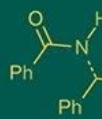


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Nanotechnology revolutionizing food packaging technology: A way forward

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Abstract

Nanotechnology, manipulating matter at the atomic and molecular levels, has emerged as a transformative force across various domains, from mechanics to medicine. In the food industry, Nanotechnology has enormous prospects for changing food processing, packaging, safety, and nutritional supplementation. This paper explores the profound impact of nanotechnology on food technology. The integration of nanotechnology into the food sector holds immense promise, facilitating the development of innovative products with enhanced nutritional profiles, extended shelf life, and improved sensory attributes. Nanoparticles and nanomaterials enable precise control over food qualities, leading to the reduction of chemical additives and preservatives. Advanced packaging solutions incorporating nanocomposites offer superior barrier properties, minimizing food deterioration and waste. Furthermore, nano sensors enable real-time monitoring of food quality, bolstering consumer trust and regulatory oversight. Despite these developments, problems remain, including safety issues, ethical considerations, and regulatory frameworks. Addressing these concerns is critical to ensuring that nanotechnology is integrated responsibly and sustainably into the food business. Furthermore, continuing research seeks to expand our understanding of how nanomaterials interact with biological systems, supporting the creation of new and safe food items. In conclusion, nanotechnology presents a paradigm shift in the food industry, offering transformative solutions to meet evolving consumer expectations and global challenges. While short-term challenges exist, the long-term benefits of food nanotechnology are substantial, promising a future where food technology is safer, healthier, and more sustainable.

Keywords: Nanotechnology, food safety, nutrient delivery, food processing, food packaging, cellulose nanocrystals

Introduction

Nanotechnology, a science that manipulate the matter at the atomic and molecular levels, has emerged as a revolutionary force in domains ranging from mechanics to medicine. Nanotechnology, defined by characteristic dimensions ranging from 1 to 100 nanometres, enables the development of innovative devices and procedures with unparalleled accuracy and usefulness. The nanoparticle is at the centre of this area, a small item that shows cohesive behaviour in terms of transport and attributes, classified according to size, structure, and features ^[1, 2]. Concurrently, nanomaterials science explores materials' features at the nano scale, unlocking novel properties and applications ^[3-5]. In the realm of food technology, the roots of food nanotechnology trace back to Louis Pasteur's pioneering pasteurization process, a method devised to eradicate spoilage bacteria marking the initial stride toward revolutionizing food processing and enhancing food quality. Subsequent milestones, such as Watson and Crick's elucidation of the DNA structure, with dimensions around 2.5 nm, catalyzed applications spanning biotechnology, biomedicine, agriculture, and production processes ^[6-8]. Notably, the discovery of carbon nanotubes, exemplified by the iconic Bucky ball fullerene at a mere 1 nm in size, heralded a new era of innovation and propelled the field of Nano science into prominence. Carbon, with its remarkable versatility, exhibits immense potential across various sectors, including the realm of food technology, promising ground breaking advancements and transformative solutions. Nanotechnology has a far-reaching and varied influence on food technologies. Food scientists are poised to alter food processing, packaging, safety, and nutritional supplements by using the unique properties of nanoparticles and nanomaterials ^[9-11].

Nanoparticles, with their small size and high surface area-to-volume ratio, enable precise control of food properties, increasing texture, flavor, and shelf life while minimizing the need for chemicals and preservatives. Nano-composites in packaging have exceptional barrier qualities, which reduce food deterioration and waste. Furthermore, Nano sensors provide real-time monitoring of food quality and safety, increasing customer trust and regulatory supervision. Also, nutritional supplements made with nanotechnology enable more effective nutrient delivery and absorption, correcting nutritional shortages and boosting general health. Despite these encouraging advances, further study is needed to address safety problems, ethical issues, and regulatory frameworks [12, 13]. Overall, the integration of nanotechnology has enormous potential to change the future of the food sector by providing new answers to changing consumer expectations and global concerns [14-16].



