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A Review of Nanotechnology Applications in Food Processing, Packaging, and Preservation

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Nanotechnology has certainly become a phenomenon that is of great significance in many regions such as the pharmaceutical, cosmetic and in particular the food sector, over the years. This is because nanotechnology overlaps with pharmaceutical sciences which involve the structural modification of materials to the nano level, increasing the dissolution rate, stability, and functionality of a variety of food safety and quality applications. The novel food supply frameworks enable firms within the food sector to emerge sustainability focused innovations, which tackle safety and nutrition deficiencies within the food industry. Narrowing down on the supply chain, this review seeks to highlight nanotechnology applications across food supply chains, stressing the importance of advancements in bioavailability, nutrition, and safety. In aid of nutrient delivery, overcoming shelf life and packaging issues – development in nanoencapsulation technology and new packaging

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materials have enhanced mechanical properties, antibacterial properties. Moreover, nanodevice-based smart packaging is considered as valuable tools for real-time monitoring of food safety and quality. Despite these benefits, degenerative concerns about nanoparticles health risks underscore the importance of sound regulatory approaches. While nanotechnology shows considerable potential for enhancing food sustainability and quality, the study ultimately finds that comprehensive regulation and increased public awareness of potential risks are necessary first steps. Continued research and global collaboration may be vital to really unlock the potential of nanotechnology in food systems while safeguarding public health.

Keywords: Nanotechnology; nanomaterials; food processing; food industry; food packaging; bioavailability.

1. INTRODUCTION

Since Richard Feynman first introduced nanoscience and nanotechnology in 1959, they have become popular subjects for research and development (Wyser et al., 2016). Nanotechnology has emerged as one of the most intriguing and alluring technologies in recent years. It has brought dynamic revolution in the world and everyone is eager to invest more into this technology. Nanotechnology is being utilized by pharmaceuticals, cosmetics, food processing and textile industries and various commercial products are also being manufactured by these industries. Nanotechnology changes materials such as atoms, molecules, particles at nanoscale range i.e. less than 100 nm which changes their physio-chemical properties eventually leading to newer applications (Berekaa, 2015).

Nanotechnology is increasingly making its way from research labs to supermarket shelves and kitchen tables, signalling a transformation in food systems (Prakash et al., 2013). From farm to fork, nanotechnology can be applied at each stage of the food supply chain (Sekhon, 2010). This review aims to explore the diverse applications of various nanoparticles in revolutionizing the food system, enhancing texture, taste, color, solubility, bioavailability, nutritional content, and shelf life, thereby providing insights into their potential for transformative advancements. Research on methods to enhance food quality with minimizing disturbance to the product's nutritional value is being driven by consumer concerns about food quality and health benefits. The food sector has expanded its need for nanoparticle-based products because many of them include critical nutrients and have been found to be non-toxic (Singh et al., 2017). In compared to big particles, nanoparticles have better chemical and biological activity, enzymatic reactivity, penetrability, catalytic behaviour and quantum characteristics due to their increased surface area and mass transfer rates (Sahoo et al., 2021). Nanotechnology-derived materials, goods, and applications are expected to boost the food and beverage industries significantly by improving the consistency, texture, taste and stability of food products and also by enhancing their bioavailability. Nanotechnology also intends to solve food-related disorders (such as diabetes and obesity), design customised nutritional diets for diverse target groups, ageing populations, and lifestyles, and ensure the sustainability of food production (Chaudhary et al., 2008).

