

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

ABSTRACT

Initially theorized by Richard Feynman, nanotechnology is now integral to sectors such as pharmaceuticals, cosmetics, and notably food. It involves manipulating materials at the nanoscale to boost their properties and applications. The research highlights nanotechnology's application throughout the food supply chain, focusing on improving bioavailability, nutritional content, and safety. Advances in nanoencapsulation and packaging technologies facilitate better nutrient delivery and prolonged shelf life. Inorganic nanoparticles improve packaging characteristics by enhancing mechanical strength and antimicrobial properties. Despite these advantages, concerns about health risks from nanoparticles highlight the need for stringent regulatory frameworks. The study concludes that while nanotechnology offers significant advancements in food quality and sustainability, it is crucial to establish robust regulations and raise public awareness to manage potential risks. Ongoing research and global collaboration are essential to fully harness nanotechnology's benefits while ensuring consumer safety.

Keywords: Nanotechnology, food industry, nanomaterials, food processing, food packaging, bioavailability

1. INTRODUCTION

Nanoscience and nanotechnology have gained popularity as research and development subjects since Richard Feynman first introduced them in 1959 (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).

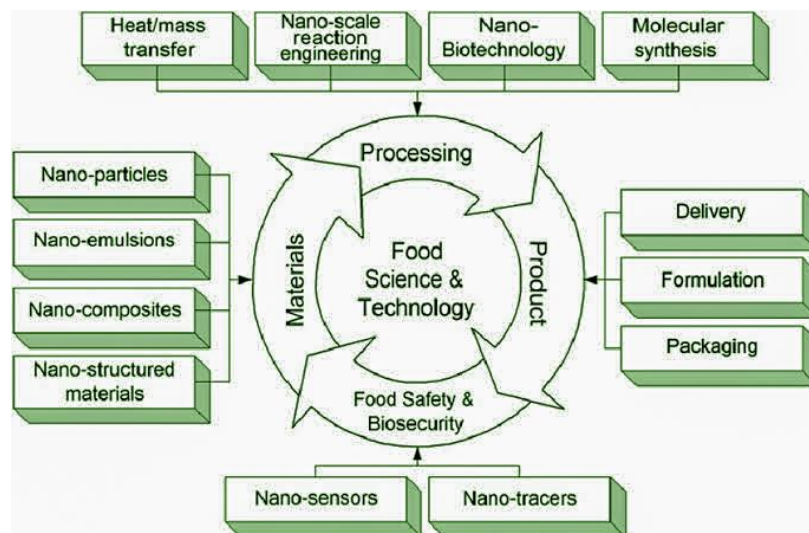


Fig. 1. Illustrating the application spectrum: nanotechnology's impact across food processing stages

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).

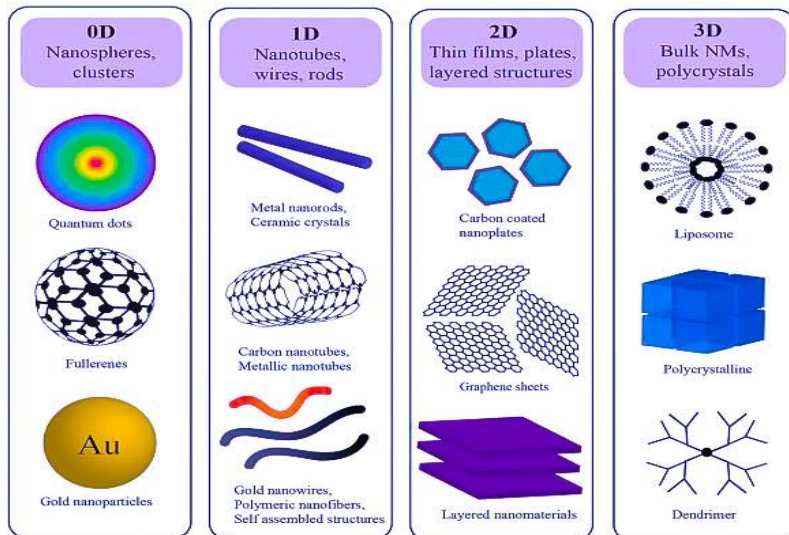


Fig. 2. Nanomaterial classification based on dimension

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.

