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Nanotechnological Applications in Current Innovative Approaches in Dairy Technology- A review

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ABSTRACT
Nanotechnology offers significant potential in the dairy industry, influencing a range of products such as milk, cheese, yogurt, butter, fermented milk, and buttermilk. The use of both bottom-up and top-down processing approaches yields extensive insights into the intrinsic and extrinsic characteristics of dairy products. A variety of nano-techniques including nanoemulsion, nanoencapsulation, nanoliposomes, nanotubes, nanofibers, and nanocapsules are employed within the dairy industry. These methods, in conjunction with nanosensors, nanolaminates, and nanocoatings, act as efficient packaging solutions, providing critical information on product safety, stability, and quality. Nanotechnology is also highly effective in detecting foodborne pathogens and excels in pathogen control. It plays an essential role in food fortification by encapsulating nutrients, ingredients, and compounds, thus enhancing the texture, taste, aroma, quality, and nutritional value of food. Notably, nanoparticles such as zinc oxide, silver, and titanium demonstrate potent mechanisms for disrupting bacterial cell walls, aiding in compound absorption, and improving physiological functions. This review presents the applications of nanotechnology in the dairy industry, along with pertinent studies and their outcomes regarding the utilization of these technologies in dairy products.

Keywords: Nanoparticles, Nanosensor, Nanoemulsion, Nanoencapsulation, Nanopackaging, Dairy Technology

1. Introduction

In recent years, the field of nanotechnology has seen significant growth, leading to the discovery of the various nano-sized materials such as nanoparticles, nanocomposites, and nanoemulsions worldwide. Nanotechnology is a multidisciplinary field that studies and manipulates nanostructures (0.1-100 nm) with various applications in different domains, including food science and dairy products (Delshadi et al. 2020; Omerović et al. 2021). Nanotechnology has introduced edible films and coatings for food packaging, preventing gas and moisture exchange and enhancing product safety and longevity (Nickols-Richardson & Piehowski, 2008; Sharma et al. 2017). Nanotechnology has also enabled the development of the functional dairy products fortified with minerals, vitamins, and biologically active ingredients that offer health benefits and address nutritional deficiencies (van der Hee et al. 2009). For example, some yogurts can increase calcium intake by 50% and provide vitamin D-3, improving bone health.

Nanotechnology enhances the sensory properties of dairy products by optimizing the functionality, solubility, stability, and bioavailability of milk components using nano-sized materials such as emulsifiers, stabilizers, nanostructured lipids, and proteins (Ghorbanzade et al. 2017; Braicu et al. 2019; Nile et al. 2020) Nanomaterials enhance the texture, consistency, emulsifying and foaming properties, taste, aroma, quality, and nutritional value of dairy products (Sharma et al. 2017). Nanotechnology opens up new possibilities for designing functional dairy products that align with consumers' needs and preferences (Nile et al. 2020). Nanotechnology has a significant impact on dairy product packaging, enhancing its safety, stability, and quality. Key features of this technology include nanosensors, nanolaminates, and nanocoatings, which aid in pathogen detection. In the dairy food industry, as with other sectors, nanotechnology plays a crucial role as a promising technology for solving problems via innovative solutions related to dairy food industry safety, processing, packaging (Figure 1), as well as functional milk products.