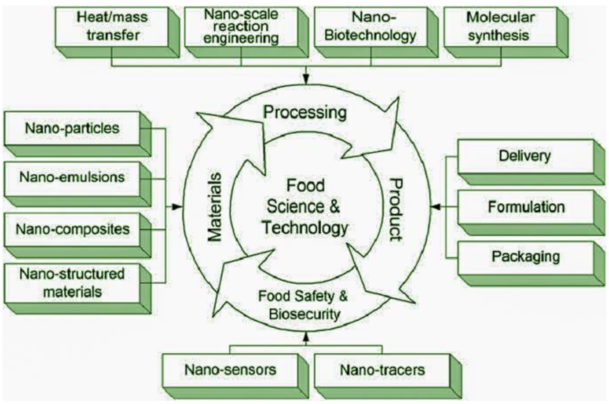

Fig. 1. Illustrating the application spectrum: nanotechnology's impact across food processing stages

Nanotechnology applications can be utilized for the characterization, fabrication, and manipulation of nanostructures and nanomaterials. Many technologies have been investigated for their development. Nanomaterials are smaller than 100 nm. They differ from their macroscale counterparts in that they have a high surface to volume ratio and unique physiochemical properties like color, solubility and thermodynamics (Zhu et al. 2012, Singh et al. 2017).

2. NANOSTRUCTURES AND NANOMATERIALS

Some foods contain nanosized elements that are distinct from synthetically created nanomaterials. There are many natural food components at nanoscale level which are safe for human consumption. They have been utilized for eating and have been safely consumed. For instance, during regular food processing protein carbohydrates, fats, etc. (present in food) undergoes structural changes on the nanoscale and micrometre scales. Milk and milk products, such as milk proteins and casein, are also natural nanostructures.

On the other hand, due to the potential benefits, several engineered nanoparticles are being developed for the food industry. A tiny quantity of nano-salt can give human taste buds the same original savory flavor because nanometer salt grains, for instance, are made to increase surface area and decrease salt consumption (Rasouli and Zhang, 2006). Numerous nanomaterials have been documented in earlier research and can be broadly classified as one-dimensional (such as nanotubes and nanorods), two-dimensional (such as thin films), three-dimensional (such as nanocomposites and nanofibers), and zero-dimensional (such as quantum dots, nanoclusters, and fullerenes) (Sharma et al., 2017).

Nanostructures with a wide range of qualities are appropriate for use in foods as well as packaging items that improve the nutritional quality of foods. Nanostructured materials are made up of nanoparticles and have at least one dimension on the nanoscale scale. A nanostructure falls between the category of nanodimension and microdimension which can be used to develop various forms (Pathakoti et al., 2017). A manufactured/engineered nanomaterial is any material that is purposefully generated at the nanoscale to have certain qualities or a specific composition. When compared to their conventional equivalents, these engineered nanomaterials offer unique properties (Sekhon BS, 2014). Nanotechnology is undeniably transforming the food industry (Shafiq et al.,2020). There are various nanostructure application in food system such as, (i) food quality improvement, (ii) bioactive compound fortification, (iii) controlled release of bioactive compounds using nanocarrier encapsulation, (iv) food structure and texture modification, and (v) detection and neutralisation of biochemical, microbiological, and chemical alterations using intelligent packaging systems (Steinvil et al., 2016). Preservatives, antibacterial sensors, flavouring agents, packaging compounds, and encapsulated food components are examples of NMs and nanoscale food additives utilized in the food processing sector.

