang and colleagues created an electrochemical sensor for Salmonella identification [64].

#### - Aptamer-based electrochemical nanobiosensors for the food safety analysis

Nowadays, ensuring food safety is a primary concern for authorities and professionals involved in the supply chain for food products. Limitations of the current methods have resulted in the development of novel and innovative

technologies, including biosensors. Biosensor design mostly depends on the development of novel receptors with higher affinity for the targets as well as high stability. Aptamers show these traits, making them promising substitutes for the natural receptors. Aptamers refer to short sequences of nucleotides generated by the systemic evolution of ligands through exponential enrichment, capable of high-affinity binding to specific ligands [65]. In 2018, Hasan et al. suggested an electrochemical biosensor using an amino-modified aptamer for the detection of whole-cell *Salmonella* spp., which was based on an indium tin oxide electrode coated with multi-walled carbon nanotubes. This designed aptasensor was well used for the identification of *Salmonella* spp. in food products [66]. Recently, Tang et al. reviewed gold-based aptasensors for detecting kanamycin in foods [67]. Kanamycin is isolated from the *Streptomyces kanamyceticus* and predominantly used in a sulfated form as an antibiotic in medicine. Moreover, kanamycin can be condensed into the human body and transmitted in the food chain. Thus, presence of kanamycin in foods derived from animals is a potential hazard to human health.

### 2.3.2. Nanomaterials for nanosensors

Nanomaterials can be synthesized through various bottom-up techniques, including cutting, ball milling, extruding, chipping, and pounding, as well as top-down methods, leading to diverse structural types [68]. Relatively, several carbon-based nanomaterials are described for an improved understanding of the differing nature of nanomaterials. Carbon-derived nanomaterials include carbon nanotubes, nanowires, nanoparticles and fullerenes. Carbon nanotube is the most-used carbon-based nanomaterial. A major use of the carbon nanotube as a sensor is in the field-effect transistor. A broad variety of field-effect transistor are manufactured by chemical doping of carbon nanotubes [69]. Carbon nanotube field-effect transistors are used to detect various types of gases such as CO<sub>2</sub>, NH<sub>3</sub>, O<sub>2</sub>, NO<sub>2</sub>, and N<sub>2</sub>. Carbon nanotube-FETs are used for detections in biological sciences [69]. Another carbon-based nanomaterial is nanowire. Nanowires are commonly used in manufacturing nanosensors, rather than carbon nanotubes. Nanowires are produced through a variety of processes such as chemical vapor deposition, laser ablation, alternating current electrodeposition, and thermal evaporation [70]. Moreover, nanowires are used to produce gas sensors that can qualitatively detect NH<sub>3</sub>.

Nanoparticles are commonly used nanomaterials not only in sensor fabricating but also in numerous other designing uses. Nanoparticles themselves are not simple molecules and therefore consist of three layers. These layers include (a) the surface layer, which can be used to functionalize the nanoparticle; (b) the shell layer and (c) the





core, which is essentially the central portion of the nanoparticles [71]. Nanoparticles can be classified into various classes of (a) carbon-based nanoparticle, (b) metal nanoparticle, (c) ceramic nanoparticle, (d) semiconductor nanoparticle, and (e) polymer nanoparticle [72].

### 2.3.3. Antibacterial characteristics of nanoparticles for food safety

Foodborne pathogens, which include bacteria, parasites, and viruses, include the potential to contaminate food products, resulting in foodborne illnesses such as foodborne infections and intoxications. Foodborne poisoning occurs when a toxin-producing pathogen contaminates food and the resulting toxin is consumed by the people [73]. The general rate of foodborne problem causes special attentions to infectious products; therefore, numerous attempts are assigned to the creation of novel and functional agents to deal with food-pathogenic microorganisms. Packaging of food products is globally used to keep the standard of food quality and broaden the shelf life. Properly designed packaging can defend food against microbial threats and various types of environmental contaminations, whereas

inadequate packaging increases food waste and occurrence of foodborne illnesses. Nanoscience develops nanomaterials with unique physicochemical and antimicrobial characteristics in the field of the food industry [32,74]. Antimicrobial nanomaterials generally involve addition of inorganic nanoparticles with antimicrobial characteristics. Common inorganic nanoparticles used in food packaging are silver nanoparticles, renowned for its outstanding toxicity against various microorganisms, as well as low volatility and stability at high temperatures [75]. TiO<sub>2</sub> nanoparticles are other types of antimicrobial nanoparticles that have been used in food packaging. Titanium dioxide nanoparticles exhibit photocatalytic characteristics that lead to the peroxidation of polyunsaturated phospholipids within the microbial cell membranes. This characteristic has been used to inactivate various foodborne pathogens [76]. In addition to silver and TiO<sub>2</sub> nanoparticles, numerous other nanomaterials have been used by the food industry. Classification of nanomaterials with antimicrobial characteristics and their uses are summarized in Table 1.

