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Nanotechnology applications in dairy industry: Safety and quality enhancement

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Abstract
Nanotechnology has emerged as a transformative technology with significant potential to enhance the safety, quality, functionality, and shelf life of dairy products. The unique physicochemical properties of nanomaterials, including their high surface area, improved reactivity, and enhanced bioavailability, have enabled the development of innovative applications across the dairy industry. This review provides a comprehensive overview of recent advances in nanotechnology and their applications in dairy processing, packaging, preservation, and quality assurance. Nanotechnology-based approaches such as nanoencapsulation, nanoemulsions, nanocomposites, nanosensors, and antimicrobial nanoparticles have been extensively investigated for improving nutrient delivery, product stability, microbial safety, and sensory attributes. Nanoencapsulation techniques have shown considerable promise in protecting sensitive bioactive compounds, probiotics, vitamins, and omega-3 fatty acids from degradation while enhancing their controlled release and bioavailability. Furthermore, intelligent packaging systems incorporating nanomaterials can monitor product freshness, detect contaminants, and extend shelf life through improved barrier and antimicrobial properties. Nanosensors offer rapid, sensitive, and real-time detection of pathogens, toxins, adulterants, and quality parameters, thereby strengthening food safety management systems. Despite these advantages, concerns regarding the potential toxicity, environmental impact, migration behavior, and regulatory aspects of nanomaterials remain critical challenges that require thorough investigation. Therefore, comprehensive risk assessment, standardized safety evaluation protocols, and clear regulatory frameworks are essential to ensure consumer acceptance and sustainable implementation. Overall, nanotechnology represents a promising tool for advancing the dairy sector by improving product quality, safety, nutritional value, and processing efficiency. Future research should focus on developing cost-effective, safe, and environmentally sustainable nanotechnology-based solutions for commercial dairy applications.

Keywords: Nanotechnology, dairy industry, nanoencapsulation, nanoemulsions, nanosensors, food safety, quality enhancement, intelligent packaging, antimicrobial nanoparticles, shelf life

Introduction
Nanotechnologies comprise a range of technologies, processes, materials and applications that involve manipulation of substances at sizes in the nanoscale range i.e. materials with one dimension of approximately 1-100 nanometers (nm) (1 nm = 10 metre or one billionth of a metre). By comparison, the bacterium *E. coli* is around 2,000-4,000 nm in length. There has been some concern about the safety of nanotechnology and its use in the food industry. It is important to remember that foods are naturally composed of nanoscale materials e.g. sugars, amino acids, peptides and proteins. Many of these substances also form organised, functional nanostructures, and we have consumed these materials in foods without evidence of adverse effects for decades. The term 'nano' is a Greek word, means dwarfaned signifying 1 billionth of a meter ($1nm=10^{-9}m$). The term "Nanotechnology" was first used in 1974 by the late Norio Taniguchi and concepts were given by Richard Feynman in 1959.

Nanotechnologies link various disciplines, including physics, chemistry, biological sciences, medicine, cognitive sciences, engineering, information, and communication technologies and, therefore, represent the real convergence of modern fields of knowledge. A special role is played by food nanotechnologies, which have become an active area for various studies and demonstrate exponential growth in publications. Nanotechnology in the food and especially in the dairy industry is constantly evolving as there is a wide area of research in the processes of efficient processing of raw materials, the development of functional products, the preservation of finished products, their packaging and storage. Food and agricultural manufacturers with proper use of achievements in nanotechnology can gain a competitive position in the markets. Nanotechnologies can provide new ways and tools for controlling the properties and structuring food products, introducing new functions and creating added value through it. The huge potential of using nanotechnologies in the field of food production is able to eliminate existing problems and give a new impetus to the production development. Potential applications of nanotechnology in dairy sector include new ways of processing raw materials, higher quality food, increase of shelf life and improvement of the safety of dairy products, use of new packaging materials with better mechanical, barrier and antimicrobial properties. Recently, there has been considerable interest in exploring the potential of nanotechnology in encapsulating and delivering biologically active substances, enhancing the taste and other sensory characteristics of food products, and introducing antibacterial nanostructures into packaging. By reducing the particle size, nanotechnology can improve the properties of biologically active compounds, such as delivery, solubility and absorption through cells, and it changes the properties of the finished product.

Two major approaches
1. Top down
2. Bottom up

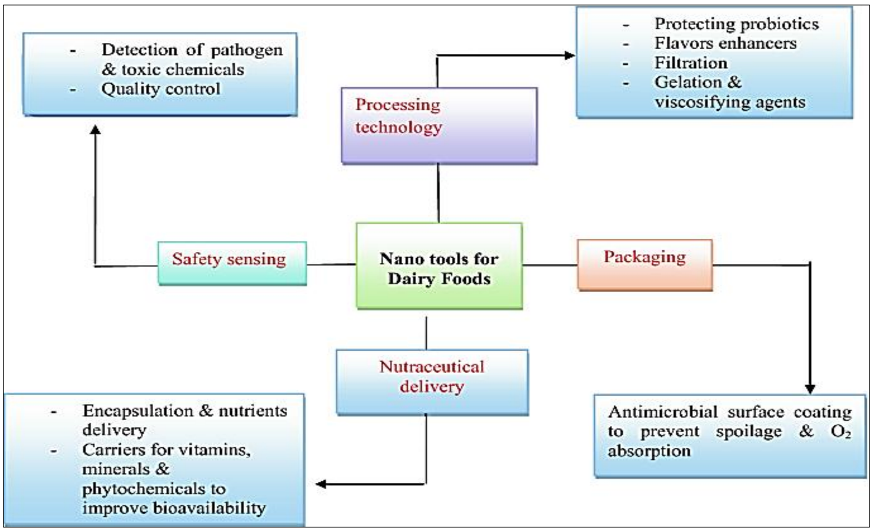
Two major approaches can be described in nanotechnologies: top down and bottom up. The top-down approach involves starting with a larger piece of material and creates nanoparticles. For example, the antimicrobial activity of silver is improved when the size of the powder is reduced to nanometer scale (Jeong *et al.*, 2014) [31].