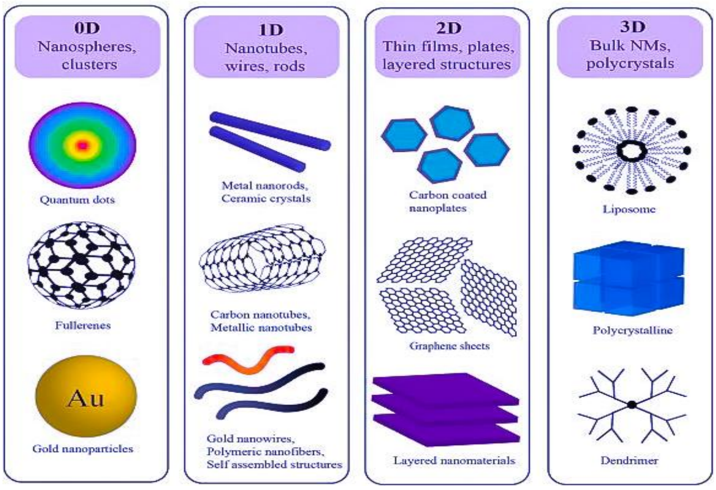

Fig. 2. Nanomaterial classification based on dimension

A key factor in increasing the bioavailability of bioactive substances is nanoencapsulation. Nanoencapsulation can also be used for protecting delicate bioactive constituents from different negativity environmental variables, incompatibilities, undesirable taste/odor, etc. Nanomaterials can provide protection for a bioactive component from oxidative, pH and enzyme degradation (Fathi et al., 2012). To summarize, the applications of nanomaterials in food provide great potential for advancing nutrition and health with a progressive path to a more sustainable and nourished future.

3. CLASSIFICATION OF NANOMATERIALS

There are three types of ENMs (engineered nanomaterials) likely to be in nanofood products, inorganic, organic and the combination of both.

3.1 Organic Nanomaterials

Organic nanomaterials are composed of lipid and polymer based nanoparticles (Yu et al., 2018). They are the most important synthetic nanostructure systems in the field of food industry. These materials help secure bioactive molecules during production and storage, enhance solubility and bioavailability, and permit controlled release (Pathakoti et al., 2017).

3.1.1 Polymeric Nanoparticles

The size ranges from tens to thousands of nanometres. They are the complex system comprising bioactive components encapsulated in a polymer or polymer blend, e.g. chitosan, alginic acid, albumin and surfactants, e.g. lecithin, tween (Sabliov and Astete, 2015). Nanoparticle synthesis can utilize a wide range of materials, such as natural polymers and synthetic types. Natural polymers are mainly of two types consisting of proteins (albumin, casein, zein and lactoglobulin) and polysaccharides (chitosan, alginic acid, carrageenan and xanthan gum). Synthetic polymers, which are frequently used to create polymeric nanoparticles like ξ-caprolactone, poly(lactic-co-glycolic acid) (PLGA), and poly(lactic acid) (PLA), are being replaced by proteins like casein, zein, and β-lactoglobulin, as well as natural polymers such alginic acid, carrageenan, xanthan gum, chitosan, and pullulan (Rahman AN, 2019). The ultimate goal is to utilize polymeric particles as potential bioactive delivery systems for the development of new high-quality food items that can prevent disease and improve consumer health.

3.1.2 Lipid-based Nanocarriers (LNs)

They can be industrially manufactured and carry the advantages of improved encapsulation efficiency and less toxic risks than polymeric nanoparticles. Among the many nanotechnology-based drug carrier systems, LNs for drug delivery are a likely contender (Badilli et al., 2018). The common preparation consists of physiological lipids that are biocompatible and biodegradable and have little acute and chronic toxicity (Jaiswal et al., 2016). Lipid-based nanocarriers are classified as liposomes, nanoemulsions, solid lipid nanoparticles, and nanostructured lipid carriers.

3.1.2.1 Liposomes

Liposomes are polymolecular structures with a spherical shape coated by a bilayer of natural or artificial surfactants or phospholipids. They are created when lipid molecules self-assemble in an aqueous fluid in which they are suspended (Celiker and Mallikarjunan, 2012). Liposomes can be made from entirely natural substances or compounds found in our bodies, making them biocompatible and suitable for human use. According to studies, liposomes can be found in the very first food consumed by humans, namely breast milk (Khorasani et al., 2018). Liposomes can incorporate other molecules in their structure, such as proteins or carbohydrates, in addition to lipid and phospholipid, to increase their stability or as a targeting approach. They have several uses in the food industry such as liposome encapsulated enzymes in dairy foods (Law and King, 1985), as a food fortifier (Ghorbanzade et al., 2017), stabilizing food components against degradation, food sensor detector (Shukla et al.2011). Liposome nanoparticles have a number of notable benefits, including low cost, ease of biocompatibility, and biodegradability (Shukla et al., 2017).

