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Nanotechnology and Nanostructures in Food Science: Advancements & Applications

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ABSTRACT

Nanotechnology is a field of science that deals with materials at a nano-scale i.e. within the range of 1 to 100 nano meters. Nanotechnology and nanostructures are revolutionizing food science by providing an innovative, effective, and sustainable approach. Nanotechnology is the science of materials which are extremely small, typically ranging from 1-100 nanometers, which finds various applications in diverse fields including but not limited to food science. Different industries like food industry, dairy industry, fruits & vegetables industry, and wine industry would benefit by implementing and integrating nanotechnology. The advancements and applications of nanotechnology and nanostructures in food science have not been explored thoroughly and require a lot more research. However, public concern about the safety of nanomaterials, toxicological aspect of nanomaterials, and food safety concerns still remains a hot topic for further research. This article provides a brief overview of the applications and advancements of nanotechnology in food science.

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Introduction

Nanotechnology is the science and engineering of manipulating materials at the nanoscale, typically between 1 and 100 nanometers (one nanometer is one-billionth of a meter). At this scale, materials often exhibit unique physical, chemical, and biological properties that differ from their bulk counterparts. Globally, nanotechnology has gradually but firmly taken over a variety of industries. In the developed world, where nanoscale markets have exploded in the last ten years, is this rapid rate of technological development evident. Since nanotechnology is now a multipurpose technology, it is not a novel notion. Four generations of nanomaterials – active and passive nanoassemblies, general nanosystems, and small-scale molecular nanosystems – have evolved and are employed in multidisciplinary scientific areas [1].

The main benefit of materials in this dimensional condition is that they exhibit special functional characteristics not seen in bulk materials, characteristics that can be used in a variety of ways. The primary cause of these characteristics is a high surface to mass ratio, which increases the reactivity of the material during contact, ion delivery, and interactions. But other physical-chemical properties like solubility, charge, composition, and form can alter their behaviours in unusual ways [2].

Nanotechnology applications primarily focus on characterisation, fabrication, and manipulation of nanostructures or nanomaterials. Nanostructured materials have at least one dimension at the nanometre scale and include nanoparticles (NPs), nanorods, nanowires, thin films, and bulk materials composed of nanoscale building blocks or structures. Nanostructured materials are classified as zero-dimensional (e.g., nanoclusters, quantum dots, and fullerenes), one-dimensional (e.g., nanorods or nanotubes), two-dimensional (e.g., thin films), or three-dimensional (e.g., nanocomposites and dendrimers) [3].

Nanotechnology Applications in the Food Industry

Nanotechnology has numerous applications in the food sector, including food manufacture, packaging, safety measures, medicine administration to specific areas, smart diets, and other advanced preservatives, as illustrated in Figure 1. Nanomaterials, such as polymer/clay nanocomposites, are employed as packaging materials because of their high resistance to environmental influences [4, 5]. Similarly, nanoparticle combinations are utilised as antibacterial treatments to prevent rapid microbial deterioration in stored food products, particularly canned goods. Similarly, various nano sensor and nano assembly-based assays are employed for microbial detection in the food storage and manufacturing industries [6].

Applications of nanotechnology in food science are going to impinge on important characteristics from food safety to molecular synthesis of new food products and ingredients [7]. Properties of these nanostructures and materials – physical, chemical, and biological properties – are considerably different from their bulk counterpart and change the understanding of biological and physical occurrences in the food systems. Various reports and reviews in recent times have identified the potential of application of nanotechnology for the food sector to achieve the following: improve safety; enhance packaging for better processing, conservation, and utility; and lead to improved processing and nutrition [3].

