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Nano-Nourishment: Unveiling the Mini Marvels Revolutionizing Food Sector

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Abstract. Nanotechnology, as a rapidly advancing field, has shown great potential in revolutionizing various aspects of the food industry. This descriptive review explores the diverse use of nanotechnology in the food sector, focusing on food's packaging, food processing, and food safety. It examines how nanotechnology can enhance the safety, quality, and sustainability of food products, while also addressing the potential concerns associated with its implementation. Additionally, it highlights the importance of regulatory frameworks and consumer perception in ensuring responsible and transparent use of nanoscience in the food industry.

Keywords: Nanotechnology, Nanocarriers, Food processing and packaging, Food safety.

1 INTRODUCTION

1.1 Unveiling the Nano Revolution in Food: Exploring Nanotechnology's Potential

Nanoscience and nanotechnology are the study and subsequent application of extremely miniature things that can be utilized in all fields of science, such as biology, chemistry, materials science, physics, etc. Nanotechnology manipulates matter on an atomic scale, designing brand-new structures, devices, materials that thrive at the nanoscale. This technology has brought industrial revolution, and both developed as well as developing countries are interested in investing more in this technology (1). Thus, nanotechnology offers a broad range of opportunities for the utilization and development of structures or systems with new attributes in various fields such as agriculture, medicine, etc.

Food sector plays an important role in meeting the nutritional demands of the growing population. However, industry faces challenges such as food safety concerns, quality maintenance, and sustainability. Over the past few years, nanotechnology has been increasingly seen as an attractive technology that has remodelled the food industry. They have distinctive properties compared to their macroscale complement due to their peak surface-to-volume ratio and unusual physicochemical attributes such as solubility, color, diffusivity, toxicity, magnetic and optical, and thermodynamic properties (1). These attributes provide chances to improve the organoleptic properties of foods like flavor, texture and color. In addition, nanomaterials can improve the protective method of food. Growing concerns about the health benefits and quality of food are forcing scientists to find ways to improve food quality while minimally disrupting the nutritional value of food. This review aims to explore how nanotechnology can enhance the industry by improving barrier properties, developing intelligent packaging systems, enabling nutrient delivery, enhancing texture and sensory attributes, ensuring food safety, and improving traceability. Additionally, it addresses the potential concerns associated with nanotechnology and emphasizes the importance of regulatory frameworks and consumer perception in ensuring responsible and transparent use of nanotechnology in the food sector.

The need for nanoparticle-based substances has grown in the food sector (2) because

- many of these carry basic elements
- found to be harmless
- found to be firm at excessive temperatures and pressures etc.

This technology offers a complete solution which includes food production, processing and packaging. Nano substances make a big difference in the quality and safety of food, as well as in the health gain that food has to provide. Using nano sensors and nano packaging materials enables fast and reliable identification of microbial contamination, pesticides, harmful chemicals, nano-encapsulation systems have the capacity to upgrade food processing. This is achieved by allowing the delivery of bioactive elements to increase bioavailability in the food stuffs. Many researchers as well as many industries are coming with new ideas and products that have a direct utilization of nanotechnology in this sector (2).

Applications of nanoscience in the food industry can be characterized in two categories:

• nanostructured additives
• nano scanning.

Nanostructured additives cover a broad area from processing to packaging. aIn processing of food, these nanomaterials are utilized as additives, antimicrobial agents, also carriers for the smart nutrient distribution, fillers to improve durability and mechanical strength of the material for packing, etc. Food nano scanning can be applied to get better quality of food as well as to evaluate safety (3). In this review paper, the job of nanotechnology in food microbiology and food science was summarized, some negative facts associated with this technology are also discussed.

2 CLASSIFICATION OF NANOCARRIERS

Nanomaterials can be classified as organic, inorganic, or as a combination of both (4). Organic nanocarriers consist of polymeric nanostructures, lipid-based structures like liposomes, nano-emulsions (example: micelle, reverse micelles), dendrimers, also carbon nanocarriers. Inorganic nanostructures consist of metallic nanoparticles like quantum dots.

2.1 Polymer based nanoparticles

Polymeric nanoparticles are based on biodegradable polymers which are derived from synthetic or natural sources. Biodegradable polymers include natural polymers that include agarose, chitosan, collagen, sodium alginate, and fibrin (5). Polymers which provide controlled release of drug from the core particles are very desirable. The popularity of polymeric nanoparticles for vaccine delivery (5) and anticancer therapy is due to these polymers. Their chemical properties and flexibility make them suitable for integration with biomaterials and for the targeted delivery which stimulates tissue regeneration (7).

