Nanomaterials and their Diverse Applications in Food Industry: A Comprehensive Review

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Abstract - *Nanotechnology presents promising opportunities for innovation and improvement across various dimensions of the food industry. While it offers numerous benefits, ensuring the safety and sustainability of nanomaterials in food applications remains paramount. Continued research efforts and regulatory measures are essential to maximize the benefits of nanotechnology while mitigating potential risks, ultimately shaping a healthier and more sustainable food future. This research paper explores the multifaceted role of nanotechnology in revolutionizing the food industry, focusing on various aspects such as production, processing, preservation, and safety. Nanotechnology offers a plethora of benefits, including advancements in food safety, quality control, and the development of novel food additives and flavors. It facilitates the creation of packaging with improved properties. Moreover, nanotechnology contributes to the development of healthier food options by enhancing nutritional quality and enables precision agriculture for enhancing plant growth and pest resistance. One of the significant applications of nanotechnology in the food sector is nanoencapsulation, which enables targeted delivery of nutrients and bioactive compounds. Nanotechnology also plays a crucial role in food packaging, offering active and intelligent packaging solutions that extend shelf life and ensure food safety. Nanosensors emerge as essential tools in the food industry for detecting contaminants, pathogens, and toxins in food products. Additionally, nanomaterials contribute to food preservation by inhibiting biofilm formation and enhancing the quality and appearance of food products. However, concerns regarding the safety of nanomaterials in food raise regulatory questions and necessitate further research to address potential health risks.*

Key words: Food Industry, Nanomaterials, Nanosensors, Nanocapsules, Food Safety, Food Packaging

1. INTRODUCTION

Nanotechnology holds significant promise in the food industry, offering advancements in food safety, quality control, and the creation of novel food additives and flavours [1]. It also facilitates the production of packaging with improved thermal and mechanical properties, enhancing food safety, and incorporating nanosensors to indicate food spoilage [2]. Moreover, nanotechnology contributes to the development of healthier food options by utilizing a variety of nanostructures with diverse properties to enhance nutritional quality [3]. A significant number of nanomaterials, out of 633 available, find application in agriculture and food sciences [4].

Nanotechnology is revolutionizing the food industry through various applications such as enhancing food quality, fortifying bioactives, and controlling the release of bioactive compounds through nanocarrier encapsulation [5]. Different nanomaterials are employed in food production and improving nutritional values, like protein nanoparticles utilized for their solubility and functional properties in food assembly [6]. Currently, key applications of nanotechnology in the food sector involve nanosensing and incorporating nanostructured food ingredients in formulations or packaging [8]. Nanodetection techniques enhance quality and safety assessment, while nanopolymers replace conventional materials in food packaging, offering improved properties [7].

The advancement of nanotechnology enables the creation of functional foods with targeted nutrient delivery and distribution [8]. The development of nanocapsules, carriers, sensors, and packages presents new opportunities for enhancing food products [9]. However, it is crucial to address toxicity and health concerns associated with nanoparticles in food, necessitating a concise overview from a regulatory standpoint [9]. This review highlights recent advancements in nanobiotechnology for enhancing food safety and quality, with attention to potential health risks associated with nanoparticle consumption in food.

2. DIFFERENT ASPECTS AND ROLES OF NANOTECHNOLOGY IN THE FOOD INDUSTRY

Nanotechnology is gaining traction in the food industry with diverse applications spanning production, processing, and preservation. Nanoencapsulation facilitates targeted delivery of nutrients and bioactive compounds, biosensors aid in pathogen detection, and edible films extend fruit and vegetable shelf life [10]. Precision agriculture benefits from nanotechnology in enhancing plant growth and pest resistance, as well as in the slow, controlled release of fertilizers and agrochemicals [11]. In food processing, nanotechnology offers controlled release and improved dispersibility of ingredients and supplements, enhancing flavors, textures, and nutritional values [12].