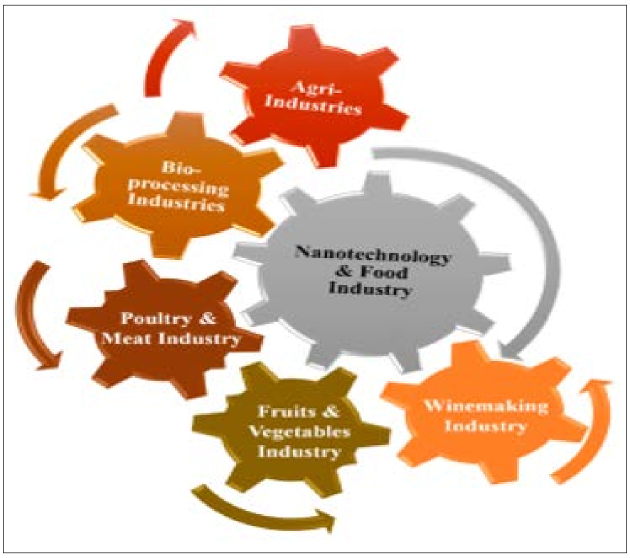

Figure 1: Applications of Nanotechnology in Various Industries.

Nanotechnology Applications in the Dairy Industry

Nanotechnology is also transforming the dairy business globally [8]. Nanotechnology could benefit the dairy industry by improving processing methods, food contact and mixing, yields, shelf life, product safety, packaging, and antimicrobial resistance [9]. Nanocarriers are being used to add biologically active chemicals, medicines, increased flavours, colours, and odours to dairy products [10]. These chemicals have better delivery, solubility, and absorption qualities for their target system. However, public acceptance of nano-based dairy and food items is a challenge due to concerns about potential negative effects. This must be handled before they can be widely commercialized [11].

As previously indicated, nanotechnology has advanced significantly in the food business. This scenario will surely impact the agricultural, medical, fruit, and vegetable businesses. Scientists aim to extend the shelf life of fresh organic food to meet the nutritional demands.

Nanotechnology Applications in the Fruits & Vegetables Industry

Nanotechnology has a significant impact on the safety and production of vegetables and fruits, including horticulture, food processing, packaging, and disease detection [12]. Nanotechnology is replacing conventional technologies because of its cost-effectiveness, improved results, and longer shelf life compared to previous methods. Although there may be concerns, nanotechnology has not yet been linked to high-grade toxicity in organic fresh green products. By decreasing postharvest waste, a significant issue in poor countries, these technologies help consumers have access to sufficient and secure food supplies [13]. The advantages of nano packaging include reduced humidity, oxygen transmission, and ideal water vapour transmission rates. In the long run, nanotechnology is therefore used to extend the shelf life of such items to the appropriate level [14].

Nanotechnology Applications in the Wine Industry

A significant global commercial application of the food industry is the winemaking sector. In this sector, the application of nanotechnology is likewise growing. Nanotechnology is used to create sensors such as nanoelectronics, nanoelectrochemicals, biological, amperometric, and fluorimetric devices. When wine is being produced and fully processed, these nanoparticles aid in the analysis of its constituents, including as polyphenols, organic acids, biogenic amines, and sulphur dioxide, to make sure their concentrations are right [15].

Nanotechnology Applications in Food Packaging

The packaging industry is undergoing improvements due to environmental concerns. It aims to provide food safety and reduce food-waste pollution. Nanotechnology is being used to replace non-biodegradable plastic with eco-friendly organic biopolymer-based materials [16]. These nanomaterials, which include anticaking agents, nano additives, and delivery systems for nutraceuticals, are used in food packaging to increase safety and address environmental issues. They are mixed with polymers to prevent contamination. Packaging nanotechnology is also being introduced in textile, leather, and cosmetic industries [17].

Nanotechnology has enhanced the mechanical and thermal qualities of packaging, resulting in more effective food safety [18]. The incorporation of nanoclays into biopolymers improved their mechanical characteristics, making them suitable for use as an eco-friendly and biodegradable substitute for food packaging [19]. In addition to improving the mechanical qualities, titanium nitride nanoparticles in packaging can act as a gas barrier to prolong the shelf life of the product by restricting oxygen penetration or stopping CO_2 leakage in carbonated drinks [20, 21].