On the other hand, bottom-up approach involves building of structures, atom-by-atom or molecule-by-molecule. Typically, large numbers of atoms or molecules or particles are used or created by chemical synthesis, and then arranged through naturally occurring processes into a desired structure (Ravichandran, 2010) [30].

What is nanofoods?

- The term "Nanofood" describes the food which has been cultivated, produced, processed or packaged using nanotechnology techniques to which manufactured nanomaterials have been added.
- Two forms of nanofood applications:
- food additives (nano inside)
- food packaging (nano outside)

The concept of nanofoods refers to the application of nanotechnology in the food industry to develop and improve food products using nanoscale materials, techniques, and processes. Nanofoods involve the incorporation of nanoparticles or nanoscale ingredients into food products to enhance their properties, functionality, and safety.
Nano inside food additives, also known as internal or primary nanofood additives, refer to the use of nanotechnology to incorporate nanoscale ingredients or additives directly into food products. These nano additives are intended to enhance various properties of the food, such as texture, taste, nutritional value, and stability.
Nano outside food packaging, also known as external or secondary nanofood packaging, refers to the application of nanotechnology on the exterior surfaces of food packaging materials. While the primary purpose of food packaging is to protect and preserve the food inside, nano outside packaging focuses on additional functionalities and properties that can be achieved through nanotechnology.

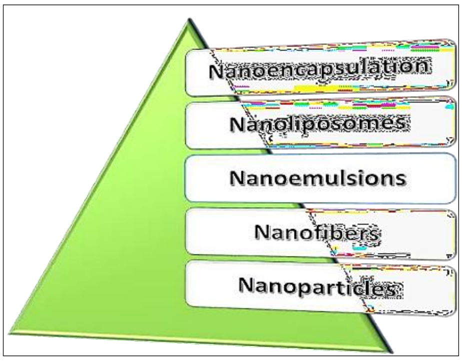


5. Application of nanotechnology in dairy industry

Nanotechnology is the most revolutionary scientific approach in food sector and especially in milk and milk products. It can be applied in different areas of food production, i.e. development of new functional ingredients, their processing at micro- and nanoscale; and in food safety and quality. There are many advantages of using nanomaterials in dairy industry. They can be useful as encapsulating agents for vitamins, antioxidants, flavours, minerals and other nutrients that are important for fortification of milk and milk products. They also play an important role in the formulation of novel-packaging materials and biosensors for protection against disease-causing microorganisms.
Various other areas like protection of milk products from spoilage and oxidation can also be benefited by the application of nanomaterials. Nanoparticles used in food and dairy industry can be divided into four major groups such as metals, polymers, natural compounds and nano-structured materials. Some biologically active nanomaterials can

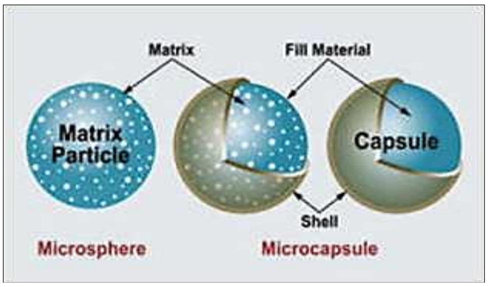
protect food from opportunistic microorganisms. Due to the greater surface area of nanoparticles, they are expected to be more biologically active than larger sized particles of the same chemical composition.

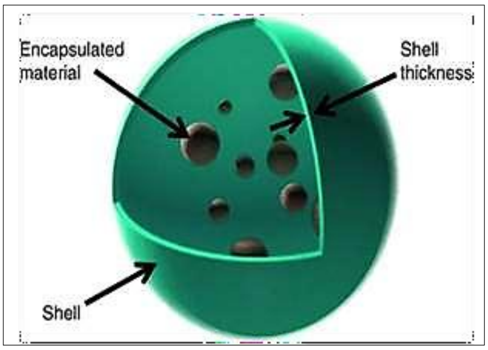
6. Nutrients delivery systems used by nanotechnology



Nanoencapsulation

- Nowadays, many nanotechnology companies are developing dairy products with different nano-encapsulated ingredient. The main function of using nanoscale food additives is to improve flavour, texture, nutritive value of the dairy foods.
- The purpose of nano-encapsulation of different food products is to formulate the particle size of these nutrients less than 100 nm so that they can cross the stomach wall into the cells rapidly than the nutrients with larger particle size.