2.2 Liposomes

Liposomes which are a concentric bilayer of lipid nanocarriers, are composed of an aqueous type core which is capped with a surfactant that can be synthetic or a natural phospholipid. Liposomes are classified as oligolamellar vesicles (OLV), multilamellar vesicles (MLV) and unilamellar vesicles (ULV). Liposome carrier systems, like stealth liposomes, immunoliposomes and archaeosomes, contain lipid based bilayers which are biologically compatible and can upgrade the stability as well as solubility of core structures (7).

2.3 Dendrimers

Dendrimers are a mono-dispersed high polymer compound. They are composed of repeating molecules which are branched, around an inside core and can be made from monomers by polymerization methods. They are used to improve target delivery (8).

2.4 Carbon nanocarriers

Carbon nanocarriers are tubular like structures which are carbon-based and they are organized in graphene sheet like shape which has been rolled into a structure of cylinder to give it a buckyball shape (35). Relying on the process of functionalization, nanoparticles are classified as surfactant-grafted, solvent-dispersed, ligand-tethered, and target-oriented.

2.5 Hydrogel based nanoparticles

Hydrogel nanoparticles are 3-dimensional network of polymers which extract a large volume of any biological fluid. The capability of hydrogel nanoparticles to absorb water is reliant on the existence of some hydrophilic groups like -CONH2-, -OH, -CONH-, -SO3H (9).

2.6 Quantum dot nanoparticles

Quantum dot nanoparticles are nano-crystals made of fluorescent semiconductor atoms which are inorganic in nature. They have a size ranging from 2nm to 10 nm. The semiconducting structure (cadmium selenide), is composed of core and an aqueous shell made of zinc sulfide which insulates the inner part to improve optical mechanisms.

2.7 Nanoemulsion

A nanoemulsion consists of droplets, which are divided into two kinds based on the spatial arrangement of water or oil phases. A system (micellar) that consists of oil droplets dangled in an aqueous phase is called oil-in-water (O/W) nano-emulsion, and reverse micelle-based system that consists of a suspension of droplets of water dangled in a phase of oil molecules is known as water-in-oil (W/O) nanoemulsion (10)

3 NANOTECHNOLOGY IN FOOD PROCESSING

Food processing involves various techniques to metamorphose raw substance into protected, nutritious, and tasty food. Nanotechnology offers numerous opportunities to enhance the processing methods and improve the quality, nutritional value, and consumer experience of food. Nanocomposite food constituents are evolved with the assertion that they offer upgraded texture, flavor and evenness (11). Nanoscience upgrades the serviceable life of various food products and also degrades the extent of wasting of food materials because of contamination due to microbes (3). Currently, nanocarriers are used as transport systems for transferring additives in food materials, especially without interrupting their basic structure and properties. Size of the particles affects the transport of biologically active compounds to the different sites in the body. It has been found that only submicron nanoparticles, but not larger microparticles (3), can be efficiently absorbed in some cell lines. An ideal delivery system should have the following characteristics:

• capable of delivering the active substance exactly to the target site

• ensure availability at the target time and specific rate

• effective for maintaining active substances at proper levels for a prolonged time (in storing conditions).

Nanoscience, which is used in the making of bio-based polymer matrices, encapsulation, emulsions and coalition colloids, provides systematic transport mechanism. Nanopolymers are on its way to replace standard compounds in packaging of food, and nano-sensors are being applied to detect the existence of contaminants, microorganisms and mycotoxins in food (3).

Nanomaterials have a far better encapsulation characteristics as well as efficiency of release than standard encapsulation process. Nanoencapsulation masks smell or flavors and also checks the interlinkage of active ingredients with matrix of food and ensure availability at target time and specific rates, control the release of active substances and also guard them from the scorching heat(11), moisture, degradation during processing, repository and use. In addition, the delivery mechanism has the capacity to perforate deep into the tissues because of their small size, enabling effective transportation of active particles to targeted sites inside the body(12). Different encapsulation delivery systems based on natural and synthetic polymers are illustrated for improved biological availability and conservation of active ingredients. The significance of nanotechnology in processing of food can therefore be assessed by taking into consideration its role in improving food in terms of:

Texture of food,
the look of the food,
taste of food,
nutrition in food
Reduced fat content
shelf life of food.

3.1 A Feast for the Senses: Food Texture, Taste and Appearance

Texture and sensory attributes greatly influence consumer preference and acceptance of food products. Nanotechnology offers innovative approaches to modify the texture and sensory properties of food. Nanoparticles, such as nanocellulose and nanogels, can be used to modify the rheological properties of food systems, creating desirable textures such as creaminess or viscosity. Additionally, nanoparticles can improve the dispersibility and stability of ingredients, enhancing the overall sensory experience of food products.