**Table 1.** Classification of antimicrobial nanomaterials and their characteristics

| Antimicrobial nanoparticles                        | Properties & applications                                                                                                                                                                                                                                                                                                                                                                                      |
|----------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Silver-based nanomaterials                         | 1) Exceptional stability combined with significant toxicity to a wide variety of microorganisms<br>2) Death of bacterial cells through increased ROS generation                                                                                                                                                                                                                                                |
| Gold-based nanomaterials                           | 1) Easy surface functionalization and high biocompatibility<br>2) Anti-angiogenic, anti-HIV, anti-malarial, antimicrobial, and anti-arthritis properties in the field of pharmacology<br>3) Gene therapy, pharmaceutical delivery systems, diagnostic tools, and catalysts for therapeutic interventions<br>4) It may influence the enzymes of the respiratory chain, resulting in the death of microorganisms |
| Zinc and Zinc Oxide-based Nanomaterials            | 1) Superior heat resistance, enhanced selectivity, reduced cytotoxicity, and greater stability in comparison to inorganic antimicrobials<br>2) Antibacterial capabilities and work well against various bacteria                                                                                                                                                                                               |
| Titanium Dioxide (TiO <sub>2</sub> ) Nanomaterials | 1) Chemical stability, natural abundance, low cost, and good thermal stability<br>2) capability to eliminate a range of microorganisms owing to its significant oxidizing strength and the generation of free hydroxyl radicals when exposed to near-ultraviolet light                                                                                                                                         |
| Copper and Copper Oxide-Nanomaterials              | 1) Copper seems to produce its lethal impact by generating reactive hydroxyl radicals<br>2) Copper nanoparticles exhibit significant antimicrobial properties due to their elevated surface-to-volume ratio, which enhances their reactivity<br>3) CuO nanoparticles hold significant value as they represent the most fundamental member of the copper family                                                 |
| Silicon Dioxide-based Nanomaterials                | 1) Silicon dioxide nanoparticles possess various advantages including Exceptional strength, thermal resilience, significant availability, and economical pricing used in active polymer-inorganic composite materials<br>2) Biofilm containing SiO <sub>2</sub> has a broad spectrum of antimicrobial effects for both gram-positive and gram-negative pathogens                                               |



#### 2.4. Developing functional foods for health and disease conditions using nanotechnology

A functional food is defined as a food that offers additional health benefits in addition to the food's usual nutritional value. The use of nanotechnology can lead to significant advancements in human health by enhancing the delivery of nutraceuticals and bioactive compounds within functional foods [77]. The use of nanotechnology extends beyond the creation of functional foods; it is used in food processing, packaging, and swift identification of foodborne pathogens in various food products. The term "nanofood" highlights products that have been grown, manufactured, processed, and/or packaged through the use of nanotechnological methods or instruments or those that have been improved with the incorporation of nanomaterials [78]. Functional foods include a diverse range of components, nutrients, and non-nutrients that enhance human health and decrease the risks of diseases. Bioactive compounds demonstrate protective characteristics against hypertension, cardiovascular diseases (CVD), and various cancers [79]. Despite this, there are some challenges that the functional food industry faces in optimizing the activity of bioactive compounds, including the stability of bioactive compounds, limited solubility in water, and low bioavailability of bioactive compounds [80]. The process of encapsulation involves enclosing active agents within a carrier substance to enhance the efficient delivery of bioactive molecules and living cells to foods. This technique is used extensively for improving the delivery of bioactive molecules and living cells to foods [81]. In this process, functional ingredients are packed in a protective coating to prevent degradation of the functional ingredients during processing, storage, and use of the ingredients [77, 82]. It must not affect the appearance, taste, flavor, texture, and shelf life of the products and materials used in the encapsulation systems, and it must be safe [79]. Various technologies are used to create nanocapsules that contain a multitude of bioactive and active ingredients; after they deliver their active ingredients, these nanocapsules are absorbed like common foods [83]. Biopolymeric nanoparticles, nanoliposomes, nanoemulsions, and nanoprecipitation are the most effective nanoencapsulation methods for creating nanoencapsulated bioactive ingredients, which enhance the stability of both chemical and physical properties, along with the bioavailability [84]. Nanotechnology has ultimately contributed to the enhancement of the safety and nutritional quality of food products by making it possible to encapsulate highly stable and highly effective antioxidants, antimicrobials, and anticancer agents [85, 86].

