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THE IMPACT OF NANOTECHNOLOGIES IN FOOD AND DAIRY SCIENCE: A REVIEW

RUAA A. HAMID [1]; MEAD W. SADALLAH [1]; ROQAYA F. LAFY [1] AND ALI M. SAADI [2, 3]

[1] Food Science Department, College of Agriculture and Forests, University of Mosul, Mosul, Iraq
[2] Department of Anesthesia Techniques, Mosul Medical Technical Institute, Northern Technical University, Mosul, Iraq.
[3] Technical Agricultural College, Northern Technical University, Iraq

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ABSTRACT

The widespread use of nanotechnology will soon cause a dramatic shift in the food and dairy industries. New packaging materials with enhanced mechanical, barrier, and antibacterial characteristics are among the possible uses, as are enhanced food contact materials, longer shelf lives for food and dairy items, and higher-quality processing methods. There has been a recent uptick in research into the possibility of using nanotechnology to encapsulate and transport biologically active compounds, improve the sensory qualities of food, and include antimicrobial nanostructures in packaging, among other uses. Nanotechnology has the potential to enhance the transport characteristics, solubility, and cellular absorption of bioactive chemicals by decreasing their particle size. Consumers' worries about the possible harm to human health from delivery systems based on nanotechnology must be allayed before these systems can be commercially implemented. Focusing on applications with the highest likelihood of commercialization shortly, this article provides a thorough overview of nanotechnology's use in food-related and dairy systems.

Keywords: Nanotechnologies, Food Science, Dairy Science

INTRODUCTION

The Food and Agriculture Organization (FAO) identified over 20 nanotechnology applications that have been approved by commercial companies, including anti-microbial and moisture barriers in packaging, biosensors in the food control process, and chemical and pathogen decontamination of food surfaces (Rizvi *et al.*, 2022; Malik *et al.*, 2023).

Nanotechnology can facilitate the formation of food industrial solutions, new applications for food, animal welfare, food safety, and efficiency in food processing, food packaging, nutrition, and health while considering national regulations, public acceptance, and sustainability precepts. This review aims to understand and discuss the dairy fields in which nanotechnologies are currently applied, and the potential constraints, protecting the rights of

Corresponding author: Ali M. Saadi
E-mail address: ali.mohammed@ntu.edu.iq
Present address: Department of Anesthesia Techniques, Mosul Medical Technical Institute, Northern Technical University, Mosul, Iraq.

consumers, suppliers, and environmental sustainability, and seeking to avoid any substantial decline in the relevant industries. (Halwani, 2022; Jafar *et al.,* 2022; Rambaran & Schirhagl, 2022).

Nanotechnology has emerged as a rapidly growing area of science with applications in various research fields, including the food industry. It has a potential in the treatment, fortification, and diagnosis of dairy commodities. Nanotechnology allows control over dimensions ranging from one to 100 nanometers, leading to improved material properties. This scale covers important features of agriculture, food processing, packaging, safety, quality, and information technology. Nanotechnology is expected to facilitate sustainable development in the food and dairy industries (Meghani *et al.,* Anilakumar, 2021; Lugani *et al.,* 2021; 2020; Madkour, 2021; Salama *et al.,* 2022)

1. Background and Significance

Interactions between nanomaterials and cells are being examined in a range of different tissues and organs to check the toxicity of nanoparticles (NPs). The utilization of NPs in the field of nanomedicine poses a risk to the environment, animals, and humans. Efforts have been made to optimize the size, shape, charge, concentration, and administration routes (Surendhiran *et al.,* 2020). This review intends to cover the recent and potential applications of nanotechnology and its opportunities in the field of dairy science, aiming to provide safer and healthier food products while maintaining a sustainable, consumer-friendly, and animal welfare-regarding production mode (Wang *et al.,* 2023). The impacts of NPs on the synthesis and lactation performance of mammary glands were also discussed. Finally, the potential concerns of NPs in animal health, environmental safety, and the prospect of the development of nanotechnology in dairy science were explained (Chaturvedi & Dave, 2020; Lugani *et al.,* 2021; Hoque *et al.,* 2021; Salama *et al.,* 2022).

Nanotechnology refers to the platform of nanometer-sized particles and materials, and the abuse of substances and compounds. Nanomaterials are currently utilized in the nutrition and food industry, providing several advantages which include the prolongation of food shelf life, increased safety, and easier processing. Over the last few decades, researchers have found different types of nanomaterials engineered with different functions to be effective, including the delivery of essential dietary vitamins and minerals, nano-encapsulation of antibacterial agents, nano-film coating, and nano-biosensors. Of particular importance, nano-technologies can be utilized in a precisely controlled manner to produce next-generation edible nutrition formulations that can challenge the existing animal health and nutrition obstacles (Anilakumar, 2021; Lugani *et al.,* 2021 and Hoque *et al.,* 2021)

2. Purpose and Scope of the Review

Also, the state of the art and state of technology of thin films in the above areas are reviewed. Future aspects of thin films are also reviewed (Anilakumar, 2021).