3.1.2.2 Nanoemulsions

Nanoemulsions are transparent colloidal dispersions made up of oil and aqueous phases, a cosurfactant and a surfactant with isotropic droplet diameters between 20 and 200 nm, thermodynamically unstable and kinetically stable (Borthakur et al., 2016). Because of their small size, they exhibit useful characteristics such a large surface area per unit volume, robust stability, optical transparency, and tuneable rheology (Dasgupta et al., 2019). The two types of nanoemulsions include W/O nanofluids and O/W nanofluids, characterized by a dispersed medium in water and tiny oil droplets in an aqueous medium, respectively (Liu et al., 2019). Bioactives encapsulated in nanoemulsions have enhanced solubility, controlled release in the gastrointestinal environment, and cellular absorption.

Table 1. An overview of the potential use of nanoparticles in food industry subsectors

Food sectors	Application	Nanoparticle types	References
1. Quality Control	a. Sensors for detection of chemical contaminants	• CNTs, NPs, Metal oxide nanoparticles	Chau et al. 2007,
	b. Sensors for detection of biological contaminants	• Nanowires, CNTs, QDs, NPs	Baeummer 2004; Viswanathan et al. 2006
2. Processing technology	a. Equipments coating for disinfection	• Nickel, silver, carbon nanoparticles	Basavaraja et al. 2008; Chen et al. 2008b
	b. Filtration	• Nanoclays, TiO2	Chau et al. 2007
3. Functional foods	a. Delivery systems for nutrients	• Natural food ingredients in nanoform	Bouwmeester et al. 2009
	b. Edible coating	• Natural food ingredients in the form of nanofibres or nanofilms	Avella et al. 2005
4. Packaging	a. Barrier Packaging	• Nanoclays, TiO2, acrylic NPs	Robinson and Morrison 2010; McMurray et al. 2006
	b. Antimicrobial packaging	• Ag, Zn incorporated in polymers	Nanowerk 2008.
	c. Biodegradable packaging	• Nanoclays, metal oxides in natural polymers, CNTs	Sherman 2005, Joshi et al. 2005
	d. Regulating the internal packaging environment	• Nanoporous calicium silicate, nanocrystalline titanium particles in an ethyl cellulose polymer film	Nanowerk 2008; Johnston et al. 2008
	e. Self-healing composites	• CdSe/ ZnS NPs	Chau et al. 2007
	f. Sensor technologies in packaging	• Fullerenes, TiO2, nanoporous silica	Chen et al. 2008a; Heugens et al. 2010
5. Nutraceuticals delivery	a. Delivery of nutrients and functional ingredients	• Nanocapsules, liposomal nanovesicles, nanoparticles	Wen et al. 2006; ElAmin 2006.
	b. Release of nutraceutical compounds	• Nanospheres, Nanocapsules	Chen et al. 2006

3.1.2.3 Solid lipid nanoparticles

Fundamentally lipid-based drug carriers, SLN normally has a particle size between 1 and 1000 nm. Since they are composed of physiologically safe and biodegradable/biocompatible lipids, the lipid matrix can carry therapeutic agents which are substantially a combination of hydrophilic and lipophilic drugs. The advantages of SLNs include: controlled drug release, good stability, better encapsulation efficiency (%EE) and percentage of drug loading (%DL), compatibility with both lipophilic and hydrophilic drugs, biodegradability and biocompatibility, simplicity and appropriateness for industrial applications, economic feasibility, site-specific targetability, simple preparation, nontoxicity, protection of sensitive drugs from degradation through an immobilization while inside the solid matrix (Kumar 2019). Other benefits of SLNs include their ability to treat a variety of diseases and their ability to deliver diverse hydrophobic compounds such as small-molecule drugs, biomacromolecules, genes, oligonucleotides, and peptides (Cacciatore et al., 2016). SLNs have been regarded as a promising oral therapy system for treating GIT disorders (Ashkar et al., 2022).