#### 2.5. Nutrition-based nanotechnology in food nutrient delivery

The alteration of the dimensions of manufactured materials to the nanoscale can significantly enhance the stability and solubility of the essential nutrients while facilitating their efficient and regulated transport through nanovehicles [87]. Significant increases have been reported in the use of nutraceuticals in recent years. Nutraceuticals are used for the management and prevention of various illnesses, including various cancers, skin diseases, gastrointestinal diseases, ophthalmic disorders, diabetes mellitus, obesity, and diseases linked to the central nervous system (CNS). Nutritious food supplies the essential nutrients necessary for the human body through dietary intake. However, many bioactive compounds in these nutrients show high lipophilicity and low solubility in water, which results in inadequate dissolution and oral bioavailability [88]. Thus, nutraceuticals such as curcumin, carotenoids, anthocyanins, omega-3 fatty acids, vitamins C and B12, and quercetin face challenges including low solubility, chemical instability, unpleasant taste, and undesirable odor. Furthermore, factors such as gastrointestinal membrane barriers, various pH levels, and interactions with gastrointestinal enzymes contribute to the degradation of specific nutraceuticals [89]. Nanotechnology-driven nutrient delivery systems have the potential to enhance oral bioavailability by improving the stability of nutraceuticals in food and the gastrointestinal tract, increasing their solubility in intestinal fluids, and decreasing first-pass metabolism in the gut and liver [90]. In recent years, food scientists have focused on creating innovative food products that possess improved functional characteristics. The development of nanocolloids for food uses has emerged as an effective approach for encapsulating nutrients and bioactive compounds, improving their absorption and bioavailability in the gastrointestinal tract [91]. Commonly encountered nanocolloids consist of nanoemulsions, nanomicelles, nanocapsules, and analogous structures. The growing interest in nanocapsules can be attributed to their uses in sophisticated drug delivery systems within the human body, as well as the development of liposomal-based nanocapsules that are used in food research, healthcare, and agriculture [92]. Nanocapsules provide a safeguard against degradation throughout the processing phase, facilitating the possibility of controlled and/or sustained releases of active ingredients. The application of delivery techniques involving synthetic chemicals in the field of biomedicine or pharmaceuticals may not be appropriate for the food industry, due to the critical need for safe substances. Therefore, probiotic nanoencapsulation presents a practical and safe method for the delivery of bioactive compounds in food products [93]. In recent years, the nanoencapsulation of probiotics has



been importantly highlighted, especially through the fabrication of nanofibers using electrospinning methods. The process of encapsulating probiotic strains within nanofiber mats composed of corn starch and sodium alginate has significantly improved their stability and viability, exceeding the performance of non-encapsulated cells [94]. The incorporation of nanoencapsulated probiotics in food products presents numerous benefits, including enhanced protection of the probiotics and effectiveness in their transport to the intestine [95]. However, it is important to address certain problems such as increased costs, production complexities, potential adverse effects at nanoscales, intricate regulatory needs, sustainability issues, and the possibility of instability during processing [96]. In the following, we more focus on the encapsulation of nutrients and nanoencapsulation methods.

### 2.5.1. Encapsulation of nutrients and nanoencapsulation methods

Nutraceutical foods have attracted significant attention in studies due to their effects on the prevention and management of various health conditions. However, bioactive compounds encounter various challenges such as inadequate stability, low water solubility, and limited bioavailability. Encapsulating bioactive compounds within an appropriate carrier is beneficial as it enhances their solubility in water and protects them from degradation due to ecological and biological effects [97]. Of these methods, microencapsulation includes the capacity to improve the stability and bioactivity of bioactive nutraceuticals. The particles that are encapsulated are generally classified into three categories; microcapsules (0.2–5000  $\mu\text{m}$ ), macrocapsules (larger than 5000  $\mu\text{m}$ ), and nanocapsules (smaller than 0.2  $\mu\text{m}$ ). Larger in size and possessing a decreased surface area, macro- and micro-particles may show inadequate absorption of nutrients and other encapsulated substances within the gastrointestinal tract. Moreover, larger particles demonstrate extended dissolution times, which may hinder the body ability to release and absorb nutrients before their transition through the digestive system. Additionally, these substances can aggregate, leading to an irregular distribution within the gastrointestinal tract and affecting nutrient absorption in specific regions [98]. The elevated levels of the elements of the wall within encapsulated particles may hinder the biodegradability of these particles in the gastrointestinal tract. Such hindrance can influence the release of encapsulated nutrients, thereby reducing their availability for absorption. Additionally, certain wall materials in the encapsulation process may provide resistance against digestive enzymes of the gastrointestinal tract [99]. This resistance may lead to a delayed release of the encapsulated nutrients, which can affect their absorption.