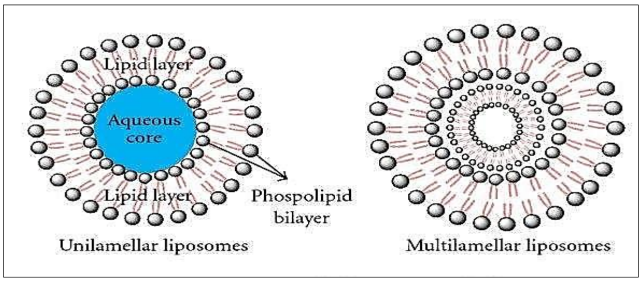
Nano-encapsulation is defined as a technology to pack substances in miniature making by using nanocomposite, nano-emulsification, and nano structuration and provides final product functionality that includes controlled release of the core.

The protection of bioactive compounds, such as vitamins, antioxidants, proteins, and lipids as well as carbohydrates may be achieved using this technique to produce functional foods with enhanced functionality and stability.

Probiotics are generally defined as live mixtures of bacterial species and can be incorporated in foods in the form of yoghurts and yoghurt-type fermented milk, cheese, puddings and fruit-based drinks. Encapsulated forms of ingredients achieve longer shelf-life of these products.

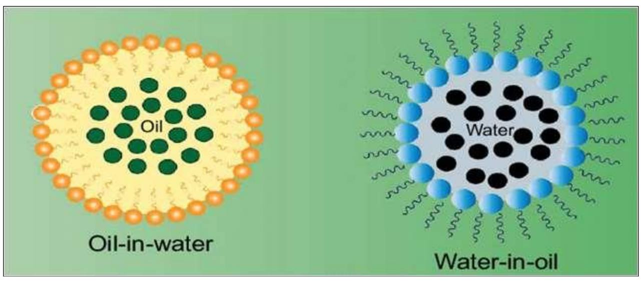
Nanoliposomes

- Nanoliposomes are a type of delivery system used in nanotechnology for the targeted delivery of drugs, nutrients, or other bioactive compounds. They are formed by one (unilamellar) or several (multilamellar) lipid bilayers enclosing water and their sizes can range between 1 to 50 nm.
- Nanoliposomes are water soluble self-assembled structures formed mainly by polar lipids.
- The liposomes can encapsulate hydrophobic or hydrophilic substances within their aqueous core or lipid bilayers, allowing for controlled release and protection of the encapsulated compounds.
- The liposomes can encapsulate hydrophobic or hydrophilic substances within their aqueous core or lipid bilayers, allowing for controlled release and protection of the encapsulated compounds. Nanoliposomes are water soluble self-assembled structures formed mainly by polar lipids.
- Addition of nanoliposomes with enzyme are able to accelerate and improve the efficiency of cheese-ripening process and also prevent the development of off-flavors.
- Gortzi *et al.* (2008) reported a 25% increase of antimicrobial and antioxidant activity of *Myrtus communis* extracts after encapsulation into nanoliposomes than the same extract in pure form.



Nanoemulsion

Nano-emulsions consist of a lipid-phase discrete in continuous aqueous phase, with each oil droplet being bounded by a thin interfacial layer consisting of emulsifier molecules. The main characteristics of NE are good stability and thermodynamically stable compared to the normal conventional emulsions. Due to their small size (50-500 nm) and mono-dispersivity, they can be diluted without any change in the droplet size.



The mechanism of action of NE and food ingredients (such as proteins, polysaccharides and phospholipids); and process such as homogenization and mixing that are being used extensively in the manufacture of food emulsions are reviewed in some reports. In one study, nano-emulsion purple rice bran oil (PRBO) was added as a source of natural antioxidants including tocopherol, tocotrienol, and oryzanol in frozen yogurts (FY), which improved the nutritional profile of the product by substantially increasing the natural antioxidant content.

Nanofiber

Nanofibres with diameters from 10 to 1000 nm, produced from synthetic polymer through electrical spinning. Because of fiber from not a food grade biopolymer, it is limited used in food industry. Nanofibers are used as structural component of green food packaging, platform for bacterial culture and structural matrix for artificial food. Nanofibers have shown promising applications in the dairy industry, particularly in the development of innovative food products, packaging materials, and filtration systems.

Food Product Development: Nanofibers can be incorporated into dairy products to enhance their texture, stability, and nutritional value. For example, nanofibers derived from natural polymers like cellulose or chitosan can be used as thickeners or stabilizers in yogurt or cheese production. These nanofibers improve the texture and mouthfeel of the products, while also providing structural stability and reducing syneresis (whey separation) during storage.

Nanoparticles

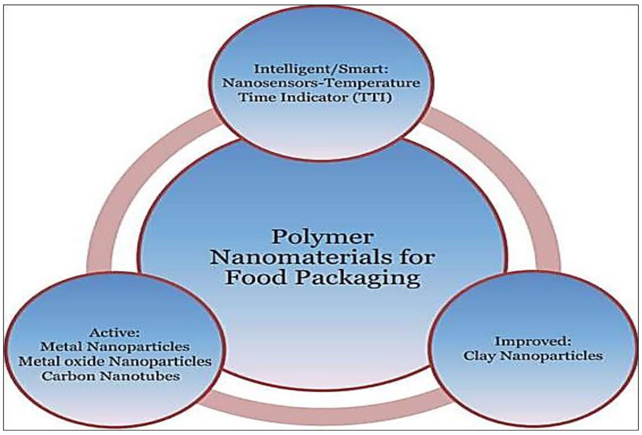
Nanoparticles used in dairy products are mainly composed of inorganic materials, such as silver, iron oxide, titanium dioxide, silicon dioxide, or zinc oxide. Weir *et al.* (2012) [29] suggest that adding titanium dioxide nanoparticles (TiO_2) could improve texture and color of some low-fat dairy products.