Nanotechnology provides many possibilities for improving the food quality and it helps in enhancing the taste. Nanotechnology encapsulation procedures are widely utilized to improve release of flavor and retaining it as well as to deliver culinary balance (13). Rutin which is a common dietary flavoring agent has important pharmacological activities, but its utilization in the industry is limited because less solubility. (14). The utilization of nanoemulsions to transfer lipid-soluble biologically active structures is very famous because they can be made from natural ingredients using simple manufacturing processes and are created to improve bioavailability as well as aqueous dispersion(15).

Metal oxides like titanium dioxide, also silicon dioxide are commonly used as colorants (15). In addition, silicon dioxide nanomaterials are one of the widely used nanomaterials in food used as conveyors of aromas and tastes (16).

3.2 Fortifying Foods: Nanostructures for Enhanced Nutrient Delivery

Nanotechnology enables the encapsulation and controlled release of nutrients, vitamins, and bioactive compounds in food products. Nanoemulsions, nanoencapsulation, and nanoliposomes are some of the techniques used to improve nutrient delivery. These nanoscale delivery systems protect sensitive ingredients from degradation, enhance solubility, and improve the bioavailability of nutrients. By upgrading the absorbing quality and utilization of nutritious substances in the human body, nanotechnology can contribute to improved health outcomes.

Small eatable capsules which are based on nanostructures are created to provide significant benefits (17) to upgrade the transportation of drugs, vitamins in everyday food products. Nanoemulsification, nanocomposite and nanostructure are various methods that are used to encapsulate compounds into small forms. This is done to deliver nutrients efficiently. Polymeric nanoparticles are suitable for encapsulation of biologically active compounds (example: flavoring agents and vitamins) for protection and transport of bioactive compounds to target functions (18), conservation or longevity.

3.3 Reduced Fat Content

The demand for healthier food options has led to the development of low-fat or fat-free food products. However, reducing fat content often negatively impacts the sensory qualities, such as mouthfeel and taste, of these products. Nanotechnology provides a solution by incorporating nanostructured ingredients that mimic the functionality of fats. Nanoemulsions and nanogels can mimic the creamy texture and mouth-coating properties of fats, allowing for the reduction of fat content while maintaining desirable sensory qualities.

3.4 Shielding Freshness: Preservation of shelf life

In foods, where the biologically active constituent degrades and leads to inactivation because of harsh environment, nano-encapsulation of such biologically active constituents extends the service life of the food products by reducing the degeneration procedure or preventing degeneration until the material is delivered to the destination. Furthermore, eatable nano-coats on food materials could supply a gas and moisture interplay barrier and deliver flavors as well as colors, antioxidants or enzymes and anti-browning agents, and could also upgrade the shelf life of manufactured products even when the package is open (19,20). The encapsulation of functional components in droplets enables the degradation process to be slowed down. For example, curcumin, the least stable bioactive constituent of turmeric showed less antioxidating properties and was f stable at various ionic strength after the process of encapsulation (21).

4 THE SILENT GUARDIANS: NANOTECHNOLOGY AND NANOMATERIALS IN FOOD PACKAGING

Food packing plays an important role in conserving the food’s quality as well as safety. Nanotechnology offers innovative solutions to enhance the functionality of food packaging materials, leading to improved barrier properties, intelligent packaging systems, and active packaging.

4.1 Enhanced Barrier Mechanism

One key applications of nanotechnology in packaging of food is improving the barrier properties of packaging materials. Nanocomposites, which consist of nanoparticles dispersed within a polymer matrix, can significantly enhance the protective capabilities of packaging materials. These nanoparticles, such as nanoclays and nanosized fillers, create a tortuous path for gas molecules, effectively reducing the permeation of oxygen and moisture. Therefore, food’s shelf-life can be increased, minimizing spoilage as well as reducing food waste.

4.2 Intelligent Packaging

Intelligent packaging involves the integration of nanosensors, indicators, and monitoring systems into food packaging materials. Nanosensors, capable of detecting changes in temperature, gas composition, and microbial activity, enable real-time monitoring of food products. For example, nanosensors can detect the presence of gases released by deteriorating food, allowing early identification of spoilage. By providing valuable information about the freshness and quality of food, intelligent packaging systems can help prevent foodborne illnesses and reduce food waste.

4.3 Active Packing

A suitable packing material must have permeability of gas and moisture along with durability and biodegradable nature (22). Nanotechnology-based “smart” and “active” packaging offers various advantages over the traditional packaging procedure which are supplying better material for packaging with upgraded barrier mechanism, mechanical strength, and films which are antimicrobial to nano sensing for identification of pathogens and warning the consumers about the safety the food (23).