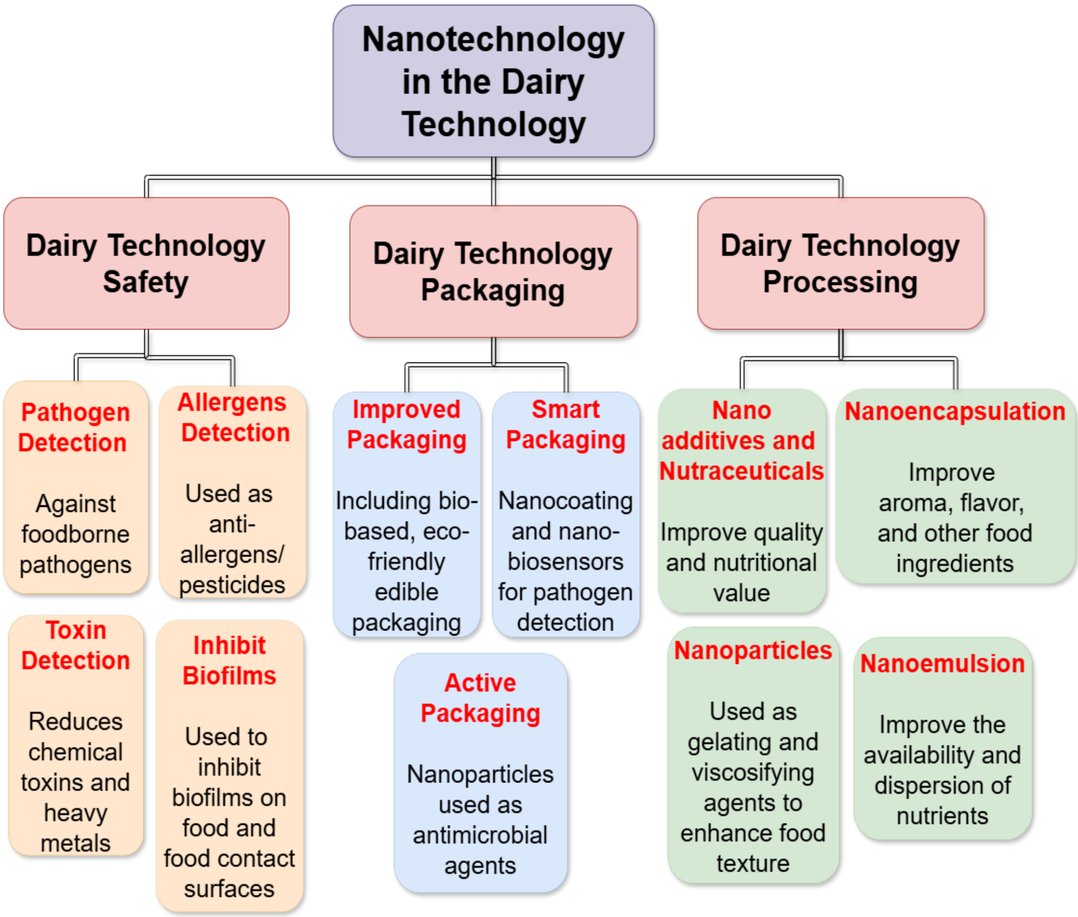

Figure 1 - The applications of nanotechnology in dairy technology safety, packaging and processing

Nanoparticles like zinc oxide, silver, and titanium disrupt the bacterial cell walls, improving bodily functions and enhancing compound absorption. These particles effectively detect the foodborne pathogens like *Listeria monocytogenes* (*L. monocytogenes*), *Salmonella typhimurium* (*S. typhimurium*), and *Pseudomonas aeruginosa* (*P. aeruginosa*), raising safety standards. Nanocapsules protect and release the bioactive ingredients, enhancing bioavailability and utilization of active components.

Nanopackaging extends the shelf life by inhibiting the microbial growth. Nanoadditives improve the sensory qualities like color, taste, and aroma. Nanosensors offer advanced traceability for the food quality and enhancing safety. Nanoemulsions can either reduce the fat content or increase the nutritional value in the dairy products, as shown by Khan et al. (2019). Nanotechnology applications in dairy products include nanoencapsulation, nanoemulsion, nanoliposomes, nanotubes, and nanofibers (Table 1). These applications improve texture, taste, and nutritional content, elevating the dairy product quality

Table 1 - Some studies on nanotechnological methods and their applications in dairy technology