4. NANOSTRUCTURE LIPID CARRIERS

Nanostructured lipid carriers are a type of modified SLN prepared by mixing solid and liquid (oil) lipids. They were implemented in order to get around SLNs' drawbacks. They are considered as second-generation lipid nano carriers composed of solid lipid matrix, SLNs being the first generation. NLCs are made from fats with a wide melting range, resulting in the production of a solidified lipid phase with imperfections. Because of the formation of a less ordered lipid matrix with many imperfections, this type of carrier/delivery system has the ability to incorporate huge quantities of drugs (Iqbal et al. 2012, Gaba et al. 2014, Kharat and McClements 2019). NLCs have several advantages over SLNs such as low toxicity, biodegradability, drug protection, controlled release, increased encapsulation efficiency (%EE), drug loading (%DL), physical stability and the avoidance of organic solvents during manufacture. The incorporated bioactive component is shielded from deterioration and the medication is immobilized within the solid particle matrix (Muller et al. 2011, Tamjidi et al. 2013). NLCs come in three different varieties: I, II, and III. While type II NLCs can be loaded with pharmaceuticals in both phases and have a high liquid lipid-to-oil ratio, type I NLCs have many flaws. Because Type III lipids are amorphous, drug ejection is hampered (Raj, 2018).

4.1 Inorganic Nanomaterials

They are made up of inorganic nanoparticles with metallic nanostructures. They are primarily found in the form of nanoparticles having one or more key dimensions in the nanoscale range (1-100 nm). These include metallic nanoparticles (like Ag, Au, and Fe), oxides(like CeO_2, CuO, SiO_2, TiO_2, and ZnO), and quantum dots

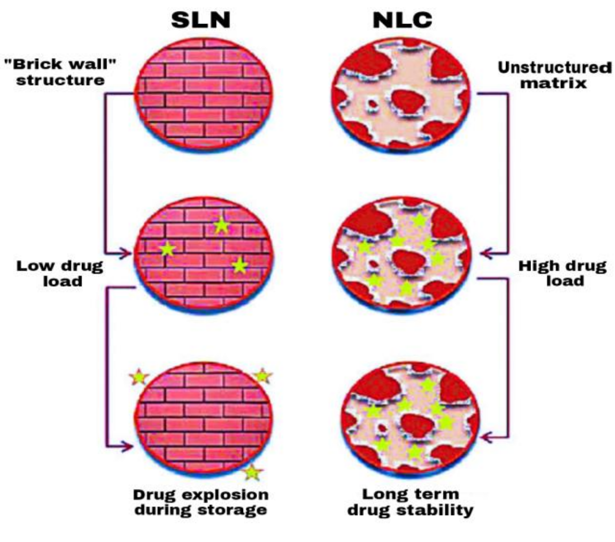

Fig 3. Comparative Analysis: Structured Lipid Nanoparticles (SLN) vs. Nanostructured Lipid Carriers (NLC)

(like CdSe and ZnS) (Laborda et al., 2016). This type of nanoparticle is frequently used in foods due of its small size, which results in desirable functional characteristics such as strong lightning power, improved powder flow qualities, high antibacterial activity, regulated mechanical properties, or advantageous nutritional features (McClements et al., 2017). At room temperature, these particles are either crystalline or amorphous solids, which can be spherical or non-spherical, have various surface features, and come in a variety of sizes, depending on the original materials and preparation conditions utilised in their manufacture. Inorganic nanoparticles differ in their tendency to dissolve under various solution circumstances (such as pH and ionic strength) as well as their chemical reactivates, which has a significant impact on their GIT fate and toxicity (McClements and Xiao, 2017).