Revolutionizing the food industry, nanotechnology designs innovative delivery systems for nano-formulated agrochemicals, improving nutritional values and generating novel products through bioactive encapsulation [13]. Nanoencapsulation enhances product nutritional values and improves aroma, texture, and taste at the nanoscale, with nanoparticles providing efficient encapsulation and release of food ingredients [14]. Various nanomaterials like liposomes and nano-emulsions improve nutrient delivery efficiency and bioavailability [15]. Nanocochleates efficiently deliver nutrients without altering food properties, while dilated micelles serve as vehicles for targeted delivery of nutraceuticals [16].

Industrial applications of food nanotechnology range from intelligent packaging to interactive food creation, with active packaging enhancing sensory quality and safety, and nanomaterials like titanium dioxide and silver nanoparticles exhibiting antimicrobial properties [17]. Nanosensors detect and eliminate contaminants in food, contributing to food safety [18]. Overall, nanotechnology applications in the food industry drive innovation across various dimensions, including texture, taste, sensory attributes, colour, and product stability [19].

2.1. Nanomaterial as Food Additives and Food Ingredients

Essentially, the digestion of ingested food components, including carbohydrates, proteins, and lipids, occurs at the nanoscale [20]. Consequently, processing food at the nanoscale could potentially enhance the efficiency and speed of digestion, as well as the bioavailability, metabolism, and absorption of nutrients in the human body [21]. In the food market, there are supplements available containing tri- and di-peptides, which are more readily digestible. However, processing substances at the nanoscale may also alter their properties, raising regulatory questions regarding these modifications [22]. Further research is needed to address this important issue.

2.2. Nanomaterial in Food Processing

Some food ingredients functioning at the nanoscale or classified as nanostructured possess unique properties that enhance attributes like texture, consistency, and taste [23].Various food nanotechnologies have been employed to extend shelf life. Presently, nanocarriers serve as delivery structures for diverse food flavors without altering the morphology. Particle sizes can significantly impact the delivery of bioactive compounds to various sites within the body; for instance, submicron particles may specifically operate on the nanoscale [24]. An ideal delivery system should possess the following characteristics:

- Precise delivery of active material to the target site.
- Ensuring availability at the target time and rate.
- Efficient preservation of active compounds at appropriate levels for extended periods (storage stability).

Nanotechnology facilitates the development of emulsions, encapsulations, simple solutions, colloid association, biopolymer matrices, and efficient delivery systems with the aforementioned capabilities [25].

Nanoparticles offer superior properties such as enhanced release efficiency and encapsulation compared to traditional methods. Nanoencapsulation effectively addresses taste and odor control issues of potent ingredients within the food matrix, ensures the release of active compounds at the desired time, and protects against various sources of contamination like heat, moisture, and biological or chemical degradation during storage, processing, and utilization [26]. These nanoparticles also demonstrate compatibility with other compounds in the system [27]. Additionally, their small size enables efficient tissue penetration, facilitating the targeted delivery of active compounds to specific sites in the body [28]. Various synthetic and natural polymer-based encapsulation delivery systems have been developed to improve bioavailability and preserve the active components of food. The significance of nanotechnology in food processing is evident from its role in enhancing food products [29].

2.3. Improving the Texture, Appearance, Taste and Nutritional Values through Nanomaterials

Nanotechnology offers significant potential for enhancing the value and taste of food products. Nanoencapsulation techniques are widely employed to achieve controlled release of flavors while maintaining culinary balance [30]. For instance, nanoencapsulation stabilizes reactive plant pigments like anthocyanins, improving their photostability and thermal stability, as demonstrated with cyanidin-3-O-glucoside encapsulated in recombinant soybean kernel H-2 subunit ferritin (rH-2) [31]. Rutin, a flavonoid with pharmacological benefits, faces solubility challenges in food applications, which nanoencapsulation with ferritin nanocages addresses by enhancing its thermal and UV radiation stability [31]. Nano-emulsions are commonly used to encapsulate lipid-soluble bioactive compounds, improving their bioavailability and water dispersion [32].