Method	*Bioactive structures*	*Applications*	*Dairy Products*	*References*
Nanoliposome	Nisin	Antibacterial	Milk	da Silva Malheiros et al. 2010
Nanoliposomes	Catechin or green tea extract	Fortification	Cheese (Low-fat)	Rashidinejad et al. 2016
Nanoliposome	Bacteriocin CAMT6	Antibacterial	Whole and Skim milk	Li et al. 2023
Nanoliposomes	β-sitosterol	Fortification	Butter	Bagherpour et al. 2017
Nanoemulsion	Oregano essential oil	Coatings	Cheese (Low fat)	Artiga-Artigas et al. 2017
Nanoemulsion	Pectin/oregano oil	Coating	Cheese	Miljkovic et al. 2017
Nanoemulsions	Curcumin	Fortification	Ice cream	Borrin et al. 2018
Nanoemulsions	Zeaxanthin	Fortification	Yogurt	de Campo et al. 2019
Nanoemulsion	Carotenoid	Functional	Yogurt	Medeiros et al. 2019
Nanoemulsions	D Vitamin	Fortification	Cheddar Cheese	Banville et al. 2000
Nanoemulsions	Conjugated Linoleic acid	Fortification	Low in fat milk	Hashemi et al. 2020
Nanoemulsion	Nigella sativa oil	Fortification	Icecream	Mohammed et al. 2020
Nanoemulsion	Curcumin	Functional	Soft Cheese	Bagale et al. 2023
Nanoemulsions	*Eugenol and Cinnamaldehyde*	Antibacterial	Yogurt	Abdelhamid et al. 2023
Nanoemulsion	*Laurus nobilis L. extract*	Fortification	Processed cheeses	Hussein et al. 2023
Microencapsulation	Astaxanthin	Fortification	Yogurt	Feng et al. 2018
Nanoencapsulation	Fish oil (EPA-DHA)	Fortification	Yogurt	Ghorbanzade et al. 2017
Nanoencapsulation	Vitamin A, D_3	Fortification	Skim milk	Loewen et al. 2018
Nanoencapsulation	Vitamin D_3	Fortification	Yogurt based beverage (Lassi)	Maurya et al. 2019
Nanoencapsulation	Vitamin D_2	Fortification	Milk	Syama et al. 2019
Nanoencapsulation	Saffron extract	Functional	Ricotta cheese	Siyar et al. 2022
Nanoencapsulation	*Curcumin*	Functional	Dairy drink	Wang et al. 2022

2. Nanotechnological Methods Applied in Dairy Technology

2. 1. Nanoencapsulation

The use of nanotechnology in food technology has ushered in a new era, particularly through advancements in enhancing the bioavailability of milk components. Nanoencapsulation involves encapsulating bioactive compounds within nanoscale carriers, thereby shielding them from environmental factors and enabling controlled release during digestion (Rezaei et al. 2019; Pateiro et al. 2021; Maqsoudlou et al. 2022; Mohammad et al. 2022; Sharma et al. 2023).

This technology plays a crucial role in fortifying dairy products with essential nutrients like vitamins and minerals, ensuring their stability during processing and storage. This helps reduce food waste and extends the shelf life of dairy products (Chen et al. 2017; Dong & Zhong 2019). Incorporating probiotics into dairy products further enhances their health benefits. Nanoencapsulation acts as a protective measure, prolonging the shelf life of products and maintaining probiotic viability upon consumption. Research has demonstrated the efficacy of nanoencapsulation in enhancing the stability of probiotics, vitamins, and bioactive peptides in dairy products (Delshadi et al. 2020; Pudtikajorn et al. 2021).

The benefits of nanoencapsulation play a pivotal role in advancing the development of dairy products with improved nutritional quality and extended shelf life. Nanoencapsulation preserves the structural integrity of these compounds and facilitates controlled release after consumption. Nanoencapsulation also aligns with the consumer demand for functional foods, which deliver essential nutrition and additional health benefits. Nanoencapsulated dairy products enriched with probiotics, vitamins, and bioactive peptides address this demand by combining nutritional value with improved bioavailability. However, nanoencapsulation in the dairy industry faces challenges such as cost, regulatory approvals, and consumer safety concerns. Ongoing research and collaboration among scientists, industry stakeholders, and regulatory bodies are needed to overcome these challenges and fully realize the potential of nanoencapsulation in the dairy sector. In conclusion, nanoencapsulation technology introduces a ground-breaking paradigm in the dairy industry, contributing to the evolution of functional dairy products with enhanced health benefits. Sustained research efforts in this domain instill optimism for a future in the dairy industry characterized by innovative and health-promoting products.

2. 2. Nanoemulsions

International Nanoemulsions, colloidal systems with oil droplets of two immiscible liquids in an oil-in-water (O/W) or water-in-oil (W/O) configuration, are characterized by their small size, ranging from 10 to 100 nm (Saxena & Bhardwaj, 2017). These nanoscale structures (Figure 2) are often used as stabilizing agents for essential oils and offer several advantages over conventional emulsions.