Fig 1: Nanotechnology Applications for Enhancing Food Quality and Safety

Overview of Nanotechnology use in the Food Industries

Nanotechnology is now widespread use in the food industry, after significant advances in the fields of electronics, mechanics, and medicine. There is widespread hope that nanotechnology will lead to significant advances in this field of agriculture in the future. 'Farm to fork' might imply higher manufacturing process control and complexity, improved functionality for present components, more efficient and targeted delivery of active ingredients to new meals, and changes in how food quality is monitored. Nanotechnology applications have the potential to profoundly transform the food business, with a significant impact anticipated [17-19]. Because of this potential, significant research has been conducted with the goal of gaining a fundamental understanding of how nanomaterials interact with biological systems and then using that knowledge to the development of novel and beneficial food products. This food revolution won't happen overnight. While food nanotechnology presents certain short-term obstacles, it also offers significant long-term advantages [20-23].

Importance of Nanotechnology in Food Processing and Preservation

1. **Advancements in Food Processing:** Nanotechnology enhances efficiency, accuracy, and quality control, transforming raw ingredients into marketable products [24, 25].
2. **Cutting-edge Food Innovations:** Nanotechnology empowers food scientists to develop novel products featuring enhanced nutritional profiles, extended shelf life, and elevated sensory attributes, catering to evolving consumer preferences and dietary needs [26, 27].
3. **Revolutionary Food Packaging Solutions:** Nanotechnology offers advanced materials with superior barrier properties, prolonging food freshness, mitigating spoilage, and enhancing safety throughout storage and transportation [28, 29].
4. **Securing Food Safety:** Nanotechnology elevates standards by detecting and eliminating contaminants, such as antimicrobial nanoparticles, and crafting nano barcodes for enhanced supply chain oversight [30-32].
5. **Maximized Nutritional Enhancements:** leveraging nanotechnology-enabled encapsulation methods to enhance the efficiency, bioavailability, and precision distribution of nutritional supplements and bioactive compounds within the body [33, 34].
6. **Refinement of Food Flavors and Textures:** Nanotechnology Facilitates Precise Ingredient Alterations at the Nano Scale, Resulting in Enhanced and Appealing Culinary Experiences [35, 36].
7. **Extending Shelf Life:** Through nanotechnology, food preservation can be enhanced by mitigating factors that contribute to spoilage, such as oxidation, microbial growth, and physical deterioration [37, 38].
8. **Elevated Food Preservation:** Nanotechnology-empowered advancements in food packaging and storage yield superior preservation techniques, safeguarding food quality and safety for extended durations [39, 40].

Nanotechnology in Food Processing

The complex transformation of basic components into edible goods, maximizing their marketability and prolonging their shelf life, is referred to as food processing. Toxin removal, disease prevention, preservation, and improving food consistency are just a few of the crucial duties that this complex process entails in order to enable effective marketing and distribution [41, 42]. Processed foods are especially well-suited for long-distance transit from manufacturing locations to end customers because of their increased resistance to early spoiling. Modern food production has undergone a revolution thanks to the use of nanotechnology, which has increased product quality and efficacy [43-46]. Nanotechnology has revolutionized food processing by offering alternative methods that enhance both the physicochemical properties of food and improve nutrient stability and bioavailability. The integration of nanotechnology into food systems has led to the creation of a wide array of innovative products boasting enhanced food quality attributes, including texture, taste, sensory properties, and stability, among others [47, 48]. The delivery method in transportation serves multiple roles, chiefly ensuring the conveyance of functional materials to their designated action sites. Moreover, it safeguards these

functional components from chemical or biological degradation, thereby preserving their efficacy. Additionally, the delivery method may regulate the release pace of the active substance and control the specific environmental conditions that trigger its dispensation^[49]. An efficient delivery system for nutrients and supplements is a crucial factor that significantly impacts the efficacy of food ingredients within the food industry. The application of nano-capsule delivery technologies, which are essential for improving functional qualities, brings about a paradigm change in food processing. These technologies precisely protect and distribute bioactive substances by encasing various solutions, colloids, emulsions, and biopolymers

inside nano-sized capsules^[50, 51]. Moreover, self-assembled structural lipids that are nano sized function as liquid transporters, making it easier to incorporate insoluble beneficial ingredients into food matrices as nano drops. Especially, these nano drops are remarkably effective in preventing cholesterol from entering the circulation via the digestive tract, which can lead to better health consequences. Utilizing nanotechnology, the food processing sector achieves previously unheard-of levels of efficiency and accuracy, encouraging the development of novel, nutritionally improved goods that satisfy the changing needs of contemporary customers^[52, 53].