Many bioactive compounds, such as carbohydrates, lipids, vitamins, and proteins, are susceptible to degradation in acidic environments and enzymatic actions in the digestive tract. Encapsulation of these compounds allows them to withstand such conditions and integrate seamlessly into food products, enhancing their delivery and effectiveness [33]. Edible capsules coated with nanoparticles are increasingly utilized to deliver vitamins, fragile micronutrients, and medications, offering health benefits when incorporated into daily foods [34].

2.4. Food Packaging and Nanomaterials

Packaging is a cornerstone of the modern food industry, vital for preserving food quality from production to consumption [35]. Nanotechnology introduces promising advancements in food packaging, enhancing package efficiency and performance. Numerous nanoparticles are harnessed for their ability to encapsulate active compounds and improve functionality, stability, and bioavailability [36]. Nanofillers find application in food packaging for their versatile functions and benefits, offering protection from environmental factors and integrating properties that open up numerous opportunities in the food packaging industry, particularly in biosensor applications [37].

Zinc oxide, a nanocomposite material, plays a crucial role in active food packaging due to its antioxidant properties, essential for combating oxidation, a key degradation reaction in food preservation [38]. Nanoparticles are not only utilized in antimicrobial food packaging but also in nanocomposites and nanolaminates, providing protection against extreme temperatures and mechanical stress, thus extending shelf life [39]. Incorporating nanoparticles into food packaging enhances both shelf life and food quality.

Smart food packaging encompasses active and intelligent packaging. Active packaging extends shelf life and enhances food quality, while bioactive packaging promotes consumer health through beneficial food products [40]. Nanoparticles with antimicrobial properties, such as metal nanoparticles like silver, are integrated into polymer films to create antimicrobial active packaging, enhancing food safety [41]. Nanotechnology finds extensive commercial applications in food packaging, improving properties like flexibility and gas barrier capabilities [42]. Active packaging utilizes nanoparticles with antimicrobial and oxygen scavenging properties, alongside smart packaging incorporating nanosensors for detecting microbial and biochemical changes in food, providing timely signals [43].

Nanotechnology revolutionizes the packaging of various food items, offering novel nanopackages with unique properties, such as antimicrobial capabilities that effectively combat microbes in food substances [44]. Nanomaterials utilized in food packaging enhance the longevity of food products without altering their essential characteristics [45]. Nanoparticles play a vital role in nanopackaging food substances, enabling modifications in foil penetration activities, enhancing mechanical, chemical, and microbial barrier effects, and increasing resistance to heat [46].

Nanotechnology contributes to reducing environmental pollution through the development of biodegradable packaging materials. Nanostructures like silicate layers find application in food packaging, enhancing sensor technology in smart packaging systems to provide real-time information on food quality, safety, and shelf life [47]. Nanocomposites are also utilized in food packaging, offering improved thermal stress resistance during food processing, transportation, and storage. Currently, nanocomposites are enhancing the shelf life of beer bottles by up to 6 months. Carbon-based graphene nanoplates exhibit heat resistance and hold promise for food packaging applications [48].

Researchers employ sonochemical coating, a versatile and straightforward technique utilizing ultrasonication, to create coating materials that demonstrate efficacy against various bacterial strains, including Gram-positive E. coli and Gram-negative S. aureus bacteria, thereby extending food preservation duration [49]. Silver nanoparticles are pivotal in material packaging, providing long-lasting antimicrobial properties and preventing contamination. While several methods incorporating silver nanoparticles have demonstrated efficacy in food packaging and preservation, only a select few are certified by the EFSA (European Food Safety Authority) for use in food preservation and packaging [50]. Zinc oxide, certified as a safe material by the FDA and deemed a food additive, serves everyday applications [51].

Nanotechnology yields various antimicrobial agents with unique properties such as zinc oxide, magnesium oxide, nickel oxide, and silver nanoparticles. These nanoparticles exhibit antimicrobial properties at the nanoscale and are incorporated into polymer matrices to impart antimicrobial activity and enhance packaging properties [52].