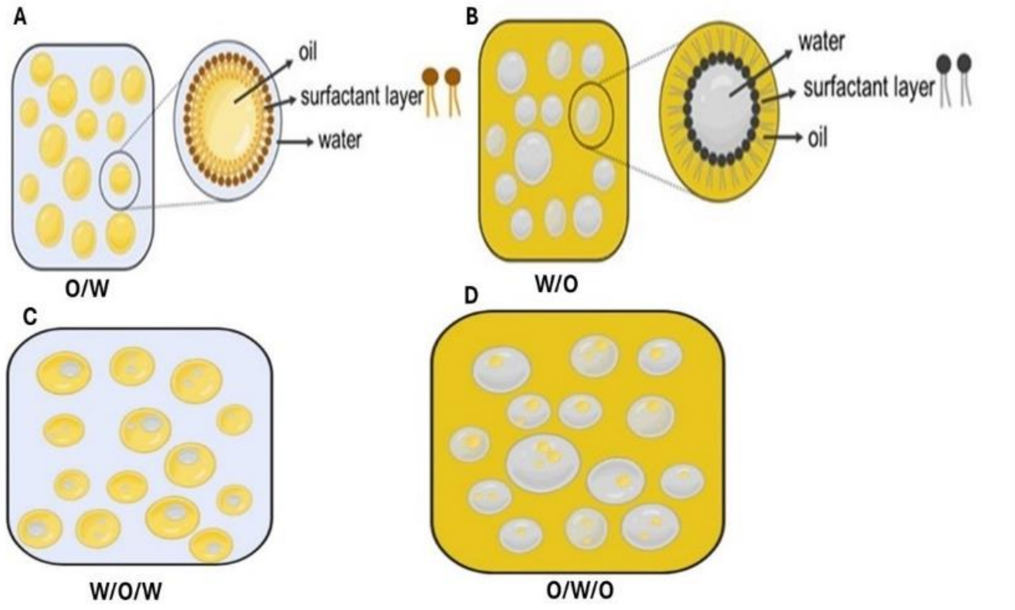

Figure 2 – Illustration of various types of nanoemulsions, depicting both two-phase (A and B) and multiple-phase (C and D) structures. A: oil-in-water (O/W) emulsion, B: water-in-oil (W/O) emulsion, C: water/oil/water (W/O/W) emulsion, D: oil/water/oil (O/W/O) emulsion

These include a higher surface area, lower light scattering, superior optical properties, enhanced bioavailability, and extended shelf life (Silva et al. 2012; Lane et al. 2013). In the dairy industry, nanoemulsions are used to encapsulate and transport various ingredients, such as antioxidants, antimicrobials, vitamins, minerals, flavors, and colorants. They also serve structural purposes by enhancing emulsion stability, reducing fat globule size, and improving creaminess and mouthfeel. The manipulation of droplet size in nanoemulsions significantly influences emulsion stability and properties such as color, taste, odor, nutritional value, and bioavailability, presenting an innovative approach to enhancing the physicochemical and sensory attributes of milk and dairy products. Nanoemulsion technology is instrumental in extending shelf life, increasing nutritional value, improving bioavailability, transporting functional ingredients, and developing novel dairy products (McClements 2010). Nanoemulsion technology, compatible with dairy processing equipment and methods, can be implemented through various techniques, including high-pressure homogenization, ultrasonic homogenization, or microfluidic devices (Lohith Kumar & Sarkar 2018).

This technology facilitates the controlled release of active ingredients, such as nutrients, proteins, and antioxidants, enhancing their effectiveness and bioavailability within the body. Traditional dairy formulations often encounter challenges such as phase separation, precipitation, and creaming. Nanoemulsion addresses these issues by decreasing droplet size, thereby increasing the surface area of dispersed phases, leading to heightened homogeneity and stability (Montes de Oca-Ávalos et al. 2017). This plays a pivotal role in enhancing the stability of dairy products by preventing phase separation, precipitation, and creaming. Critical sensory attributes like taste, texture, and appearance influence consumer acceptance of dairy products.