Nanosilver is a commonly used antimicrobial agent in active packaging. Its high surface area to volume ratio enables effective release of silver ions, which exhibit strong antimicrobial activity against various pathogens. Additionally, nanoclays incorporated into packaging films can create an environment unfavorable for microbial growth, further enhancing the preservation of products.

The utilization of nanostructures is not only limited to antimicrobial packing but nanocomposites as well as nanolaminates have been rapidly used to supply a barrier from extreme conditions which upgrades the shelf life of food. Therefore, the embodiment of nanomaterials into materials for packaging of food provides quality food with more shelf-life.

5 NANOSCIENCE IN SAFETY OF FOOD

Ensuring safety of food is a primary task for food industry. Nanotechnology offers novel approaches for the detection and identification of contaminants, control of foodborne pathogens, and improvement of traceability throughout the food supply chain.

5.1 Detection and Identification of Contaminants

Nanotechnology-based biosensors and nanoprobes enable rapid and sensitive detection of contaminants in food. These nanoscale devices can detect various contaminants, including pathogens, pesticides, toxins, and allergens, with high specificity and sensitivity. Nanobiosensors utilize the specific binding interactions between target analytes and receptor molecules attached to nanoparticles. The detection signals can be amplified and measured, providing accurate and timely information about the presence of contaminants in food samples. Rapid detection methods facilitated by nanotechnology can significantly reduce the time required for analysis, enabling early identification and prevention of potential hazards.

5.2 Fighting Back: Nanosensors for Pathogen Detection

Nano biological sensors are utilized for identifying pathogens in food, assessment of available food composition and warning the consumers, also distributors or dealers on the safety-status of the food products (24). The sensor works as indicator which answers to alterations in the environment conditions such as microbial contamination, humid climate, temperature, or degradation of product (25). Many nanostructures like nanorods, thin films, nano-fibers have been scrutinized for use in biological sensors (26). Thin film-based visual immunosensors which helps in the observation of microbial substances have led to the fast and very sensitive observation systems and in these immunosensors, antigens, antibodies, or protein-based molecules are immobilized on thin nano chips that discharge signals on identification of target molecules (27).

Biological sensors based on carbon-based nanotubes gained notice because of their:

- rapidly detection
- simple nature
- cost effective nature

They have been efficiently used in toxin detection, microorganisms and other depraved products in foods and drinks (28). Toxic antibody structures hooked to the nanocarriers cause a commute in conductivity when they are bounded to toxins which are waterborne and thus they are utilized to locate them (29). The utilization of devices like electronic tongue which comprises of a bundle of nanosensors keep a check on food condition by giving signals on the release of aroma by food (29). Another device named quartz crystal microbalance (QCM)-based electric nose is capable of identifying the interplay between many odors and chemical based substances that have been coated on the crystal-like surface of the device.

5.3 Improved Traceability

Traceability throughout the food supply chain is essential for ensuring food safety, quality control, and addressing issues related to fraud and counterfeit products. Nanotechnology offers tools and techniques for improved traceability, enabling accurate monitoring and tracking of food products from farm to fork. Nanotags, nanosensors, and nanofluidics can be utilized to tag and identify food products, record and transmit data, and ensure transparency in the supply chain. These technologies provide valuable information about the origin, processing, and storage conditions of food products, enabling prompt intervention in case of safety or quality issues.

6 POTENTIAL CONCERNS AND REGULATORY CONSIDERATIONS

The integration of nanotechnology in the food sector raises certain concerns that need to be carefully addressed. These concerns include the safety of nanomaterials, consumer perception, and the development of appropriate regulatory frameworks (28,29).

6.1 Consumer Perception and Labelling

Transparent communication about the utilization of nanoscience in food is crucial to address consumer concerns as well as ensure trust. Consumer perception and acceptance play a significant role in the successful implementation of nanotechnology in the food sector. Effective communication strategies that provide clear and accurate information about the benefits and safety of nanotechnology are necessary. Additionally, clear labelling regulations are important to inform consumers about the presence of nanomaterials in food products. Labelling provides transparency and empowers consumers to make informed choices about the food products they purchase and consume.

6.2 Regulatory Frameworks: Navigating the Path of Nanotechnology in Food

Governments and regulatory bodies worldwide are actively involved in the development of guidelines and regulations for the responsible use of nanotechnology in the food sector. Collaboration among researchers, industry stakeholders, and regulatory authorities is crucial to establish comprehensive frameworks that ensure the safety and efficacy of nanotechnology-based food products. Regulatory frameworks need to balance innovation, safety, and consumer protection while keeping pace with the rapid advancements in nanotechnology.