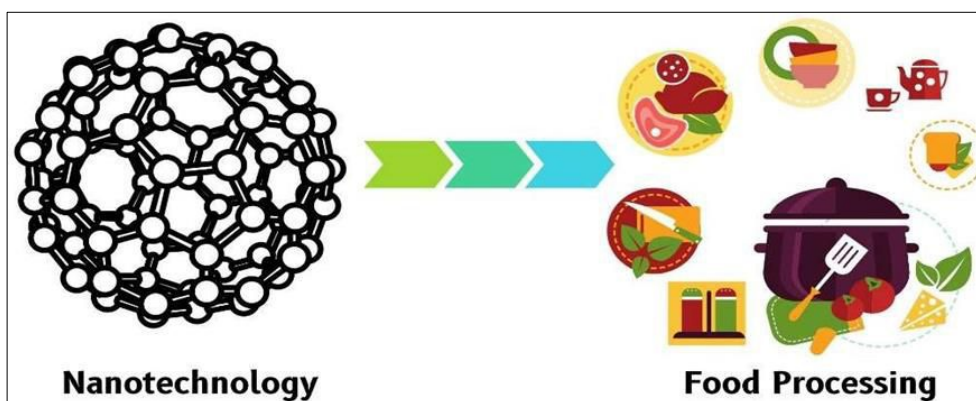


Fig 2: Employing Nanotechnology to Advance Food

Food Packaging

Food packaging is an essential component in the preservation and marketing of food. It serves a range of vital objectives, including resistance to manipulation, protection against external contaminants, and fulfilling particular chemical, biological, or physical criteria^[54, 55]. Furthermore, packaging provides customers with a means of receiving critical nutrition information, assisting them in making educated food decisions. Packaging is crucial for reasons other than keeping food confined; it influences how marketable and long-lasting food items are. Recent breakthroughs in packaging technology have brought about a revolution in the business, leading to improvements in packaging quality, design aspects that are aimed at the customer, and accurate shelf life determination. Additionally, the development of biodegradable packaging materials minimizes environmental effect and is in line with sustainability goals^[56, 57]. Due to its ability to prolong shelf life and ensure food safety, nanotechnology is essential to food packaging. It protects against environmental elements while maintaining food quality using active packaging. Food stability is improved with active packaging, which releases healthy compounds like antioxidants and antimicrobials. Nanocomposites facilitate controlled-release packaging, promoting the absorption of functional supplements like nutrients, vitamins, and probiotics in food. In this context, nanotechnology appears as a key facilitator, providing customized solutions for a range of packaging applications, from sophisticated sensors to barrier improvements, so accurately and effectively meeting particular packaging demands. Incorporating nanoparticles into food packaging opens up numerous possibilities, such as enhancing the existing capabilities of polymers *viz.* are barrier or mechanical characteristics or introducing new features such as active or biologically active packaging, sensing, and

control utilizing the intrinsic characteristics of nano additives^[58, 59].



Fig 3: Nanomaterial: Application in Food Packaging

Barrier Protection

Preserving food products necessitates creating an inert, low-oxygen environment to thwart microbial growth and spoilage, demanding packaging materials that effectively block gas permeation. Nano composites, integrated into polymer matrices, offer a compelling solution due to their expansive surface area, fostering robust filler-matrix interactions and heightened performance. Among these innovations, polymer nano composites stand out, featuring nano-reinforcements that impede gas transmission by intricately obstructing material pathways^[60, 61]. When nano-sized fillers are dispersed in a polymer matrix, they impact the barrier characteristics of the film in two ways. Firstly,

they create a tortuous pathway for gas diffusion, including oxygen, carbon dioxide, and vapor. These fillers, being impermeable inorganic crystals, force air molecules to disperse around them instead of following a straight-line channel perpendicular to the film surface. As a result, the inclusion of fillers increases the average channel for gas exchange across the film, improving its barrier characteristics. Notably, nano clays generated from complicated metallic ores such as Montmorillonite act as effective gas barriers. These chemicals improve the quality

of food packaging. They can be manufactured synthetically using nylons, polyolefin, PET, PA, epoxy resin, and poly methane, or from volcanic ash [62]. The enhanced thermal resistance and barrier properties of nanocomposite films incorporating graphene nano plates in food packaging applications. Synthesized starch-based composites (biodegradable polymers) containing nano clays with montmorillonite nanoparticles to improve barrier and mechanical properties [63].