Nanoemulsion technology provides a platform to tailor these sensory properties by precisely controlling droplet size and distribution. Research suggests that nanoemulsions have a positive effect on creaminess, mouthfeel, and the overall sensory experience of dairy products, thereby influencing consumer preferences (Panghal et al. 2019). Successful applications of nano-sized emulsions with low-fat content have been demonstrated in ice cream production (Silva et al. 2012). The incorporation of nanoemulsion purple rice bran oil into frozen yogurts has improved the nutritional profile by increasing the natural antioxidant content (Sanabria 2012). Furthermore, stable curcumin nano-emulsions have exhibited effective oxygen scavenging in commercial milk samples, remaining stable at room temperature for up to a month (Joung et al. 2016). Moreover, nanoemulsion technology has been investigated for its potential in controlled lactose hydrolysis within milk. Freeze-dried capsules from S/O/W emulsions containing lactase have demonstrated the potential to gradually release lactase into dairy products, offering controlled lactose hydrolysis over three weeks of storage (Zhang and Zhong 2018). This suggests that S/O/W emulsions have the potential to enhance the quality and functionality of milk and dairy products by enabling the controlled release of lactase. In conclusion, nanoemulsion technology represents a substantial advancement in the dairy industry, providing a versatile and efficacious method for enhancing the quality, stability, and functionality of milk and dairy products.

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2. 3. Nanoliposome

Nanoliposome technology has been recognized for its potential to significantly improve the quality and functionality of dairy products. These nanocarriers, which are spherical lipid-based structures typically ranging from 20 to 200 nanometers, utilize a phospholipid bilayer to encapsulate an aqueous core. This allows for the efficient delivery of both hydrophobic and hydrophilic molecules (Khorasani et al. 2018; Brandelli et al. 2023).

With attributes such as a high surface area, biocompatibility, and customizable functionality, nanoliposomes enable a wide range of applications, particularly in the encapsulation of bioactive compounds like antioxidants, vitamins, and antimicrobial agents. They play a significant role in the development of functional dairy products by delivering nutrients to targeted cells or tissues (Zarrabi et al. 2020; Bondu & Yen 2022; Khafoor et al. 2023). The excellent encapsulation efficiency, stability, and controlled release properties of nanoliposomes ensure the protection of sensitive compounds during processing and storage, leading to optimal bioavailability in dairy products (Li et al. 2019). Nanoliposomes specifically designed to contain antioxidants are crucial in preventing oxidation reactions, thus preserving the nutritional quality and extending the shelf life of dairy products. When added to dairy product formulations, nanoliposomes effectively shield both hydrophilic and hydrophobic compounds, enhancing the bioavailability and stability of nutrients and aiding in the development of functional dairy products (Ghorbanzade et al. 2017; Srinivasan et al. 2019).

Antimicrobial nanoliposomes act as effective barriers against microorganisms, significantly prolonging the shelf life of dairy products. Research has shown that nanoliposomes, including those containing garlic extract, are effective in exerting antimicrobial effects against Listeria species in milk (Schmidt et al. 2009; Pinilla et al. 2017; Todorov et al. 2022). The combination of liposome-encapsulated nisin and garlic has been effective against pathogens such as *Escherichia coli* (*E. coli*), *Staphylococcus aureus* (*S. aureus*), Salmonella enteritidis, and *L. monocytogenes* in whole milk (Pinilla & Brandelli, 2016).

In cheese production, the use of nanoliposomes encapsulating antimicrobial peptides has been shown to extend the shelf life of cheese. This includes the use of partially purified soybean phosphatidylcholine (PC) and PC-cholesterol (7:3) nanoliposomes (Bagale et al. 2023). Bagale et al. (2023) also highlight the antimicrobial activity of curcumin encapsulated in liposomes against *S. aureus* and *E. coli* in milk-based soft cheese. Nanoliposomes have been effective in addressing related challenges to the incorporation of free antimicrobials into dairy products, demonstrating broad antimicrobial activity in white soft cheese (Mohammadi et al. 2015; Lopes & Brandelli 2018; El-Sayed & El-Sayed 2021.