2.5. Nanomaterials as Food Preservative

Nanoparticles play a significant role in food preservation, offering various benefits such as antimicrobial activity and enhancing product appearance, function, and nutritional quality. For instance, zinc oxide nanoparticles exhibit antimicrobial properties that aid in food preservation. Nanotechnology contributes to maintaining food quality and prolonging shelf life by encapsulating bioactive components to prevent degradation until consumption. Additionally, metallic nanoparticles like silver have antimicrobial properties and are used in preserving food products. Titanium dioxide nanoparticles enhance the white colour of dairy products like milk and cheese [53]. Edible nano-coatings with nanoparticles act as barriers to gas exchange and provide functionalities such as flavour enhancement, colour retention, and antioxidant properties, thereby extending the shelf life of food products. Encapsulation of nanoparticles alters interfacial layer properties, reducing degradation processes and enhancing food preservation [54].

3. NANOSENSORS AS EMERGING DEVICES IN THE FOOD INDUSTRY

Nanosensors, bioanalytical devices constructed using various nanostructured materials and biological receptors, play a pivotal role in the food industry and have garnered significant attention due to their rapid detection capabilities, reliability, and cost-effectiveness [55]. These sensors boast high sensitivity and specificity, enabling integration with a wide array of analytes. Their superior surface-to-volume ratio and exceptional optical and electrical properties stem from their association with diverse nanomaterials such as carbon nanotubes, metallic and non-metallic nanoparticles, metal oxides, semiconductor nanoparticles, nanorods, nanowires, nanobiofilms, nanofibers, and quantum dots [56].

Presently, nanosensors find application in detecting food borne pathogens, adulterants, toxins, chemicals, and pesticides present in various food products [57]. They are also utilized to monitor food freshness and packaging integrity [44]. Employing techniques like cyclic voltammetry, surface plasmon resonance, differential pulse voltammetry, interdigitated array microelectrode-based impedance analysis, amperometry, flow injection analysis, and bioluminescence, nanobiosensing tools facilitate rapid and precise detection of pathogens, toxins, and adulterants in food [58].

3.1 Nanosensors and Detection of Toxins

Microfluidic sensors, a type of nanosensor leveraging microfluidics and liposomes, offer advantages in detecting toxic substances in aqueous samples, even within the microliter range [59]. Electrochemical sensors and biosensors based on novel nanomaterials like carbon nanotubes (single and multi-walled), metallic nanoparticles (silver, gold, platinum, copper, and zinc), and superparamagnetic nanoparticles are utilized for detecting various toxins in food [57]. Aflatoxins, toxic and carcinogenic compounds found in food contaminated with Aspergillus flavus and Aspergillus parasiticus, are detected using gold nanoparticles functionalized with anti-aflatoxin antibodies [60]. Superparamagnetic beads containing anti-aflatoxin M1 antibodies and gold nanoprobes are also employed for aflatoxin M1 detection in milk samples [61]. Similarly, gold nanoparticles serve as nanoprobes in enzyme-linked immunosorbent and immune-chromatographic assays for detecting botulinum neurotoxin type B and brevetoxins in processed foods [62]. Carbon nanotube-based electrochemiluminescent sensors detect marine toxin palytoxin in contaminated seafood [63].

3.2 Nanosensors and Detection of Food Pathogens

Detecting foodborne pathogens traditionally involves identifying bacterial genetic material or whole bacterial cells, a reliable yet complicated process [64]. Nanotechnology introduces low-cost nanosensors in food packaging to detect various pathogenic microorganisms [65]. The nanobioluminescent spray, a highly effective nanobiosensor, utilizes magnetic nanoparticles to produce a visual glow for easy detection of pathogen strains in food products [66]. Magnetic iron oxide nanoparticles are utilized to isolate DNA from milk pathogenic bacterium Listeria monocytogenes [67]. Various nanosensors incorporating different nanomaterials are documented for detecting pathogenic bacteria in both standard bacterial cultures and complex food samples.