A key factor in increasing the bioavailability of bioactive substances is nanoencapsulation. Protection of sensitive bioactive components from unfavorable environmental conditions, eliminating incompatibilities, preventing of undesirable taste or odor is all possible with nanoencapsulation. Nanomaterials can protect a bioactive component from harmful environmental factors such as oxidation, pH and enzyme breakdown (Fathi *et al.*, 2012). In conclusion, the integration of nanomaterials into food holds immense promise for revolutionizing nutrition and health, offering a path towards a more sustainable and nourished future.

3. CLASSIFICATION OF NANOMATERIALS

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

3.1 Organic Nanomaterials

Nanoparticles based on lipids and polymers make up organic nanomaterials (Yu *et al.*, 2018). In the food industry, they are the most significant synthetic nanostructure systems. These substances protect bioactive ingredients during manufacturing and storage, improve solubility and bioavailability, and enable regulated release (Pathakoti *et al.*, 2017).

3.1.1 Polymeric Nanoparticles

They are typically 20 to 1000 nm in size. They are complex systems made up of bioactive components entrapped in a polymer or mixture of polymers (e.g., chitosan, alginate, albumin) and surfactants (e.g., lecithin, tween) (Sabliov and Astete, 2015). Materials for nanoparticle synthesis come in a variety of forms, including synthetic polymers and natural polymers. The two main types of natural polymers are proteins (albumin, casein, zein and lactoglobulin) and polysaccharides (chitosan, alginate, 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 as alginate, 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 produced and have the advantages of increased encapsulation efficiency and reduced toxicity as compared to polymeric nanoparticles. LNs for drug delivery are one possible choice among the several drug carrier systems based on nanotechnology (Badilli *et al.*, 2018). Physiological lipids, which are biocompatible and biodegradable and have low acute and chronic toxicity, are typically used to make them (Jaiswal *et al.*, 2016). Lipid-based nanocarriers are classified as liposomes, nanoemulsions, SLNs and NLCs.

3.1.2.1 Liposomes

Liposomes are spherical polymolecular structures that are bilayered and made primarily of natural or manufactured surfactants such as 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 as a large surface area per unit volume, robust stability, optical transparency, and tuneable rheology (Dasgupta *et al.*, 2019). Water-in-oil (W/O) and oil-in-water (O/W) nanoemulsions are two forms of nanoemulsions that depict the distribution of tiny water droplets in an oil medium and the dispersion of tiny oil droplets in an aqueous medium, respectively (Liu *et al.*, 2019). Bioactive substances encapsulated in nanoemulsions have higher solubility, controlled release and absorption in the gastrointestinal system, and cell absorption.

3.1.2.3 Solid lipid nanoparticles

SLNs are sub-micronic solid colloidal nano carriers that have a size range of 1–1000 nm. The lipid matrix can contain substantial amounts of both hydrophilic and lipophilic medications since they are composed of physiological and biodegradable/biocompatible lipids. SLNs have advantages such as controlled drug

release, good stability, better encapsulation efficiency (%EE) and percentage of drug loading (%DL), compatibility with lipophilic and hydrophilic drugs, biodegradability and biocompatibility, simplicity and suitability for industrial applications, cost effectiveness, site-specific targeting, ease of preparation, non-toxicity, protection of sensitive drugs from degradation due to their immobilization within 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).