Additionally, in fortifying milk matrices with omega-3 fatty acids, nanoliposomes have been effective in enhancing acceptance and improving taste, aroma, texture, and appearance compared to unencapsulated fish oil (Ghorbanzade et al. 2017; Rasti et al. 2017; Patel et al. 2020). Nanoliposomes play an important role in preserving bioactive compounds in milk that are sensitive to environmental factors, thus maintaining nutritional quality and extending the shelf life of dairy products. For products designed for lactose intolerance patients, nanoliposomes encapsulating the β-galactosidase enzyme have been determined to exhibit long-term activity at low temperatures, maintaining functional activity for 20 days to one month at +5 °C. In conclusion, nanoliposomes play a diverse role in the dairy industry, offering advantages in enhancing nutritional value, improving stability, and extending the shelf life of dairy products. The dynamically evolving field of nanoliposome technology in the dairy industry presents continued opportunities through advancements in nanotechnology

2. 4. Nanotubes

Nanotubes represent significant innovations in dairy technology, offering several advantages such as enhancing food texture and increasing colloidal stability (Katouzian & Jafari 2019). Nanotube-shaped nanocarriers, particularly those derived from milk protein α-lactalbumin, possess unique properties that can improve the quality of milk and extend its shelf life (Li et al. 2019). These nanotubes can be utilized for nanoencapsulating bioactive compounds, including vitamins and antioxidants, in fortified dairy products. This protective technique prevents the degradation of these compounds during processing and storage, ensuring consumers derive maximum nutritional benefits from milk.

Nanotubes are formed through the partial hydrolysis of α-lactalbumin by a protease from Bacillus licheniformis (BLP) under specific conditions, a process that has been studied extensively (Ipsen et al. 2001; Graveland-Bikker et al. 2006). Whey-based α-lactalbumin nanotubular gels, known for their stable structures and ability to carry active agents, show promise for various industrial applications (Tarhan et al. 2021). Protein nanotubes (PNTs) exhibit stability by forming a β-sheet structure, which arises from interactions between aromatic side chains and charged residues. This stability makes PNTs valuable nanocarriers in drug delivery applications (Wei et al. 2018). PNTs offer advantages such as prolonged intestinal retention time, enhanced cellular absorption, and increased membrane permeability, ultimately increasing the bioavailability of hydrophobic bioactive compounds (Bao et al. 2020).

In dairy applications, the addition of lycopene-loaded α-lactalbumin nanotubes to beverages has been shown to increase viscosity and enhance long-term stability, which is promising for the encapsulation and delivery of hydrophobic compounds (Chang et al. 2022). Furthermore, α-lactalbumin nanotubes have facilitated the survival of soy isoflavones through simulated in vitro gastric digestion and promoted their release in the intestinal phase when added to soy milk (Liu et al. 2023). Nanotubes also offer a promising solution for challenges related to the water solubility, stability, and bioavailability of compounds such as curcumin. Encapsulation within α-lactalbumin nanocarriers enables curcumin to exhibit responsive release behavior in the intestines, suggesting potential for developing functional dairy beverages (Wang et al. 2022).

In conclusion, nanotubes present significant potential for various applications within the dairy industry. This technology holds promise for improving milk quality, extending shelf life, enhancing heat transfer efficiency, implementing milk monitoring through sensors, and facilitating the nanoencapsulation of bioactive compounds (Li et al. 2019).

2. 5. Nanofiber

Nanofiber technology investigates materials composed of fibers at the nanoscale. This includes biopolymer nanofibers produced via electrospinning, which are made up of cross-linked biopolymer molecules (Al-Abduljabbar & Farooq, 2023). Nanofibers, whether synthesized from synthetic or natural polymers, offer advantages such as lightweight, straightforward processing, and important loading capacity. In the dairy industry, nanofibers contribute to enhanced milk processing efficiency, improved product quality, and extended shelf life by facilitating the development of antimicrobial and active food packaging materials, as well as sensors that monitor pH or temperature changes during storage (Kumar et al. 2019; Senthil et al. 2019; Rostamabadi et al. 2020). A significant application of nanofibers in the dairy industry is filtration, where electrospun nanofiber membranes prove effective in separating impurities, bacteria, and contaminants in milk, surpassing traditional filtration methods (Li et al. 2019). Furthermore, nanofiber technology aids in developing packaging materials with improved barrier properties, creating an effective shield against oxygen, moisture, and external factors, leading to reduced microbial growth and product spoilage (Zhang et al. 2023).