1. **Silver nanoparticles**: Silver nanoparticles have antimicrobial properties and are used in dairy products to inhibit the growth of bacteria and extend shelf life. They can be incorporated into packaging materials or added directly to dairy products to reduce microbial contamination and improve food safety.
2. **Zinc oxide nanoparticles**: Zinc oxide nanoparticles have been studied for their potential antimicrobial effects in dairy products. They can help inhibit the growth of pathogens and spoilage-causing microorganisms, thereby improving product quality and extending shelf life.
3. **Titanium dioxide nanoparticles**: Titanium dioxide nanoparticles are used as food additives in various industries, including dairy. They are primarily used as whitening agents and can improve the color and appearance of dairy products such as cheese, yogurt, and ice cream.
4. **Silica nanoparticles**: Silica nanoparticles have been investigated for their ability to improve the texture and stability of dairy products. They can act as stabilizers, emulsifiers, or thickeners, enhancing the mouthfeel and sensory properties of products like yogurt and ice cream.
5. **Iron oxide nanoparticles**: Iron oxide nanoparticles have been used in dairy products to fortify them with iron, addressing nutritional deficiencies. These nanoparticles are encapsulated with food-grade materials to ensure stability and bioavailability of the iron.
6. **Calcium carbonate nanoparticles**: Calcium carbonate nanoparticles have been explored to fortify dairy products with calcium. They provide a highly bioavailable source of calcium, contributing to the nutritional value of products such as milk, cheese, or yogurt.

7. Application of nanotechnology in packaging

Nanotechnology can provide solutions for some problems in packaging systems, for example

1. Modifying the permeation behaviour.
2. Increasing barrier properties (mechanical, thermal, chemical and microbial).
3. Improving mechanical properties.
4. Heat-resistance properties.
5. Developing active antimicrobial and antifungal surface sensing as well as signaling microbiological and biochemical changes



The application of nanotechnology in food packaging opens new possibilities for improving packaging materials properties by adding reinforcing compounds to polymers to enhance their thermal, mechanical, barrier, and antimicrobial properties (Sorrentino *et al.*, 2007) [32]. Nanocomposites can improve mechanical strength; reduce weight; increase heat resistance; and improve barrier against oxygen, carbon dioxide, ultraviolet radiation, moisture, and volatiles of food package materials. Most food packaging applications developed to date incorporate metal or oxide nanoparticles or more commonly nanoclays to improve the barrier property and the antimicrobial property of the packaging materials. Biodegradable starch-based polymers have poor moisture barrier properties due to their hydrophilic nature and inferior mechanical properties compared to plastic films. The incorporation of nanoclay particles in starch polymers has been reported to improve moisture barrier and mechanical properties (Avella *et al.*, 2005) [33]. Therefore, the application of nanocomposites promises to expand the use of biodegradable films.

The improvement of packaging materials quality can subsequently increase food shelf life. In particular, success of packaging materials for fresh products greatly depends on the control of internal gas composition and water loss in the packaging. In this context, the addition of silver and titanium dioxide nanoparticles in polyethylene film significantly decreased the oxygen and water vapor permeability of film and reduced kiwifruit decay and maintained their quality during postharvest storage (Hu *et al.*, 2011). Moreover, the use of metal nanoparticles in polymeric matrices developed materials with new properties, such as active packaging for ethylene oxidation or oxygen scavenging. For example, photoactive titanium dioxide can oxidize ethylene to water and carbon dioxide, thus controlling microbial development and oxygen in the headspace.

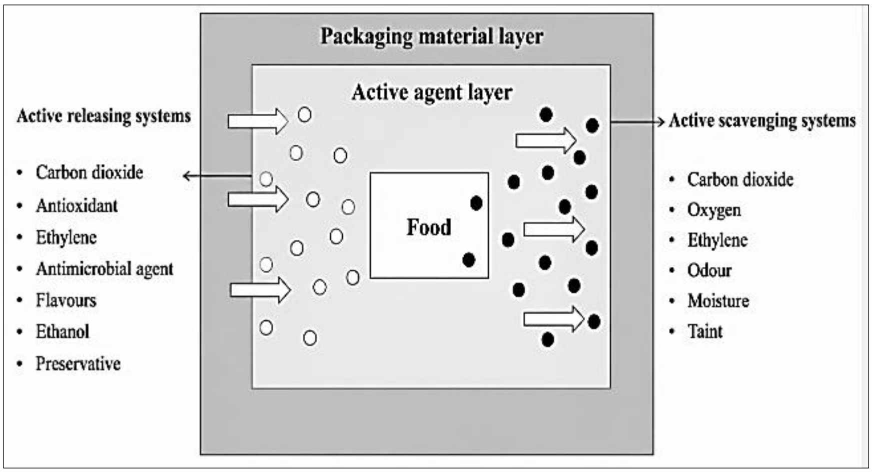
In addition, nano-packaging is also designed to release antimicrobials, antioxidants, enzymes, flavors and nutraceuticals compounds (Cha and Chinnan, 2004) [34]. Nanocomposite films with antimicrobial activity could help to control growth and development of spoilage microorganisms in food. Antimicrobial packaging systems include the addition of an antimicrobial nanoparticle into the polymeric matrix, the dispersion of bioactive agents on the packaging or the deposition of an active coating on the material surface (Neethirajan and Jayas, 2011) [35]. Antimicrobial nanoparticle coatings on the polymeric matrix can reduce bacteria development on the food product put in contact with the film and can prevent any post-contamination.