Surface-enhanced Raman spectroscopy, coupled with silver nanosensors, stands out as an efficient technique for pathogenic bacteria detection [68]. Additionally, nanosensors integrated with nanorods, nanocolloids, graphene oxide, carbon nanotubes, plasmonic gold, and magnetic beads are routinely used for this purpose [69]. An array-based immunosorbent assay, coupled with liposomal nanovesicles, demonstrates efficacy and specificity in detecting E. coli, L. monocytogenes, and Salmonella spp. [70]. Furthermore, silicon-based nanosensors coupled with proteins vibrating at different frequencies according to their biomass are employed for pathogen detection in various liquid food systems [71]. Recent advancements include nanoparticle-based detection platforms like lateral-flow immune test strips with palladium nanoparticles against Klebsiella and field-effect transistors with graphene-based nanoparticles against E. coli [72].

3.3 Nanosensors and Sensing of Chemicals and Pesticides in Food

Various nanosensors composed of different nanomaterials play a crucial role in detecting pesticides, fertilizers, and other harmful chemicals in food products. For instance, colorimetric and fluorometric nanosensors utilizing gold nanoparticles have been developed for detecting organophosphorus and carbamate pesticides [73]. Core-shell quantum dots comprising cadmium selenide and zinc sulfide are investigated for paraoxon sensing [74]. Potentiometric sensors based on silica nanocomposites and multi-walled carbon nanotubes are utilized for detecting toxic cadmium ions [75]. Additionally, voltametric nanosensors, including nanocomposite biofilms (gold/zirconium dioxide) and fluorescent nanosensors conjugated with gold nanoparticles, are developed for detecting parathion and melamine pesticides, respectively [76].

Food dyes and preservatives can also pose toxicity risks when used in excess. Ionic-liquid nanocomposites modified with multi-walled carbon nanotubes are employed for detecting food dyes like sudan-I (a carcinogenic red dye found in chili powder, tomato ketchup, strawberry, and chili sauce), sunset yellow, and tartrazine [77]. Similarly, nanocomposites combined with zinc oxide nanoparticles and carbon nanotubes are utilized for simultaneous detection of bisphenol A (a toxic compound from plastic containers) [78].

3.4 Nanosensors and Sensing of the Quality of Key Food Ingredients

Vitamins and essential food components, such as antioxidants, play critical roles in maintaining metabolic pathways in the body, and their deficiency can lead to severe health issues like anemia, cardiovascular diseases, and carcinogenesis. However, these vital nutrients are susceptible to degradation in processed foods. To address this, various nanosensors combined with different nanomaterials have been developed. For instance, ionic liquid nanocomposites incorporating carbon nanotubes and nickel oxide nanoparticles have been utilized for detecting ascorbic acid and folic acid in fruit juices, wheat flour, and milk samples [79]. Monitoring the levels of succinic acid, citric acid, L-malic acid, fructose, D-sorbitol, sucrose, glucose, hydrogen peroxide, and L-glutamic acid in stored food products serves as an indicator of food quality [80]. Various nanosensors, in conjunction with silver, zirconium dioxide, iron, nickel-platinum, chitosan, gold, tin dioxide, prussian blue-gold, and cuprous oxide nanoparticles, have been employed to monitor the quality of these food components across different food matrices [81].

4. NANOMATERIALS AND DEVICES IN FOOD SAFETY

In the food industry, ensuring the safety of food products is paramount, with over 45% of processed and packaged food items susceptible to degradation and contamination, as indicated by a recent survey [82]. Nanotechnology has emerged as a valuable solution to address various challenges pertaining to the quality and safety of food products [83]. Presently, a variety of nanomaterials and nanodevices, including polymeric nanoparticles, liposomal nanovesicles, nanoloaded emulsions, and temperature–time indicators, are deployed to enhance food quality by extending shelf life, assessing freshness, and detecting chemical, heavy metal, and allergen contamination in food items [84].