Nanofibers containing milk proteins find applications in yogurt and cheese production, while those containing nano cellulose and nano chitin are proposed for use in the packaging of dairy products (Li et al. 2019; Senthil et al. 2019). Electrospun nanofibers of sodium alginate, used to encapsulate probiotic *L. brevis* cells, have been determined to significantly increase the survival of these cells compared to free bacteria when included in a functional yoghurt drink (Mohaisen et al. 2019). In addition, a smart promoter/polyvinyl alcohol film containing anthocyanin and limonene (Lui et al. 2017) has been reported to exhibit inhibitory activity against *S. aureus*, *B. subtilis*, and *A. niger* in pasteurized milk, demonstrating effectiveness in pH monitoring. Furthermore, an antimicrobial packaging material, created by separating allyl isothiocyanate in the vapor phase and incorporating it into gelatin electrospun fibers, was reported to extend the shelf life of cheese (Al-Moghazy et al. 2020). Additionally, nanofibers composed of moringa oil-loaded chitosan nanoparticles, utilized as preservatives for the biocontrol of *L. monocytogenes* and *S. aureus* in cheese, have been stated to exhibit high antibacterial activity without compromising sensory quality (Lin et al. 2019).

These systems encapsulate bioactive compounds within nanofiber structures during the production of milk and dairy products, thereby increasing stability, enabling controlled release, and providing protection against external factors such as heat and oxidation (Xue et al. 2019). In conclusion, research continues on the development of innovative nanofiber delivery systems in the dairy industry.

2. 6. Nanosensors

Advances in nanotechnology have accelerated the development of nanosensor technology, with recent progress in nanomaterials opening up potential applications in various fields, including the monitoring of milk and dairy products (Baranwal et al. 2022). Nanosensors, designed at the nanoscale (1 to 100 nm), offer advantages such as simple synthesis, easy surface chemistry, and cost-effectiveness. In the dairy industry, nanosensor technology serves purposes such as quality control, safety assurance, and real-time monitoring. The nanosensors, commonly used as labels and reporters, offer notable improvements in speed, selectivity, and sensitivity compared to traditional methods. Typically, nanosensors consist of a receptor that interacts with the analyte and a transducer that converts the response into measurable signals such as electrical, electrochemical, or optical signals. Constructed from nanomaterials like carbon nanotubes, quantum dots, graphene oxide, metallic gold, iron oxide particles, and electrospun polymeric nanofibers, nanosensors enhance the efficiency and sensitivity of analyses. The unique properties of nanomaterials, such as flexible shapes, enhanced optical, mechanical, electrical, and thermal properties, as well as high specific surface area and nanoconfinement, significantly enhance their signal transduction capabilities (Manoj et al. 2021). When evaluating nanosensors, key considerations include selectivity, which describes the system's ability to distinguish the analyte from other sample components.

Nanosensors are classified based on the transducer mechanism that generates output signals. These mechanisms encompass electrical, electrochemical, thermal, mechanical, optical, gravimetric, piezoelectric, and magnetic methods (Manoj et al. 2021). Electrochemical nanosensors measure electrochemical reactions with the analyte effectively (Stasyuk et al. 2022) using nanomaterials on carbon-based (Zhou et al. 2020) or glassy carbon electrodes (Jena & Raj 2008). Optical nanosensors, utilizing nanomaterials like metallic nanoparticles, upconversion nanoparticles, carbon nanotubes, and quantum dots, detect and analyze light, for measuring various physical, chemical, and biological parameters (Khansili et al. 2018; Pu et al. 2021). During the processing, storage, and distribution stages, the dairy industry consistently encounters challenges in ensuring the safety and quality of milk and dairy products. Recent advances in nanotechnology have addressed these issues by developing nanosensors that offer real-time monitoring and precise detection capabilities (Wang et al. 2021; Kadam et al. 2022). Nanosensors contribute to improving product quality by enabling real-time monitoring of critical parameters such as temperature, humidity, and gas composition of milk and dairy products during processing, storage, and distribution (Kumar et al. 2021). Nanosensors have also been utilized to detect biological contaminants such as antibiotics, toxins, and pathogens, as well as chemical compounds such as pesticides and heavy metals in milk and dairy products (Liu et al. 2008; El-Ansary & Faddah 2010; Lopez & Merkoci 2011; Yotova et al. 2013; Berekaa 2015; Song et al. 2017; Bajpai et al. 2018). Moreover, nanosensors expedite the identification of substances that compromise milk purity, including urea, melamine (Kaneko et al. 2018), formaldehyde (Agharkar & Mane 2021; Hegde et al. 2021), detergents, ammonium sulfate, benzoic acid, salicylic acid (Bueno et al. 2014), and hydrogen peroxide (Nanda et al. 2016; Guinati et al. 2021; Vasconcelos et al. 2021), thus playing a pivotal role in preventing contaminated products from reaching consumers.