Metal oxide nanoparticles are the main nanoparticles used for active food packaging. Their activity can be described to several mechanisms, including induction of oxidative stress, due to generation of reactive oxygen species, which may cause the degradation of the membrane structure of the cell and release of ions from the surface of nanoparticles that cause bacterial death. The most common nanocomposite is the silver-based system, well known for its high stability and its strong toxicity to a wide range of microorganisms. Dairy products shelf life is influenced by both microbial and sensorial change due to the development of undesirable microorganisms. Some of them are spoilage microorganisms that may produce change in visual appearance of cheese; other ones are pathogens that affect product safety. Pseudomonas spp. is considered a very common spoilage microbial group able to proliferate in dairy products. The most common spore-forming bacteria found in dairy products are Bacillus spp. responsible of cheese alterations and defects. *E. coli* and *Listeria monocytogenes* are two of the major pathogens present in unpasteurized milk and soft cheese. A brief overview of some recent study on nanocomposite systems to enhance the antioxidant and antimicrobial activity of packaging to improve shelf life of dairy products is reported.

Active packaging

Active packaging in the context of nanotechnology refers to the integration of nanoscale materials or structures into packaging systems to provide enhanced functionalities for food preservation, safety, and quality. Nanotechnology offers unique opportunities to develop active packaging solutions with improved performance and efficiency. Here is some detailed information about active packaging in the context of nanotechnology:

Nanoscale Materials: Nanotechnology enables the use of nanoscale materials, such as nanoparticles, nanocomposites, or nanofibers, in active packaging. These materials possess unique properties due to their small size and high surface-to-volume ratio, which can be harnessed to deliver targeted functionalities. For example, silver nanoparticles can provide antimicrobial activity, while nanoclays can enhance barrier properties.



Enhanced barrier properties: Nanoscale materials can enhance the barrier properties of packaging films or coatings. By incorporating nanoparticles or nanocomposites, active packaging can offer improved resistance to gases, moisture, and light, reducing the permeation of oxygen, water vapor, and UV radiation. This helps extend the shelf life and maintain the quality of packaged food.

1. **Antimicrobial activity**: Nanotechnology enables the development of active packaging with antimicrobial properties. Silver nanoparticles, zinc oxide nanoparticles, or other nanomaterials with antimicrobial activity can be incorporated into packaging materials to inhibit the growth of microorganisms, thereby improving food safety and reducing spoilage.
2. **Oxygen scavenging**: Nanoscale oxygen scavengers can be integrated into packaging materials to remove oxygen from the package's headspace, thereby reducing oxidative reactions and extending the shelf life of oxygen-sensitive products. Nanoscale iron-based or enzyme-based systems can efficiently scavenge oxygen, protecting the quality and freshness of food.
3. **Intelligent packaging and sensors**: Nanotechnology can enable the development of intelligent packaging with built-in sensors and indicators. Nanosensors can detect and provide real-time information about changes in temperature, moisture, or gas concentrations, helping monitor the freshness and quality of the packaged food. This information can be relayed to consumers or supply

chain stakeholders to make informed decisions about product usability or safety.

4. **Controlled Release Systems**: Nanotechnology allows for the development of controlled release systems within packaging materials. Nanocarriers or nanocapsules can encapsulate active substances, such as antimicrobials, antioxidants, or flavor compounds, and release them gradually over time. This controlled release enables targeted and sustained functionality, improving food preservation and enhancing sensory attributes.
5. **Nanobiosensors for food safety**: Nanotechnology can facilitate the development of nanobiosensors for food safety applications. These nanosensors can detect and identify foodborne pathogens, contaminants, or toxins with high sensitivity and specificity. Nanobiosensors can be integrated into packaging materials to provide rapid and on-site testing capabilities, enhancing food safety and reducing the risk of foodborne illnesses.

8. How NC increase the barrier properties of packaging material?

The presence of nano fillers (clays, silicate) creates a complicated path for water and gas molecules to pass through the packaging material (Radha K., 2014) [25].

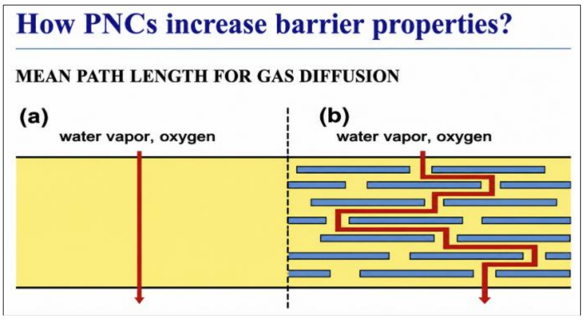
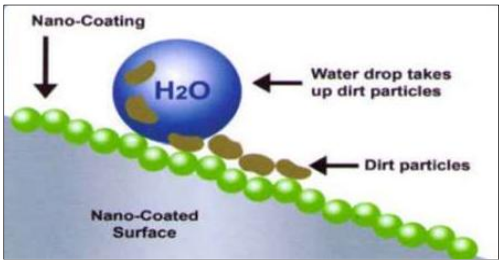


Illustration of the "tortuous pathway" created by incorporation of exfoliated clay nanoparticles into a polymer matrix film.