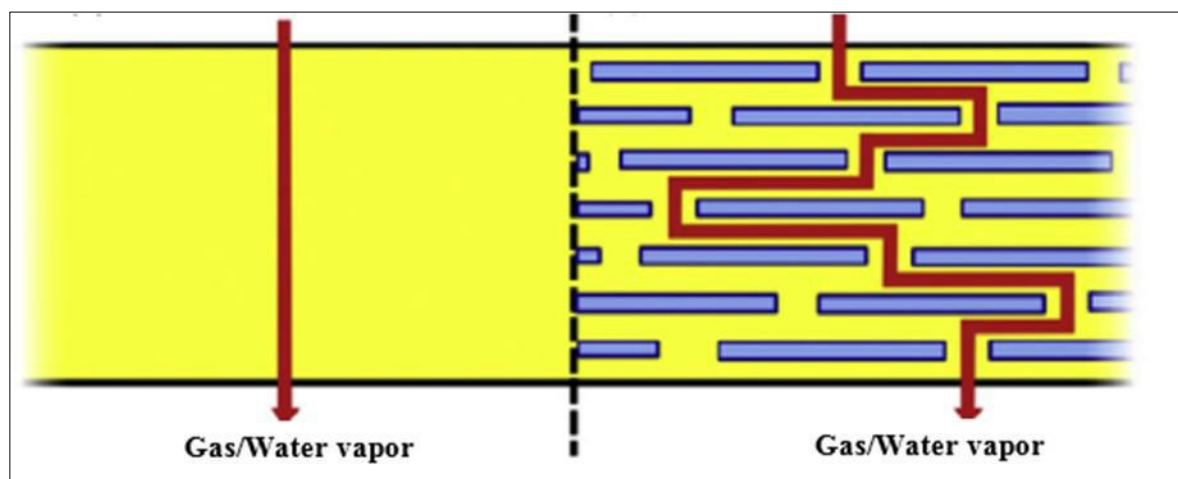


Fig 4: Barrier properties improvement due to nano-fillers

Commercial names such as Durethan, Imperm, and Aegis are examples of Nano clays that are based on polyamide and embody strength and resilience. New Nano composites are being investigated, such as those made of cells and carbon nanotubes, and packaging is crucial to the commercialization of a product, as research on this topic continues [64–67]. Different food packaging materials such as active/smart packaging uses nanotechnology. Nano devices or nano sensors integrated with polymers are utilized in smart food packaging to detect pathogens and contaminants during storage and transportation [68]. Furthermore, smart food packaging not only safeguards the integrity of the food package but also ensures the validity of the product. These devices can monitor factors such as duration, temperature, and expiration date. Recent studies indicate that nano sensors integrated into food packaging can effectively detect food spoilage organisms such as pathogens, contaminants, and toxins. In active food packaging, antibacterial nanocomposites utilize nano fillers such as ZnO, Cu, Cu₂O, CuO, TiO₂, and Ag, while self-cleaning surfaces employ TiO₂ and SiO₂-based nano fillers.

Antimicrobial Packaging

Antimicrobial packaging that contains natural nanoparticles effectively limits microbial growth and lowers the risk of pathogen contamination or food spoilage. It is a key milestone in food preservation. Silver nanoparticles are the most effective antibacterial agent available and are used extensively in a variety of applications, including kitchenware, electrical appliances, and bio fabrics. Silver nanoparticles, by virtue of their intrinsic antibacterial characteristics, demonstrate strong activity at the bulk level, stifling a wide range of bacterial biological activities. Silver antibacterial agents function through mechanisms including adhesion to cellular surfaces, disruption of cellular