Table 1: Nanoparticles Used in Food Packaging

Types of nanoparticles	Source	Applications	Reference
AgO	Apple	Inhibits microbial spoilage	22
TiO_2	Strawberry	Slows down ripening and decay	23
ZnO	Orange	Reduces yeast and mold counts	24
Ag	Asparagus	Antimicrobial effect against E. Coli	25

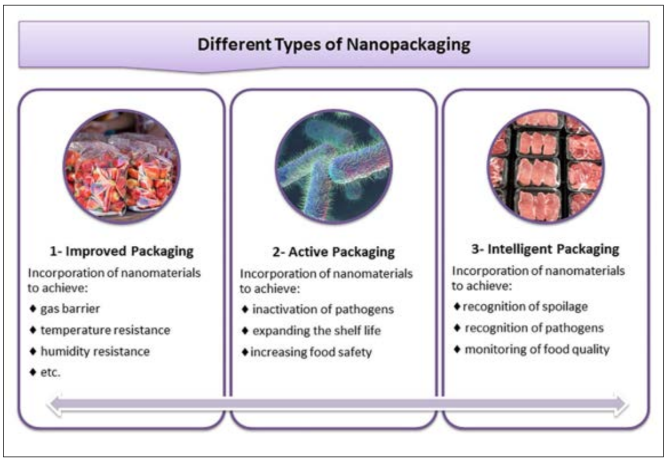

Figure 2: Classification of Types of Nano packaging [26].

Novel Packaging Materials

Nano-enabled solutions also allowed the integration of various bioactive molecules and nanoparticles to prevent oxidation and food degradation. Selenium and cellulose NPs can be integrated into food packaging to retard or inhibit the ROS that can degrade food quality [27]. The nano-encapsulation of other entities such as phenols can also provide protection against degradation, particularly of fatty foods [28]. Other essential oils can also be integrated in nanofibers to prolong the lifespan of fresh produce [29, 30].

A new packaging material that has gained significant attention is nanocellulose [31]. Nanocellulose nanofibrils and nanocrystals have been incorporated as a reinforcement phase in nanocomposites [31]. Also, nano cellulose is used as a base material that is enhanced with other nanomaterials such as photocatalysts [32]. In other instances, it can be the carrier of other antimicrobial agents with controlled release [33].

With biopolymers, NSMs can either increase the functional qualities of active and intelligent packaging or the neat polymer's property features in food packaging. The terms "Improved," "Active," and "Intelligent" packaging indicate which types of packaging materials are appropriate for specific uses [34]. However, the European Union (EU) has placed formal restrictions on the use of "intelligent" and "active" food packaging materials, with the exception of titanium nitride in plastic bottles [35].

Nanotechnology through a Toxicological Perspective

Nanotechnology is growing, and public concern about the toxicity and environmental impact of nanomaterials is increasing. Nanoparticle-mediated toxicity is stimulated by dynamic, kinetic, and catalytic properties, as well as functionalization, net particle reactivity, agglomeration, and functional environment [36]. Nanoparticles on packaging materials are not harmful to humans, but their translocation and integration into food may affect human health. Nanoparticles reach the animal system via skin penetration, ingestion, inhalation, intravenous injections, or implanted medical apparatus. Toxicokinetic issues are mainly due to their persistent, non-dissolvable, and non-degradable nature [37].

The lack of consumer awareness, government guidelines, policies, and detection methods for nanotechnology risk assessment warrants better understanding of nanomaterial-based toxicity characterization and regulatory processes. Nanoparticles are highly reactive substances that can readily cross membrane barriers and capillaries, resulting in different toxicokinetic and toxicodynamic properties [38]. Some NPs bind to proteins and enzymes, stimulating ROS production and oxidative stress, leading to mitochondrial degeneration and apoptosis.

Extensive studies on the impact of nanomaterials on human health warrant extensive research. The International Conference on Harmonization (ICH) and the Organization for Economic Co-operation and Development (OECD) have proposed widely accepted genotoxicity detection methods, such as gene mutations, DNA breaks, Ame's test, and mammalian cell assays. However, Ame's test and chromosomal aberration tests are not reliable for detecting nanoproduct-related toxicity assessments [39].