1. In a nanocomposite film, diffusing molecules navigate around impenetrable particles and through interfacial zones which have different permeability characteristics than those of the virgin polymer. The tortuous pathway increases the mean gas diffusion length and, thus, the shelf-life of foods (Duncan, 2011) [7].
2. Diffusing gas molecules migrate via a pathway that is perpendicular to the film orientation in a film composed only of polymer.

Nano coating

Recently, waxy coating is used extensively for increasing the shelf-life of apples, cheeses and other foods. By using nanotechnology edible coatings in nanoscale (5 nm) can be developed which are invisible to the human eye. These coatings and films are currently used on a large variety of foods, including fruits, meats, chocolate, vegetables, candies, bakery products, cheese. Nanocoatings used in dairy products play an important role as they serve as a barrier for moisture, lipid and gas and also act as carriers of releasing agents of colours, flavours, nutrients, antimicrobials and antioxidants (Radha *et al.* 2014) [25]. In nanocoatings, two or more than two layers of nano-laminates are used with nanometer dimensions. These nanomaterials are bonded physically or chemically to each other, and various functional components like antioxidants, flavours, enzymes and colours can be incorporated in these nanostructures. Spray drying technique is used for the nanocoatings with nano-laminates. Some researchers have reported that use of nano-laminate coatings for the preservation of Coalho cheese and found it effective to increase the shelf-life of cheese than the uncoated cheese due to gas barrier and antibacterial properties of nanocoatings.

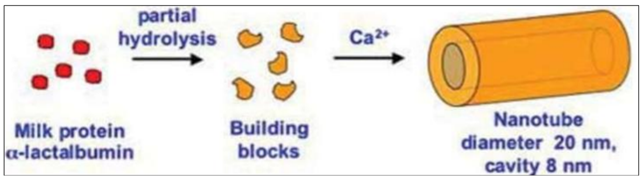


Nanotubes

Certain globular proteins from milk can be made to self-assemble to form nano tubes under appropriate conditions. A-lactalbumin is a milk protein which is beneficially used in the production of nanotubes. A-lactalbumin nano tubes are formed by self-assembly of the partially hydrolysed molecule. At neutral pH and in the presence of an appropriate cation, these building blocks self-assemble to form micro meter long tubes with a diameter of only 20 nm. These features of the α-lactalbumin nano tube make it an interesting potential encapsulating agent. Nanotubes of α-lactalbumin have a cavity diameter of 8 nm which enables the binding of food components such as vitamins or enzymes. The cavities can also be used to encapsulate nutraceuticals or to mask undesirable flavour/aroma compounds (Bikker and Kruif, 2006). Since, α-lactalbumin is a milk protein it will be fairly easy to apply the nano tubes in foods or pharmaceutics.

Advantages

- Enable to bind with food components. E.g. vitamins or enzymes.
- Mask undesirable flavor or aroma compounds
- Considered food-grade material



9. Nano sensor

Packaging equipped with nanosensors is also designed to track track either the internal or external conditions of dairy products throughout the supply chain. Such packaging can monitor temperature or humidity over time and then provide relevant information of these condition such as through changing packaging color.

Biosensors are being used in every area of food technology, starting from monitoring of raw materials, processing, packaging, shelf-life and judging the quality of food during long-term storage. Nanosensors can be used to track the quality (external and internal conditions) of the milk and milk products throughout the supply chain. They are also used to detect the bacteria and other contaminants Application of nanoparticles in packaging system to extend the storage of dairy products Material used Product Tested microorganisms References Copper nanoparticles Dairy products *Pseudomonas spp* Longano *et al.* (2012) [36] Silver nanoparticles loaded in the edible coating Fiordilatte cheese Pseudomonas spp, Enterobacteria Mastromatteo *et al.* (2015) 1% nanosilver and 0.1% titanium dioxide Soft cheese and milk powder Enterobacteria Metak and Ajaal (2013) ZnO nanoparticles coated on polyvinyl-chloride-based film Dairy products *E. coli, S. aureus Li et al.* (2009) Zinc nanoparticles coated on packaging film Butter - Contreras *et al.* (2010). Some gas sensors can translate the chemical interactions between particles on the food into a response signal. They are used to detect preservative food contaminant in dairy products. In dairy industry, the nanosensors are used to estimate the antibiotics residual amount in milk and milk products (Poonia *et al.* 2017) [23, 38, 39, 40, 41].

General applications of nanosensors

- **Cost-effectiveness**: Nanosensors are rapid and high-throughput detection, simple and cost-effective, less power requirements, easier recycling and the unnecessity of exogenous molecules or labels.
- **Quality assurance**: Nanosensors can track the food processing line to assure the quality of food. They can also check the product tempering and able to track ingredients and products through the processing chain and commercialized products.
- **Monitoring and controlling specific stages of milk processing**: Nanosensors can also monitor and control the various stages of a milk-processing unit (Sekhon 2010).
- **Food safety**: Gasses produced with off flavours can be detected by nanosensors with plastic packaging. When a food spoil, the packaging materials automatically change colour itself and alert us about the food spoilage. Nanosensors with silicate nanoparticles reported to reduce O_2 in the package and retain the freshness of food by reducing the flow of O2.
- **Detection of foodborne pathogens and microbial load**: Salmonella typhymurium, Eschirichia coli, Listeria monocytogensis cells can be detected using aptasensors. DNA biochips are used to detect pathogens and other harmful bacteria in meat and sea foods.
- **Detection of drugs and heavy metals**: By using aptasensors antibiotics, drugs and their residues and heavy metals like Hg 2+ and Cu 2+ can be detected.
- **For intelligent food packaging**: Nanosensors used in packaging can assess the internal and external conditions of food products through the supply chain. The nanosensors are used into the packagings to indicate the storage conditions. Some microbes and physical parameters such as pathogens, temperature, pH, humidity, oxygen content, toxins and freshness are assessed by finding the fermented end-product of the food. Example: OxyDot ® is a commercially available nanosensor being used for quantitative analysis of sealed drink product.