While nanotechnology holds great promise for revolutionizing the food industry, it is important to critically review research in this field to ensure its safety, efficacy, and ethical implications. Here are some critical aspects to consider when evaluating research on the utilization of nanotechnology in food sector:

Precision Nutrient Delivery: Nanoscience offers potential to precisely deliver nutrients to specific areas of the body, maximizing their absorption and utilization. By encapsulating vitamins, minerals, or other essential nutrients at the nanoscale, targeted delivery systems can be developed to address specific nutritional deficiencies or enhance overall well-being.

Sustainable Agriculture: Nanotechnology can take part in an important role in sustainable farm practices. By establishing nanomaterial-based fertilizers and pesticides, it's possible to enhance nutrient uptake efficiency, minimize chemical usage, and reduce environmental impacts. Nanostructured materials can also improve water management and soil health, promoting sustainable farming practices.

Personalized Nutrition: Nanotechnology has the potential to enable personalized nutrition tailored to an individual's specific needs. Nanosensors integrated into wearable devices or embedded in food products can monitor various biomarkers and provide real-time feedback on nutritional status. This data can then be utilized to formulate personalized dietary recommendations for optimal health and well-being.

Enhanced Nutrient Bioavailability: Nanoscale delivery systems can improve the bioavailability of nutrients, unlocking their full potential in the body. Encapsulation of certain compounds at the nanoscale can protect them from degradation during digestion and facilitate their absorption in the gastrointestinal tract. This could lead to enhanced nutrient uptake and utilization, addressing issues of nutrient deficiencies and malnutrition.

Customizable Textures and Flavors: Nanotechnology can offer innovative ways to create customizable textures and flavors in food products. In addition to enhancing flavor and texture, nanotechnology can potentially revolutionize how we perceive and interact with food. By manipulating the size and structure of particles at the nanoscale, it becomes possible to modify the sensory properties of food, resulting in novel taste experiences, improved mouthfeel, and enhanced product appeal. Imagine a chocolate that melts at a specific temperature, releasing bursts of different flavors, or a drink that changes color or texture when mixed. Nanotechnology opens up a realm of possibilities for creating truly immersive and multisensory culinary experiences.

Controlled Release of Functional Ingredients: Nanotechnology allows for precise control over the release of functional ingredients in food products. This can be particularly valuable for encapsulating sensitive components such as bioactive compounds, probiotics, or pharmaceuticals. Controlled release mechanisms can protect these ingredients from degradation and ensure their optimal delivery and effectiveness.

Future Food Exploration: Nanotechnology opens doors to futuristic possibilities in the food sector. For instance, the development of nanostructured artificial meat could revolutionize the way we produce and consume protein, addressing sustainability and ethical concerns associated with traditional livestock farming. Additionally, nanotechnology could pave the way for novel food production techniques, such as 3D printing of personalized meals or edible nanosensors for in-body diagnostics.

Long-Term Effects and Sustainability: Research should consider the long-duration effects as well as sustainability aspects of nanoscience applications in food industry. It includes evaluating the environmental footprint of nanomaterial production, assessing the potential for waste generation, and considering the overall life cycle impacts. This is crucial to ensure that the utilization of nanotechnology in nourishment science aligns with principles of sustainability and circular economy.

Ethical Considerations: Ethical implications surrounding the use of nanotechnology in food science should be addressed in research. This includes considerations related to equitable access, potential impact on traditional food practices, and addressing any unintended consequences on socioeconomic factors. Research should strive to promote ethical practices and evaluate the social, cultural, and economic implications of nanotechnology in the food sector.

By critically reviewing research in these areas, we can better understand the potential benefits and challenges associated with the application of nanotechnology in food science and ensure responsible and safe implementation (24-29).

7 CONCLUSION

7.1 The Bite-Sized Future: Embracing Nanotechnology in the Food Sector

Nanotechnology offers significant potential to transform the food sector by improving food packaging, food processing, and food safety. Through enhanced barrier properties, intelligent packaging systems, improved nutrient delivery, texture and sensory enhancement, and effective detection of contaminants, nanotechnology can contribute to safer, higher quality, and more sustainable food products. However, careful attention must be given to potential concerns related to the safety of nanomaterials, consumer perception, and the development of appropriate regulatory frameworks. With responsible implementation, nanotechnology has the power to revolutionize the food industry, benefitting both producers and consumers alike. Continued research, collaboration, and transparent communication are essential for harnessing the full potential of nanotechnology in the food sector.

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