Various nanosensors and nanotracers, coupled with diverse nanomaterials such as gold nanoparticles, silicon nanorods, magnetic beads, quantum dots, single-walled and multi-walled carbon nanotubes, immunomagnetic liposomes, and aptamer-conjugated gold and palladium nanoparticles, exhibit high efficacy in detecting contaminants and degradants that impact food quality [85]. Furthermore, the advent of the radio frequency identification (RFID) technique proves to be well-suited for various food engineering and supply chain management operations, owing to its rapidity and efficiency [86]. RFID technology also holds potential for enhancing safety and security within food corporations by enabling the tracing of contaminant sources in different food products [87]. This review briefly discusses the role of various nanomaterials and devices in ensuring food quality and safety.

4.1 Nanobarcodes: Ensuring Product Authenticity and Traceability

Globally, two-dimensional barcodes are commonly employed for visual product authentication. However, they are susceptible to alteration, forgery, and damage. To address these challenges, unique invisible barcodes based on nanoparticles and nanodisks have emerged for verifying the authenticity of various food products [88]. These nanodisk barcodes can be scanned using a Raman microscope and come in various forms, including linear gold nanodisk arrays, silver–gold heterodimer nanodisks, and silver nanodisk codes [89]. Functionalization and incorporation of metal composites can further enhance the properties of nanodisks. Fluorescent-based barcode nanorods, invisible nanobarcodes, and fluorescent DNA dendrimer nanobarcodes have also been developed for product labeling and pathogen detection in food and biological samples [90]. Consequently, nanotechnology is poised to play a crucial role in the development of efficient nanobarcode systems to ensure food quality and safety.

4.2 Shielding Against Allergens: Nanomaterial Solutions

Nanotechnology plays a crucial role in controlling and managing various food allergens [91]. Conventional adjuvants like aluminum hydroxide (alum) are associated with several side effects, including indurations, swelling, erythema, granulomas, and cutaneous nodules at the injection site [92]. In contrast, nanomaterials such as polymer or protamine-based nanoparticles containing Toll-like receptor 9 (TLR-9) ligand cytosine phosphate guanine-oligodeoxynucleotides are utilized as adjuvants and delivery systems due to their biodegradability, low toxicity, minimal dosage, reduced allergen exposure to IgE, and enhanced efficacy [156,204]. These protamine-based nanoparticle adjuvants also serve as a novel carrier system in allergen immunotherapy by counteracting Th2-type immune responses [93].

The development of aptamer-based gold nanorod and magnetic nanoparticle fluorescence assays has enabled the detection of ochratoxin A in grape juice samples (a food mycotoxin causing allergies) and allergens in various food matrices [94]. Additionally, other nanomaterials such as polyanhydride nanoparticles, quantum dots, and dendrimers have demonstrated effectiveness as oral vehicles for immunotherapy against experimental peanut allergies [95]. Moreover, newly synthesized bioinspired nanostructured materials (green synthesized) hold potential for addressing food allergen issues in the food industry due to their low toxicity and cost-effectiveness [96].

4.3 Countering Biofilm Formation: Nanotechnology Approaches

Biofilms represent a significant challenge in the food industry, comprising bacterial cells that tightly adhere together and secrete a polymeric extracellular matrix, rendering them impervious [97]. Formed through the adherence of free-floating microbes on substrate surfaces via Van der Waals forces, biofilms lead to issues such as biofouling, biocorrosion, and interference in food processing [98]. Various nanomaterials have demonstrated efficacy in controlling biofilm formation in food items. For instance, filter membranes composed of nanofibers have proven highly effective in inhibiting biofilm formation by numerous multi-drug resistant bacterial strains [99]. Additionally, the utilization of different nanoparticles including silver, nickel oxide, and zinc oxide has been extensively documented for their anti-bacterial, anti-fungal, and anti-biofilm formation properties [100].

In industrial settings, the fermentation of Bacillus subtilis yields high-value products but also hampers food processing through biofilm formation. Ranmadugala et al. evaluated the efficacy of naked and coated superparamagnetic iron oxide nanoparticles against B. subtilis [101]. Both types of iron oxide nanoparticles significantly reduced bacterial growth and biofilm formation without compromising cell viability. Likewise, gold nanoparticles conjugated with chlorhexidine effectively prevented biofilm formation by K. pneumoniae and S. aureus [102].