The nanoencapsulation of bioactive substances typically offers significant advantages [100]. The bioavailability of food components is greatly improved when the surface region available for their uptake increases [101]. This is especially important for flavoring agents that have a low solubility in liquids and for flavors and aromas that can be perceived at minimal concentrations [102]. Nanocarriers play a critical role in enhancing nutrient absorption by protecting these compounds during the digestive process and enabling a regulated release along the digestive tract [103]. Furthermore, the nanoencapsulation of bioactive compounds decreases undesirable connections with other constituents and provides protection against spoilage both during and after consumption [102]. The solubility of ingredients that are poorly soluble in water, like omega-3 fish oil, can be enhanced through the formation of a micelle network or by minimizing interactions with other components within the matrix [103]. This approach not only avoids discoloration but also mitigates off-flavors by covering undesirable tastes and odors. Furthermore, it facilitates the controlled release of mineral components, ensures optimal preservation during production and storage, and also improves the physical properties of the products [104]. Nanoencapsulated bioactive compounds are capable of releasing their contents in a controlled and sustained state, which further enhances their solubility and bioavailability for biological procedures. The enhanced solubility in water and regulated release of food substances when encapsulated at the nanoscale can be ascribed to particular factors [105].

### 2.6. Personalized nutrition

Nanotechnology has made significant progress in the medical sciences and allows for biological processes that were not previously possible. A nanotechnology approach is used to determine the positioning of nutrients or bioactive food components within tissues, cells, and cellular components with high accuracy. This detects nutrient and biomolecular interactions within specific tissues, as well as improves the nutritional standard quality of food, presenting numerous opportunities for a deeper understanding of the structures and functions of foods. Nanotechnology has the potential to improve nutritional assessment and measure bioavailability. In nutrition research, it may enable the identification of targets for nutrient action and biosignatures of nutrient efficacy to improve "personalized nutrition" [106]. Personalized nutrition develops tailored dietary strategies that address the unique nutritional needs of each individual; thereby, managing and potentially preventing various diseases [107]. An individual's needs are described by biological data (e.g. genetics, epigenetics, proteomics, metabolomics, microbiome, and physical descriptions), lifestyle, and health statuses [108, 109]. Omics technologies are used to capture risk variants in specific genes that can be



used to modify diseases before symptoms appear [110]. Nutrigenomics is the study of how bioactive dietary compounds affect genes involved in signaling and biological pathways of various diseases [111].

Although dietary supplements make a significant contribution to disease prevention and include biological effects such as antioxidants and anticancer effects, some dietary supplements are difficult to dissolve in water and are not readily absorbed via the oral cavity, so delivery systems are vital [112]. Food colloids science focuses on improving human health through dietary interventions, and it can be useful for developing delivery systems [113]. As a result of stable-state precision delivery mechanisms, food functional factors can be delivered accurately to different individuals, enriching them in specific cells or tissues. Furthermore, functional factors are protected during transport and released at the designated location to enhance their efficacy [106, 114]. For example, the colloidal delivery systems are designed to break down in the gastrointestinal system and release their contents there, and then the bioactives are absorbed via the epithelial cells and carried into the body by the lymphatic system [115]. Nano-delivery systems such as nanocapsules and nanosphere, can enhance the bioavailability of bioactive compounds. This bioavailability causes more nutritional absorption and subsequently results in the production of active substances. The use of nanomaterials optimizes health outcomes by delivering nutrients and bioactive compounds in the right amounts and at the right time based on the genetic profile of the individual [116].

The integration of the use of omics-based technologies and biostatistics to investigate food and nutrition interactions at the molecular level is called "foodomics" [117]. Advances in the combination of food technology, omics-based data, and nanotechnology could pave the way for the development of personalized nutrition products and reveal the important role of nano-omics-based technologies in food science.