By using the nanosensors, very less concentration, i.e. $1*10^{-9}$ M, of antibiotics could be detected by general colour change. The occurrence of aflatoxin M_1 in 386 A. Poonia milk is very common and specially found in milk from animals fed with aflatoxin B1 contaminated feed. The use of gold-nanoparticles labelled aflatoxin M_1 conjugate is very beneficial. It has been reported that a very small amount, i.e. 27.5 mg L^{-1} in a sample solution was possible to detect (Zhang *et al.* 2015) [37].

10. Case studies

Dairy Product	Nanomaterial Used	Level Used	Key Findings	Conclusion	Reference
Yogurt	Nano-sized Eggshell Powder (nano-ESP)	Cow milk: 0.1, 0.2, 0.3%; Buffalo milk: 0.1, 0.3, 0.5%	Increased total solids and calcium content, improved curd firmness, acceptable sensory quality up to 0.3% nano-ESP, calcium content increased by ~15%	High-calcium yogurt with acceptable quality can be produced using up to 0.3% nano-ESP, offering potential benefits against osteoporosis	Hassan, A. N., *et al.* (2018) [11].
Low-fat Butter	Titanium Dioxide Nanoparticles (nano-TiO_2)	0.25%, 0.50%, 0.75%	Improved emulsification, texture, hardness, cohesiveness, microbial stability, and shelf life; prevented water separation	Nano-TiO_2 acts as an effective emulsifier and antimicrobial agent for manufacturing stable low-fat butter with acceptable sensory properties	Al-Saadi, J. A., & Al-Hilphy, A. R. S. (2021) [1]. .

S.No	Title	Researcher & Institute	Introduction	Objective	Treatment / Intervention Combination	Methodology	Results	Conclusion
1	Nanotechnology-Based Dipstick for Instant Detection of Multiple Adulterants in Milk	Dr. Vimal M. Ramani, College of Dairy Science, Kamdhenu University, Amreli, Gujarat	Milk adulteration is a serious concern in India. Traditional tests are slow and lab-dependent. Nanotechnology provides rapid, sensitive, on-site tools.	Develop a low-cost, portable, rapid dipstick to detect multiple milk adulterants.	Paper-based nano-capillary strip with functional nanoparticles sensitive to urea, starch, detergent, neutralizers, hydrogen peroxide.	Tested strip across multiple milk samples for sensitivity, specificity, and reproducibility. Each adulterant triggers a distinct color change.	Detected multiple adulterants simultaneously; results within 2-3 minutes; high accuracy.	Effective, rapid, affordable tool for milk safety in rural and urban settings.
2	Comparative Assessment of	Kabariya, A. & Ramani,	Validation of the nano-dipstick	Compare efficacy of	Nano-capillary dipstick	Tested 100 milk samples for urea,	Up to 12% adulteration	Nano-dipstick is a reliable, rapid

	Milk Quality Using Nanotechnology-Based Dipstick	V. M., Kamdhenu University, Amreli, Gujarat	against conventional lab methods in real-world milk samples.	nano-dipstick vs standard lab techniques.	(nanoparticle-based) vs conventional chemical tests (REIL EMAT Plus).	detergent, hydrogen peroxide, neutralizer, and starch.	detected; nano-dipstick results matched lab methods; practical for field use.	screening tool for milk adulteration.
3	Development of Nano-Biosensors for Milk Toxin Detection	Kamdhenu University, Gujarat	Aflatoxin M1 contamination poses health risks; sensitive, rapid detection methods required.	Design nano-biosensors and microfluidic systems for aflatoxin M1 detection.	Gold and iron oxide nanoparticles conjugated with bioreceptors, integrated into microfluidic chips.	Milk samples spiked with aflatoxin M1 tested for sensitivity and specificity.	High sensitivity and specificity; rapid detection (<10 min).	Nano-biosensors are promising for improving milk safety, especially for toxin monitoring.
4	ICAR-NDRI Training on Nanotechnology in Dairy Applications	ICAR - National Dairy Research Institute, Karnal	India's dairy sector adoption of nanotech requires skilled human resources.	Provide hands-on training on emerging nanotechnology applications in dairy.	Practical demonstrations of nano-encapsulation, nanosensors, and nano-packaging for milk quality and safety.	Lectures and experiments on functional nanoparticles for milk testing.	Participants gained practical knowledge; enhanced national research capacity.	Training enhances implementation of nano-enabled solutions in dairy safety and functional products.
5	Nanoparticle Synthesis for Sensor Applications Relevant to Dairy Safety	IISER Pune and IIT Bombay, India	High-sensitivity sensors for milk require uniform, stable nanoparticles.	Develop metal nanoparticles for nanosensor applications in dairy quality monitoring.	Confined dewetting technique to fabricate monodisperse gold and silver nanoparticles.	Characterized particles for size, morphology, optical properties; designed for sensor integration.	Uniform nanoparticles suitable for sensor applications; improved sensitivity and reliability.	Provides foundation for next-generation dairy safety sensors in India.