5. ENSURING FOOD SAFETY: ADDRESSING NANOMATERIAL RISKS

The utilization of various nanomaterials in the food industry offers numerous benefits; however, it also presents significant threats to human health, the environment, and ecosystems due to their cytotoxic effects [103]. Recent concerns have emerged regarding the use of nanomaterials, even those devoid of toxic elements, owing to their inherent potential risk stemming from their small size and subcellular interactions with cells [104]. For instance, certain nanoparticles can penetrate the skin, posing health risks to humans and animals alike. Additionally, nanoparticles have been shown to induce genomic and proteomic changes in plants, affecting their growth rate [105]. Experimental studies have demonstrated that both single and multi-walled carbon nanotubes can trigger fibrosis and oxidative stress in the lungs of model animals such as mice and rats [106].

Understanding the toxicity mechanisms of different nanomaterials to human health and the environment requires a clear delineation of the various exposure routes and entry pathways of nanomaterials from the food industry to the human body. Through intentional or accidental ingestion, several processed food items containing numerous nanomaterials are consumed via intraoral, dermal, and pulmonary pathways. Oral ingestion is the primary pathway through which chemicals, water, and nutrients are absorbed into the body. With many food items incorporating nanomaterials, the digestive organs are consistently exposed to these nanoparticles, posing potential health risks [53].

To assess nanomaterial toxicity, zebrafish serve as a model organism due to their rapid reproduction and viability, circumventing challenges associated with cell culture maintenance. Both the U.S. Food and Drug Administration (FDA) and the European Union (EU) have approved the use of zebrafish for nanomaterial toxicity evaluations [107]. Comprehensive toxicity evaluations in zebrafish show no developmental defects, mortality, or behavioral alterations caused by nanomaterial exposure. Moreover, uptake and biodistribution analyses reveal specific nanostructure localization within the body [108]. Recent studies on cytotoxicity of green synthesized zinc oxide nanoparticles, conducted in vitro and in vivo, demonstrate their biocompatibility and reduced toxicity compared to chemically synthesized counterparts [109]. Murine models are employed for biosafety and biokinetics assessments of metallic nanoparticles like gold, silver, and platinum. These studies confirm enhanced renal excretion of nanoparticles due to their small size. Additionally, full biosafety evaluations of metallic nanoparticles are conducted in zebrafish to assess whole-body toxicity [110].

Bioaccumulation of nanomaterials from nanopackaging or nanoprocessed items has been observed in food and human tissues, necessitating stringent risk assessment procedures during food processing [40]. Despite the advancements in nanotechnology, challenges persist in developing a healthy and sustainable food industry. With nanotechnology's integration into the food sector, public awareness of potential risks to human health and the environment is crucial. Several EU and non-EU countries have established regulatory frameworks to ensure the safety of nanoproducts in feed, agriculture, and food sectors [111]. Additionally, regulatory bodies like the FDA and Environmental Protection Agency (EPA) have amended criteria for marketable food products to prioritize health, quality, and safety [112].

6. CONCLUSIONS

As nanobiotechnology progresses, nanomaterial-based devices are becoming increasingly sensitive and compact. These devices play a pivotal role in the food industry, particularly in packaging, processing, and preservation. Nanomaterials contribute to prolonging the shelf life of food products by safeguarding them against moisture, gases, and lipids, while also serving as efficient vehicles for delivering bioactive compounds. Additionally, various nanomaterials and nanosensors ensure the safety and quality of food.

However, alongside these advancements come challenges. Environmental impacts and safety concerns associated with the use of nanomaterials and nanodevices in the food industry must be prioritized in research efforts. Despite these challenges, nanotechnology has initiated a revolution in the food industry, driven by advanced nanomaterials and nanodevices. With ongoing exploration, nanotechnology holds immense potential for novel applications across various sectors of the food industry. Nevertheless, it is evident that emerging security and safety issues necessitate careful consideration and proactive measures in the future.

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