### **2.7. Integration of artificial intelligence into nanotechnology in food science**

Nowadays, the execution of cutting-edge innovation of AI, particularly machine learning, with its advantages and disadvantages, in several scholarly and mechanical areas is well known. Food science and technology and their associated issues are no exceptions to this rule. Improving agriculture, facilitating crop classification, developing formulation and novel food and nutraceutical-associated products, more accurate sensory evaluation, industrial processing, improving food quality, ensuring the safety of food, controlling the supply chain, reusing waste, saving costs and time, and lastly estimating calorie and nutrient amounts are some achievements of the combination of food science and artificial intelligence. Consequently, the

merging of artificial intelligence with nanotechnology in the food science sector has formed a fresh domain of study and creativity called artificial intelligence -nanotechnology in food science. Consequently, artificial intelligence can play a crucial role in discoveries and innovations, resulting in the identification of novel nanomaterials that exhibit enhanced electrical, optical, and mechanical properties, along with unique functionalities suitable for various applications such as energy storage, sensing, and biomedicine. In summary, the future exploration of the challenges and opportunities linked to the integration of artificial intelligence in food science nanotechnology is worthy of investigation. Data collection related to food security and quality can help to develop suitable models and highlight the effective role of artificial intelligence in food quality assessment.

## **3. Conclusion**

Nanotechnology involves the manipulation and use of materials at small scales, where characteristics of the materials differ significantly, compared to their bulk similar materials, allowing useful alterations of their physical, chemical, mechanical, electrical and biological attributes. Hence, the field of nanotechnology as a transformative and promising platform can lead to the advancement of innovative and high-quality products in food systems. The applicability of nano-based materials in the fields of food processing, packaging, safety and the improvement of taste, appearance, texture and nutritional quality of foods is well known. Compared to traditional monitoring methods, the use of smart nanosensors helps ease operation and save costs and time at various stages of food production. Omics technologies in food science can uncover possible molecular mechanisms of food and nutrition interactions and can create promising approaches in combination with nanotechnology to improve personalized nutrition and food security. However, there are various obstacles associated with the application of nanomaterials in food biotechnology, including health effects and environmental damage that require to be overcome.

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## **5. Conflict of Interest**

The authors report no conflict of interest.

## **6. Author contributions**

All authors participated in project administration and writing of the first draft of the manuscripts, providing critical revision and editing. All authors approved the final version of the manuscript.





## 7. Ethical Code

This project was approved via  
IR.SBMU.RETECH.REC.1403.422 ethical code.

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## مروری بر ارتباط بین صنایع غذایی و فناوری نانو

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### واژگان کلیدی

- صنایع غذایی
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- فوداومیکس
- نانوومیکس
- هوش مصنوعی

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### چکیده

**سابقه و هدف:** با توجه به رشد جمعیت جهان، تقاضا برای غذا رو به افزایش است. از این رو، نیاز به روش‌های کارآمدتر برای تولید مواد غذایی با کیفیت بهتر، ایمن تر و پایدارتر ضروری به نظر می‌رسد. در دهه‌های گذشته، استفاده از مواد در مقیاس نانو به دلیل خواص شیمیایی، فیزیکی و بیولوژیکی منحصر به فرد نانومواد در مقایسه با مواد با ابعاد بزرگ افزایش زیادی یافته است. این مقاله نقش فناوری نانو را در بهبود خواص حسی (طعم، ظاهر، بافت)، جنبه ایمنی، و همچنین فراوری و بسته‌بندی مواد غذایی ارائه می‌کند. کاربرد فناوری‌های مبتنی بر نانوومیکس و هوش مصنوعی-فناوری نانو در صنایع غذایی نیز مورد بحث قرار می‌گیرد.

**یافته‌ها و نتیجه‌گیری:** پیوند علم مواد غذایی و نانو تکنولوژی به عنوان یک حوزه علمی چند رشته‌ای می‌تواند به حفظ امنیت غذایی، تولید، فراوری، ذخیره‌سازی و کنترل کیفیت غذا کمک کند. اگرچه فناوری نانو چالش‌های موجود در بخش‌های گوناگون‌تر فناوری مواد غذایی را برطرف کرده است، اما هنوز مشکلات و فرصت‌های زیادی برای بهبود شرایط کنونی و همچنین عوارض و خطرات بهداشتی ناشی از فناوری نانو وجود دارد که نیاز به مطالعه دارد.