5. APPLICATIONS OF NANOMATERIALS IN FOOD SECTOR

The food sector has recently been transformed by revolutionary nanotechnology. The application of nanoparticles in the food industry is improving, mostly in the areas of food processing, packaging, storage, and product development (Berekaa, 2015). The two main categories of nanotechnology applications in the food sector are food nanomaterials and food nanosensing. Food nanostructured ingredients have numerous applications, including food processing and packaging.

5.1 Food Processing

Food nanostructured ingredients have numerous applications, including food processing and packaging. Food processing is a process by which raw ingredients are transformed into marketable foods that last longer. Processing may include toxin removal, disease control, food preservation, and improved food consistency to facilitate distribution and marketing. Because processed foods do not spoil quickly relative to those that are fresh, they are more suitable for long distance travel from producer to consumer. All this has been made easier due to advances in nanotechnology (Chellaram et al., 2018). Other proposed applications include better texture, consistency, and taste by the production of nanostructured food components. One such approach is also called "nanoencapsulation." Nanoencapsulation employs nanocapsules (Suthar et al., 2020). Nanocapsules play an important role in drug delivery, trapping of odours, and food preservation. In the gastrointestinal tract, nanocapsules transport food supplements for enhanced bioavailability of the bioactive (Samal 2017 and Pradhan et al. 2015). LycoVitTM, a gelatin nanosized delivery agent, has been found to enhance the bioavailability of carotenoid lycopene relative to lycopene from fresh whole tomatoes (Hoppe et al., 2003). Another important food ingredient is titanium dioxide (E171), which functions as a colourant that masks any undesirable colour in, for example, dairy foods and confections.

TiO_2 is also employed as a flavour enhancer and food additive in a number of nonwhite foods, such as dried vegetables, nuts, seeds, soups, and mustard, as well as beer and wine. The US Food and Drug Administration (FDA) has approved SiO_2 (E551), TiO_2 (E171), and MgO (E530) as anticaking agents, food colour additives, and food flavour carriers (Weir et al., 2012). Iron fortification of certain meals may be possible with nanostructured iron-containing substances (Zimmermann and Hilty, 2011). An additive for tea that has more redox balance and antioxidant activity is nanoselenium (Zhang et al., 2018).

Maintaining the stability of nutraceuticals during the manufacturing process is always a challenge but by producing nutraceuticals at the nanoscale, will offer greater stability and increased nutrient content. Functional foods can incorporate nanomaterials as bioactives. In functional foods, nutraceutical components such as bioactive proteins are used to provide customers with a health benefit in addition to the nutrients that the food provides (Chau et al. 2007, Cushen et al. 2012). Polymeric nanoparticles have been discovered to be useful for encapsulating bioactive chemicals (e.g., flavonoids and vitamins) in order to protect and transport them to their intended functions (Langer and Peppas, 2003).

5.2 Food Packaging

Nano-based "smart" and "active" food packaging, in contrast to traditional packaging methods, provides several advantages, such as improved packaging materials with improved mechanical strength, barrier qualities, and antimicrobial films, as well as nanosensing for pathogen detection and informing consumers of the food's safety status (Mihindukulasuriya & Lim, 2014). Nano-enabled packaging can safeguard the taste, flavour, colour, texture, and consistency of foods by increasing the mechanical, barrier, and/or antimicrobial capabilities of packaging materials (Bumbudsanpharoke et al., 2015). Additionally, some of them are generally harmless and even include minerals that are essential for human health, and they are more stable in difficult environments like high temperatures and pressures (Espitia et al., 2012).

Improved, active and intelligent food packaging are possible because of nanotechnology (Mahendra, 2017). First, polymer nanocomposites can be used in nano-food by employing improved packaging to enhance mechanical and packaging barrier qualities such as elasticity, gas barrier characteristics (a barrier against the diffusion of oxygen, carbon dioxide, and flavor compounds), and stability under various temperature and moisture conditions (Youssef and Sayed, 2018). Secondly, active packaging for delaying or inhibiting microbial growth and food spoilage and reducing loss of food products by extending their shelf-life (Wang et al 2017; Suh et al 2016). Thirdly, intelligent packaging that uses mechanisms triggered by innate and/or acquired factors (biodegradable activity, antimicrobial activity) to monitor the status of food (Wyrwa and Barska, 2017).