Exogenous materials, including nanomaterials, can cause genetic damage in cells and animal systems, resulting in genotoxicity. Primary genotoxicity occurs when nanomaterials directly contact genomic DNA without causing inflammatory reactions [40].

Indirect methods of primary genotoxicity involve the generation of reactive oxygen species (ROS) in NP-induced target cells or the reduction in intracellular antioxidants. Quartz particles, TiO_2 and C60 fullerenes, and Zano nanoparticles can induce primary genotoxicity through ROS generation from mitochondria, proximities formation, and DNA fragmentation [41].

Secondary genotoxicity occurs when macrophages and neutrophils are activated by nanomaterials, causing inflammatory reactions and genetic damage. The ROS and reactive nitrogen species (RNS) and mediators of phagocytes are responsible for the inflammation-associated DNA damages. Zano nanoparticles can cause elevated inflammatory reactions and genotoxicity in human monocyte cells. Prolonged oxidative stress from extreme ROS generation and obstruction in physiological redox-regulated functions results in DNA damage, uncontrolled cell signaling, altered cell motility, cytotoxicity, apoptosis, and tumor formation. Frequent exposure to nanomaterials affects various organs, including inflammatory, immune, and cardiovascular systems [42].

DNA fragmentation results from DNA single-strand breaks, double-strand breaks, oxidative damage, or chromosomal damage. Zano nanoparticles have unique characteristics, such as semiconductor property, biocompatibility, pyroelectric, and piezoelectric properties. They are used in the food industry for food packaging, smart packaging, and nutritional additives due to their antimicrobial nature. However, lower concentrations of 3-mercaptopropanoic acid–CDs/ZnS quantum dots can induce cytotoxicity and genotoxicity [43].

Food Safety Considerations in Nanotechnology

Food safety is a developing public health concern on a global scale. Ensuring that food won't hurt consumers during preparation or consumption is the main objective of food safety [44]. Food processing, handling, and distribution must be done with precautions to prevent physical, chemical, and biological contamination [45]. With its numerous uses in food processing, safety, and security as well as its advancements in increasing nutraceutical value, prolonging shelf life, and decreasing packaging waste, recent advances in nanotechnology have completely transformed the food business [45]. Due to the quick changes in food recipes and eating patterns, food safety is a big problem nowadays. Toxins, other pollutants, and foodborne pathogens can pose major risks to human health.

Nanotechnology may have dangers and hazards of its own, even though these are unknown. This is because any technology may have similar risks and hazards. Environmentalists fear that toxins produced by nanotechnology could be extremely harmful due to their nanoscale [46]. The way these particles interact with items can be hazardous even if the particles themselves are not dangerous. There is still much to learn about how nanoparticles interact with living cells. By consuming food and drinks that contain these incredibly small, highly reactive, and potentially hazardous particles, consumers are exposed to nanomaterials. The small size of nanomaterials might make accumulation in bodily tissues and organs more probable [47].

In addition to being more mobile and reactive, the nanoparticles are probably more hazardous. Before being employed in the food business, the components in these nanoparticles must pass a thorough safety evaluation conducted by the appropriate scientific advisory association.

Conclusion

Nanotechnology research for commercial food applications has rapidly progressed, but the development of nanostructures has been slower. Public concern over the safety of nanotechnology-based goods for human consumption and use has increased, necessitating thorough evaluation of potential risks to human health. Nanotechnology has various applications in the food industry, dairy industry, fruits & vegetables industry, and wine industry. Toxicological perspective of nanotechnology in the food sector needs to be explored thoroughly. However, there are still challenges in building a healthy and sustainable food sector, including regulation of health, safety, and environmental effects. Transparency on safety concerns and mandatory testing of nanofoods is essential. Public education is also crucial for the long-term success of nanotechnology in the food industry. Nanotechnology has the potential to significantly impact packaging, food processing, and agriculture sectors, with nanocomposite materials providing enzyme immobilization, oxygen scavenging ability, and antibacterial characteristics. It is also used to develop edible coatings and films. Future advances in nanotechnology and nanostructures inf food science will require a thorough inspection of their impact on the environment, water, land, and public health.

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