membranes, DNA damage, and the silver ions discharge [69, 70]. In a similar vein, zinc oxide nanoparticles exhibit increased antibacterial activity as their particle size decreases, a characteristic that is intensified when exposed to visible light [71, 72]. The antibacterial properties of certain polymers, such as polypropylene, are enhanced by the smooth integration of these nanoparticles. Another crucial element is titanium dioxide, which is utilized as a coating in packaging materials to effectively prevent E. Coli development. Moreover, the synergistic pairing of antimicrobial compounds, such silver and titanium dioxide, strengthens the protective layer of packaging materials by improving the disinfection process. Chitosan, which is made from chitin, is an example of how recent developments in biopolymer technology have revealed new antibacterial qualities, increasing its usefulness in encapsulating and packaging applications. A new age of food safety and customer confidence is heralded by the introduction of antimicrobial packaging, which promises healthier and more consumer-friendly products [73, 74].

Biodegradable packaging

Pollution is a major issue that has a significant effect on the balance of the environment. The spread of non-biodegradable plastics exacerbates the threat of global warming by degrading soil and encouraging the build-up of harmful gasses. Biodegradable polymers have emerged as a possible option to mitigate these detrimental impacts, but they have historically battled with issues including low mechanical strength and susceptibility to gas and water leakage. Presenting packaging materials enhanced by nanotechnology, which include both natural and manmade nanoparticles with unique characteristics including robustness and biodegradability. These nanoparticles, which are derived from proteins, carbohydrates, lipids, and metal

oxides, provide a strong answer to packaging problems [75, 76]. Additionally, nanofibers made from cellulose, zein, and collagen have extraordinary porosity, which increases their usefulness in packing. When these nanomaterials are mixed with nano clays, packaging solutions are produced that include sensors, biocatalysts, and antibacterial action in addition to being environmentally sustainable. Fundamentally, the use of nanotechnology into biodegradable packaging signals a paradigm shift toward environmentally responsible solutions that balance technical advancement and environmental care [77, 78].

Smart Packaging

Sensors play an important function in sensing the physical properties of substances and translating them into identifiable signals in order to aid the regulation of internal food environment. Timely interventions to uphold quality and safety requirements are made possible by continuous monitoring of food attributes. At the moment, oxygen scavengers, moisture absorbers, and barrier packing goods make up around 80% of the market share in the smart packaging environment. Particularly in the bread and meat product industries, nano-enabled packaging methods have gained considerable popularity. As soon as they detect changes in temperature, oxygen concentrations, or the presence of pathogens, smart packaging systems continually monitor the food environment and send out appropriate alarms. By identifying changes in important indicators, nano sensors are essential in assessing the shelf life of products. For example, enzymes integrated into gold nanoparticles enable the detection of microorganisms, whereas perylene-based nano fibrils fluorophore-based gaseous amines signal the spoiling of fish and meat. Moreover, the identification of volatile organic chemicals is made possible by nano composites made of zinc oxide and titanium oxide, which improves food safety procedures [79–81]. Furthermore, Nano barcodes support security measures and make product tagging easier for tracking purposes. Packaging that incorporates smart sensors helps both manufacturers and customers. Producers gain from increased food product authenticity and distribution efficiency, while consumers benefit from greater quality identification and assurance. Therefore, implementing smart sensor technology is a critical step forward in guaranteeing food safety, quality, and transparency all the way through the supply chain.

Nutritional Supplements

In recent decades, the intersection of nutrition and nanoscience has flourished, fostering a significant interest in the precise delivery of micronutrients. Nano-capsules have emerged as a method to enhance the delivery of drugs and micronutrients, including vitamins and minerals, within the body. Various techniques, such as nano-composite, nano-structuring, and nano-emulsification, are employed to encapsulate materials into miniature forms, enabling more efficient delivery of bioactive compounds. Polymeric nanomaterials are utilized to formulate encapsulated bioactive constituents, such as flavonoids and vitamins, ensuring protected nutrient delivery [82]. This strong expansion highlights the significant influence of Nano cuticle supplements, often known as "Nutrition-benanootech" supplements, which have the potential to completely transform the field of nutritious supplementing. One notable breakthrough that improves the body's nutrition