Furthermore, food packaging uses silica and metal oxide nanoparticles like zinc oxide, aluminum oxide, and titanium dioxide. In addition to being employed as photocatalysts with antibacterial and ethylene-scavenging capabilities, these nanoparticles can enhance the nanocomposite's tensile strength, gas barrier, and UV barrier qualities (Bumbudsanpharoke and Ko, 2015; Llorens et al, 2012).

5.3 Food Preservation

Recent advancements in the food processing sector gave rise to a variety of food products, and to preserve the product's freshness for as long as possible, these sectors used various types of packaging materials. But the toxins that various microbes produce could contaminate these processed and packaged food items (Sharma et al., 2017). There is always a chance of a widespread food borne disease since agricultural raw materials undergo an extensive chain of processing and are contaminated with spoilage and pathogenic microorganisms. These issues need to be addressed with the emerging innovative technologies.

Food preservation is a significant public health concern on a global scale. The main objective is to guarantee that food production and consumption will not harm consumers. In comparison to conventional material-based sensors, nanomaterials-based sensors have a high degree of sensitivity and specificity (Kumar et al., 2020). Additionally, edible nanocoatings on a variety of food ingredients can provide a barrier to gas and moisture exchange, disseminate flavors, colors, enzymes, antioxidants, and anti-browning agents, and extend the shelf life of manufactured meals even after the packaging has been opened. Nanoparticles can be used in preserving food by detecting food pathogenic bacteria, toxins, etc. Nano-biosensors are bioanalytical tools created by integrating a variety of NSMs and biological receptors.

Pathogenic bacteria in food products are detected using nanoparticle-assisted deoxyribonucleic acid (DNA), which is more sensitive and takes less time than other traditional methods. For the detection of food contaminating toxins such as aflatoxin B1, gold nanoparticles functionalized with anti-aflatoxin antibodies are employed (Kumar et al., 2017).

6. POTENTIAL HEALTH RISKS, SAFETY ISSUES AND REGULATORY ASPECTS

The use of nanotechnology in food science and research has advanced significantly. Food quality is preserved through tracking, tracing, and monitoring, while nanotechnology helps identify diseases, toxins, and pesticides. The effects of these tiny particles on humans, animals, and the environment are unpredictable because of changes in their characteristics throughout time. Certain nanoparticles can even pass through biological barriers, such the blood-brain barrier, and penetrate various organs and cells (Bajpai et al., 2018). Because of the subsequent transfer of particle nanomaterials from the packaging into the food due to poor packing performance, eating foods that have come into touch with nanopackaging may generate an exposure pathway and pose a serious health risk. The kind of packing matrix, the degree of migration, and the rate at which the particular product was consumed would all have a significant impact on this outcome (Cushen et al., 2012). Moreover, a single oral dose of ZnO nanoparticles may result in problems such liver, kidney, and lung damage (Esmaeillou et al., 2013). The expansion of a sustainable and healthful food industry is nevertheless hampered by the advancement of nanotechnology. As nanotechnology is introduced and developed in the food chain, the general people should be made aware of the related health, safety, and environmental consequences. Effective rules and regulations are therefore needed for the safer application of nanoparticles in the food industry. Nanofoods and food packaging are regulated in the USA by the regulatory organization USFDA. The Food Standards Code's regulatory agency, Food Standards Australia and New Zealand (FSANZ) actively regulate nanofood additives and components in Australia (Bowman and Hodge, 2006).