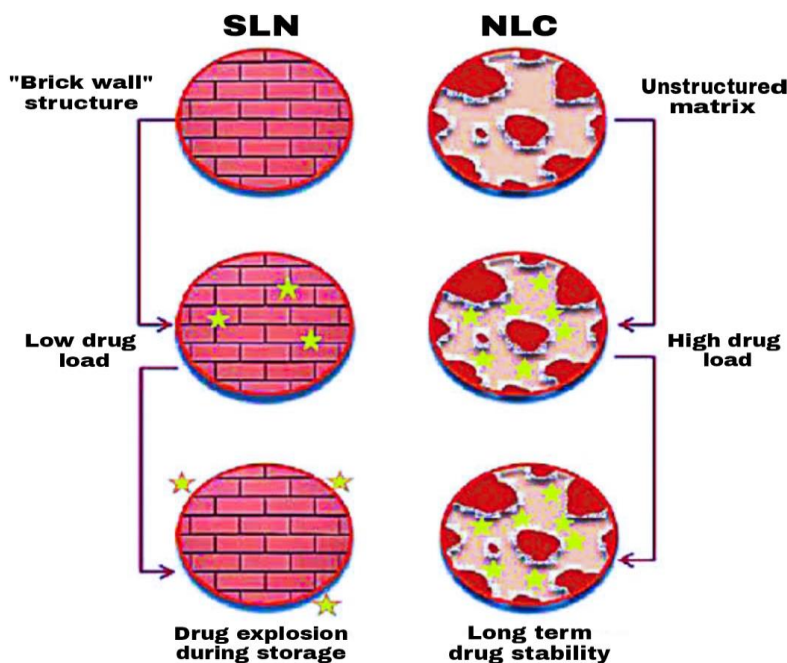


Fig 3. Comparative Analysis: Structured Lipid Nanoparticles (SLN) vs. Nanostructured Lipid Carriers (NLC)

3.2 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 CeO₂, CuO, SiO₂, TiO₂, and ZnO), and quantum dots (like CdSe and ZnS) (Laborda et al., 2016). This type of nanoparticle is frequently used in foods due to its small size, which results in desirable functional characteristics such as strong lightening 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 reactivities, which has a significant impact on their GIT fate and toxicity (McClements and Xiao, 2017).

4. 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 processing and packaging are just two of the many uses for food nanostructured components.

4.1 Food Processing

The process of turning basic ingredients into marketable foods with extended shelf lives is known as food processing. Processing includes things like removing toxins, controlling diseases, preserving food, and improving food consistency for better distribution and marketing. Processed foods are better suited for long-distance transportation from the supplier to the customer since they are less prone to spoil fast than fresh foods. All of these are now more effective due to the incorporation of nanotechnology (Chellaram et al., 2018).

The production of nanostructured food ingredients promises improved consistency, taste, and texture. Nanoencapsulation is one such method to do so. Nanocapsules are used to carry out nanoencapsulation (Suthar et al., 2020). Nanocapsules play a huge role in drug-delivery, odour entrapment and food preservation. Nanocapsules transport food supplements through the gastrointestinal tract, increasing the substance's bioavailability (Samal 2017 and Pradhan et al 2015). It has been discovered that LycopVit™, a gelatine-based nanoparticulate substance containing synthetic lycopene, increases the bioavailability of the carotenoid lycopene as compared to lycopene from fresh, unprocessed tomatoes (Hoppe et al., 2003).

Titanium dioxide is yet another essential food ingredient (E171). As a pigment, it enhances the whiteness of foods like dairy and confections. TiO₂ 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 SiO₂ (E551), TiO₂ (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).

4.2 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).

4.3 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).

5. 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 as 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 contact with nanopackaging may generate an exposure pathway and pose a serious health risk. The kind of packaging 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 as liver, kidney, and lung damage (Esmailou 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 public 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).

6. 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.

7. CONCLUSION

This paper looks at how nanotechnology is changing the food sector and highlights how it might completely change how food is processed, packaged, and preserved. By manipulating materials at the nanoscale, nanotechnology enhances bioavailability, nutritional content, and safety, thereby improving overall food quality. Key findings underscore the versatility of engineered nanomaterials—both organic and inorganic—which contribute to texture enhancement, flavor retention, and targeted nutrient delivery. The significance of these advancements lies in addressing critical challenges, including food safety, preservation, and sustainability. Incorporating nanotechnology into food items not only increases their shelf life but also makes it possible to deliver nutrients more effectively, which is crucial in the fight against diseases like diabetes and obesity that are linked to current diets. Future implications include the need for ongoing research focused on optimizing the safety and efficacy of nanomaterial applications while addressing potential health risks and environmental concerns. Developing comprehensive regulatory frameworks is crucial for ensuring the safe adoption of these technologies and maintaining public trust.

In conclusion, nanotechnology presents significant opportunities to enhance food quality, safety, and sustainability. By fostering interdisciplinary collaboration among scientists, industry stakeholders, and policymakers, the food sector can effectively navigate challenges and leverage innovations. Ultimately, the successful integration of nanotechnology into food systems can lead to a healthier and more sustainable food future, meeting the needs of consumers worldwide while addressing global food security challenges.

CONSENT

It is not applicable.

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