absorption is the use of powders containing nanoscale particles. In the meanwhile, Nano cochleate became a powerful instrument for nutrition food products' color or flavor while enabling effective absorption through distribution to cells. By dispersing Nano droplets, vitamin sprays enhance the bioavailability and absorption of nutrients [83, 85]. In order to deliver probiotics, other bioactive compounds, and other nutrients to the human body in a targeted manner, encapsulation techniques are critical to supplement development. Target cells are precisely delivered to by use of iron and zinc nanostructured capsules, which act as efficient transporters. Dietary supplements enabled by nanotechnology, in particular, provide a variety of advantages over their traditional counterparts due to their increased effectiveness. Their small size makes it possible for them to interact with human cells more effectively, which improves their bioavailability and absorption. Therefore, with their unmatched potential to improve human health and wellbeing, food supplements improved with nanotechnology mark a paradigm change in the field of nutritional supplementation [86, 87].

Innovative approaches to improving the bioavailability and targeted distribution of nutrients in food items are provided by nanotechnology. Vitamins, antioxidants, and other bioactive substances can be encapsulated in nanostructured carriers as liposomes, nano emulsions, and nanoparticles to prevent degradation during processing and digestion. By increasing nutrient absorption in the gastrointestinal tract, these nanoscale delivery systems can augment the nutritional and therapeutic advantages of nutrients. Additionally, the regulated release of nutrients made possible by nanotechnology allows for continuous administration over time, which is especially advantageous for functional meals and dietary supplements. Nanotechnology improves the bioavailability and effectiveness of nutrients, which helps the creation of more nutritious food items that are healthier, perhaps resolving nutritional deficiencies and advancing general health and wellbeing [88-90]. Curcumin mixed with colloidal nanoparticles was observed to have better absorption effectiveness than natural curcumin powder [91].

Challenges and Considerations in Integrating Nanotechnology into Food Industry

Advances in nanostructures have been rather restricted, despite tremendous scientific breakthroughs in bringing nanotechnology to the food sector. Despite the potential of nanotechnology to revolutionize food manufacturing and processes, numerous barriers remain to be addressed. As research in food nanotechnology progresses, concerns about the safety of nanotechnology products for human consumption continue to grow [92-94]. As a result, a thorough evaluation of the possible health risks connected with nano food items is required before they are commercialized. However, no standardized guidelines for assessing the safety of nanomaterials in food items have been created. A significant problem is the development of edible delivery methods that are both inexpensive and safe for human consumption [95, 96]. Food safety requires resolving issues linked to the migration and absorption of nanoparticles from packaging materials into food items. Understanding the impact of nanoscale materials is difficult because of their distinct characteristics. Understanding the functions and toxicities of nanomaterials at the nanoscale will improve the

safety requirements for their practical use. It is critical to improve safety assessments of nanoparticles in food by concentrating on exposure and hazardous response mechanisms. The biological impacts of nanoparticles in food include oxidative stress, protein denaturation, and DNA damage [97]. Currently, there is no established approach for evaluating the safety of nanoparticles, particularly those used in food. To successfully control the use of nanoparticles in food, risk assessments and safety management methodologies must be developed that are matched with contemporary toxicity testing aims.

Conclusions

To summarize, nanotechnology represents a new frontier in the food sector, providing revolutionary solutions that will transform food processing, packaging, safety, and nutritional supplements. The combination of nanoparticles and nanomaterials allows for precise control over food quality, resulting in enhanced texture, taste, and shelf life while decreasing the need for chemical additions. Advanced packaging materials with exceptional barrier qualities help to preserve food freshness, reduce spoiling, and improve safety throughout storage and transit. Furthermore, nano sensors provide real-time monitoring of food quality and safety, increasing customer trust and regulatory supervision. Nutritional supplements produced using nanotechnology improve nutrient delivery and absorption, correcting nutritional shortages and enhancing general health. While these developments show great potential, further study is required to address safety problems, ethical considerations, and regulatory frameworks. Finally, nanotechnology integration has the ability to meet changing consumer demands and global concerns, so profoundly impacting the future of the food sector.

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Authors' Contribution

Dr. Meet, Dr. B. L. Jani and Dr. B. M. Devani collected all reviews and have prepared the contents in the manuscript which was then rectified by Dr. S. H. Akbari and Dr. J. J. Dhaduk.

Conflict of Interest

The authors declare that there is no conflict of interest.

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