Nanosensors are instrumental in monitoring the shelf life of these products by evaluating freshness, spoilage, and microbial growth. This monitoring capability significantly enhances quality control within the dairy industry (Nascimento et al. 2017). Early detection is paramount for ensuring food safety and maintaining the integrity of dairy products. Consequently, nanosensor technology is becoming an indispensable tool for guaranteeing the safety and quality of milk and dairy products. Integrating nanosensors into the dairy industry's quality control processes is a vital step towards fulfilling the growing demands for precision and efficiency in dairy production

3. Challenges

In the dairy industry, the effective utilization of nanotechnology for innovative products and processes faces several challenges. A primary concern is developing safe and efficient distribution systems suitable for human consumption, requiring advanced yet cost-effective processing methods. Recognizing potential hazards, assessing toxicity, and addressing environmental concerns regarding nanoparticles are critical steps in this process. Specifically, attention should focus on the leaching and migration of nanoparticles from packaging materials into dairy products. Nanoparticles can bypass biological barriers, penetrating various tissues and organs, which raises significant safety concerns. Moreover, the synthesis of nanoparticles through different chemical processes poses a risk of harmful by-products, contributing to environmental pollution.

Therefore, a comprehensive understanding of the functions and toxicity of nanomaterials is essential for establishing practical usage and safety standards for nanotechnology in the dairy industry. A significant challenge lies in the fact that materials behave differently at the nanoscale, and our understanding of how to analyze these behaviors remains limited. Before the commercial use and production of antibacterial nanoparticles with environmentally friendly properties, more *in vitro* and in *vivo* studies involving the interaction of nanoparticles with living organisms are necessary. These studies are crucial for the responsible and safe integration of nanotechnology into the dairy industry, ensuring that all factors are carefully considered.

Consequently, a comprehensive risk assessment program, the establishment of regulatory frameworks, biosecurity considerations, and the resolution of public concerns are necessary prerequisites for the production, packaging, and consumption of nanotechnology-based dairy products.

4. Conclusions

Recent breakthroughs in nanotechnology for the dairy industry have shown promising advancements in enhancing the quality, safety, and efficiency of dairy products. One notable innovation is the nanoencapsulation technique, which improves the water solubility and antimicrobial activity of compounds. These encapsulated compounds can also be integrated into food-packaging films to act as antimicrobial agents, thereby enhancing food safety. Nanosensors are another significant development, being developed for smart packaging that monitors the quality of stored foods and detects contaminants, ensuring higher standards of food safety. Nano-based delivery systems have been successfully employed in dairy products to encapsulate vitamins, antioxidants, flavors, and minerals. This approach not only enhances the bioactive properties but also boosts the nutritional value of dairy products.

Nanostructured materials are being explored for their role in preventing spoilage and oxidation, thereby extending the shelf life of dairy products. These advancements reflect a broader trend where nanotechnology is leveraged to develop new functional ingredients, optimize processing at micro- and nanoscales, and enhance overall food safety and quality. However, integrating nanotechnology into the dairy industry poses challenges. Establishing a safe distribution system is complex and costly, while understanding the behaviors of nanomaterials and ensuring regulatory compliance are crucial for managing their potential toxicity and optimizing their functions. Despite these challenges, nanotechnology holds promise for revolutionizing functional dairy formulation and production, offering novel opportunities for innovation in the industry.

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