Although nanotechnology has advanced to improve food safety and quality, there are still significant concerns regarding the unpredictability of nanoparticle health dangers, such as the possibility that they could seep into food from packaging. The need for strict standards is crucial since public debate continues to emphasize how important safety and openness are to preserving consumer confidence. Addressing these issues and maximizing the advantages of nanotechnology in the food sector would require ongoing research and revised regulatory frameworks.

7. FUTURE PROSPECTS

Nanotechnology can be used to detect toxins, viruses, and pesticides. It also aids in tracking, tracing, and monitoring to guarantee that food quality is preserved. Nanotechnology has made significant contributions to the food industry, including the improvement of food flavor and texture, as well as the advancement of food quality through improved processing, packaging, and long-term preservation. Nanomaterials and nanosensors enhance security and help customers by detecting pathogens and by giving them information about the condition of the food within and its nutritional status. Due to the hydrophobic nature of many food bioactives, which have the lowest bioavailability and stability, nanotechnology-based delivery systems have improved the bioavailability and targeted delivery of food bioactive compounds.

To protect consumer safety, it is essential to give continuing research into possible health hazards related to nanoparticles top priority. In order to promote innovation and protect public health, future regulatory frameworks must adjust to these developments. This will eventually allow for the responsible incorporation of nanotechnology into food systems for increased sustainability and nutritional advantages.

The successful integration and deployment of nanotechnology in the food business depends on consumer approval. Addressing safety concerns regarding the health dangers connected with nanoparticles is one of the key elements influencing acceptability. Building consumer trust requires open and honest communication about the advantages of nanotechnology, such as increased food safety, quality, and nutritional content. Continuous communication with customers can yield insightful information about their preferences and issues, enabling stakeholders to modify their strategies appropriately. Ethical behavior will make it easier for nanotechnology to be adopted responsibly, increasing its beneficial effects on food systems and consumer welfare.

8. REGULATORY CHALLENGES IN NANOMATERIALS FOR FOOD APPLICATIONS

In order to ensure consumer acceptance and safety, it is essential to comprehend the difficulties associated with the standardization, testing, and approval of nanomaterials for use in food applications. Specialized testing techniques are needed to properly evaluate the safety and effectiveness of nanomaterials in food products because of their distinctive qualities, which include their small size and high surface area. Because there are currently no established procedures for assessing the possible health hazards and environmental effects of nanomaterials, regulatory approval procedures vary widely among nations and regions. Furthermore, the dynamic nature of nanotechnology makes it more difficult to create thorough laws due to the quick changes in material properties and applications.

Building public trust and guaranteeing consumer safety need the establishment of strong regulatory frameworks that include rigorous testing procedures, unambiguous labeling guidelines, and continuous monitoring. To successfully handle these issues and enable the safe and responsible integration of nanotechnology in the food sector while satisfying consumer demands and legal requirements, cooperation between scientists, regulatory bodies, and industry stakeholders is essential (Haldkar et al., 2024).

9. CONCLUSION

Ensuring food safety, its preservation, and its sustainability are major issues that have been made easier to deal with thanks to these advancements. Injecting nanotechnology in food stuff does not only increase the shelf life of such food materials but also helps in the enhanced delivery of essential nutrients which is important since current diets have made many suffer from diabetes and obesity. There is a political and social action: the constant need to develop in depth research projects aimed at improving the safety and the efficiency of the nanotechnology applications while preventing potential risks against people's health and the environment. Establishing comprehensive regulatory frameworks is essential for the responsible deployment of these technologies and the protection of public confidence.

To sum up, it is possible to refer to the need improvements to be made in food regard nanotechnology application which is the perfect candidate. By promoting cross disciplinary interaction between various scientists, industry, and politicians, the food industry can demonstrate its resolve to overcome challenges and drive changes. In the end, enhancing the food system with nanotechnology promises to be one trustworthy and secure answer in addressing global food and nutrition crisis. Even if the food industry stands to gain tremendously from using nanotechnology, it is still important to proceed with caution.

CONSENT

It is not applicable.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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