11. Risk

The use of nanotechnology in the dairy industry has the potential to bring about various benefits, such as improving the quality and safety of dairy products, enhancing nutritional properties, and extending shelf life. However, like any emerging technology, there are potential risks associated with its use. Here are some of the risks that should be considered:

- Lack of understanding on how to evaluate the potential hazard of nanomaterials by the food route. Currently available data are not sufficient for proper risk assessment.
- Possibility that the high surface area and active surface chemistry of some nanomaterials could give rise to unwanted chemical reactions.
- Dairy nanofood could include additional nanoparticles as a consequence of indirect contact with nanomaterials during their production, food processing, food packaging, and ingredients as well.

Safety concerns: One of the primary concerns is the potential for nanoparticles to enter the human body through ingestion. The long-term effects of consuming nanoparticles are not yet fully understood, and there is a need for further research to assess their safety.

1. **Environmental impact**: The disposal of nanomaterials used in dairy products could pose environmental risks. The release of nanoparticles into the environment, either during production or through the disposal of packaging or waste, could have unknown ecological consequences.
2. **Regulatory challenges**: Nanotechnology is a rapidly evolving field, and regulatory frameworks may not be fully equipped to address all potential risks associated with its use in the dairy industry. Establishing appropriate regulations and standards to ensure the safe use of nanomaterials in food products can be challenging.
3. **Consumer acceptance**: There may be concerns among consumers regarding the safety and ethical implications of using nanotechnology in food products. Transparency and clear communication about the use of nanotechnology may be necessary to gain consumer trust and acceptance.
4. **Manufacturing challenges**: Incorporating nanomaterials into dairy products may require changes in manufacturing processes, which could introduce new challenges or impact product quality and consistency.

12. Conclusion

Nanotechnology holds considerable promise for transforming the dairy sector by improving food quality, safety, functionality, and sustainability. The application of nanoscale materials and processes enables the development of dairy products that are tastier, healthier, and more nutritious, while also facilitating the creation of innovative food products, advanced packaging systems, and improved storage solutions.

One of the most significant contributions of nanotechnology lies in enhancing food safety and quality. The use of nanosensors and nano-enabled detection systems allows for rapid and sensitive identification of pathogens, toxins, and chemical residues in dairy products, thereby ensuring product safety and consumer confidence. In addition, nanotechnology-based interventions can aid in the control and elimination of microbial contamination during processing and storage.

Nanotechnology also plays a vital role in packaging and preservation. The incorporation of nanomaterials into packaging systems improves barrier properties against oxygen, moisture, and light, effectively extending the shelf life of dairy products and reducing post-harvest losses and food waste. Furthermore, active and intelligent packaging systems incorporating antimicrobial nanoparticles can inhibit microbial growth and maintain product freshness throughout the supply chain.

Another important application is in nutrient delivery and fortification. Nanoencapsulation and nanocarrier systems enable the protection, controlled release, and enhanced bioavailability of bioactive compounds such as vitamins, minerals, omega-3 fatty acids, and probiotics in dairy products. This approach significantly enhances the nutritional and functional value of dairy foods while maintaining their stability during processing and storage.

Nanotechnology further contributes to improving the texture and sensory attributes of dairy products. By modifying the rheological and structural properties at the nanoscale, it is possible to enhance mouthfeel, creaminess, consistency, and overall sensory acceptance of products such as milk, yogurt, and cheese. These improvements can lead to greater consumer satisfaction and product differentiation in the market.

In terms of processing efficiency, nanotechnology-based approaches offer opportunities to optimize dairy manufacturing operations. The use of nanostructured catalysts, enzymes, and membranes can improve reaction efficiency, reduce processing time, lower energy consumption, and minimize waste generation, thereby supporting sustainable dairy production.

Despite these promising advantages, the potential risks associated with the use of nanomaterials in food systems must be carefully addressed. Comprehensive safety assessments, toxicological studies, and clear regulatory frameworks are essential to ensure the safe and responsible application of nanotechnology in the dairy industry. Collaboration among researchers, industry stakeholders, and regulatory authorities will be critical in establishing standardized guidelines and gaining public acceptance.

In conclusion, nanotechnology offers a powerful and versatile tool for advancing the dairy industry by enhancing food safety, quality, nutrition, packaging, and processing efficiency. Continued research, innovation, and interdisciplinary collaboration will be key to fully harnessing the benefits of nanotechnology while ensuring consumer safety and sustainable development in the dairy sector.

Abbreviations: AgNPs (Silver Nanoparticles), AuNPs (Gold Nanoparticles), GRAS (Generally Recognized as Safe), NPs (Nanoparticles), NEs (Nanoemulsions), NLCs (Nanostructured Lipid Carriers), DHA (Docosahexaenoic Acid), EPA (Eicosapentaenoic Acid), SLNs (Solid Lipid Nanoparticles), TAG (Triacylglycerol), CLA (Conjugated Linoleic Acid), MCT (Medium Chain Triglycerides), O/W (Oil-in-Water), W/O (Water-in-Oil), FAO (Food and Agriculture Organization)

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