The present paper reviews thin film properties, types of film deposition techniques, and materials used for thin films. Thin films are used in nanotechnology, pinpoint X-ray sources, welding electrodes, electronic eyes, thermoelectric generators, thermoelectric cooling, heated seats, electrochemical and chemical sensors, gas sensors, anodic alumina, capacitors, micro-electromechanical systems, solar energy converters, supercapacitors, lead-free ceramics, autocatalytic activity, cancer treatment, deeper laser printers, hard disks, and solid polymer batteries (Madkour, 2021; Salama *et al.,* 2022).

Thin films are materials that possess a large length and width, but much smaller thicknesses in the range of 1 nm to 1 μm. Films with several nanometers of thickness have been studied for many decades. Thick films and thin films have two different types

of applications due to their different properties (Chaturvedi & Dave, 2020).

Fundamentals of Nanotechnologies

1. Definition and Classification

Nanotechnology is the systemic application of scientific knowledge in nanoscale systems for the manipulation and manufacturing of materials at the atomic and molecular scale. The term "nanoparticle" is often interchangeably attributed to various nano-technological systems, such as clusters, nanotubes, nanowires, or even nanostructured materials based on nanomaterials. These are all self-explanatory, as their definitions are mainly attributed to their obvious morphological characteristics: clusters refer to the "grouped" generic nanomaterials, nanotubes are materials in the shape of tubes, and nanowires are nanomaterials in the shape of wires. Nanostructured materials, on the other hand, are more complex, as they result from the combination of various chemical species in the production of the product to present physical, chemical, and structural properties. Generally, such classes of nanomaterials are assembled structures or even disordered agglomerates of nanoparticles (Chaturvedi & Dave, 2020; Hoque et al. 2021)

Several studies have demonstrated the impact of nanotechnology on various sectors, from advanced materials to medicinal and computer systems. Nanoparticulated systems have been used in a wide range of applications including food, agriculture, and cosmetics. However, the relative novelty of nanoparticles may interfere with the public acceptance of such innovation, demanding new regulations and strategies to increase the level of information regarding nanotechnology. This review provides information concerning the various nanotechnologies available in dairy science today, along with their evident and conceivable advantages and downsides in dairy production and milk preservation (Anilakumar, 2021)

2. Definition and Principles

Nanotechnology can be applied to animal science at many levels, from medical systems for animals at the base of molecular and cellular level analysis to embryo biotechnology and transgenic applications. Animals can also be effectively included in the nanomaterial characterization process. Nanotechnology has many practical advantages for animal production too. For instance, nano-clays can be used to remove odor and gases from slurry produced by pigs; the new nanocomposites with gas barrier properties can enhance feed quality and shelf life; nano-hydroxy apatite can be used to limit heavy metal uptake by plants in soil enriched by swine slurry. It is also useful to study the interaction between nanomaterials and animal and plant genomes and to disclose potential usages in clinical diagnosis and veterinary services. Furthermore, the animal production and food industry can benefit from nanoscience and nanotechnologies through the development of cost-effective and precise delivery systems, food safety monitoring, disease treatment, and enhanced animal nutrition. Nanotechnology can have a considerable impact on dairy science as well as other agricultural and animal products (Anilakumar, 2021).

Nanotechnology is an emerging field of science and technology that is expected to change our lives in several ways. It will also bring about significant changes in agriculture, animal sciences, and veterinary science in the future. It involves the selective manipulation of species resulting in the implementation of systems, mechanisms, and processes that have specific physical, chemical, and biological behaviors and effects. As a fundamental scientific approach, nanotechnology investigates the manufacturing of nanoscale devices to atomic and molecular precision. It also represents a powerful and leading-edge technology playing a more and more significant role in modern life and development. In general, nanotechnologies are more powerful in their effects because

they are used in a new manner, which is traditionally unexpected by other configurations and parameters (Hoque *et al.,* 2021 and Salama *et al.,* 2022).

3. Types of Nanomaterials

3.1. Protein nanocarriers for nutraceutical delivery:

Legumes, whey proteins, casein, sesame, or any other proteins exhibit good emulsification properties and can act as a nanocarrier. Although chemically, whey or casein proteins have active functional groups, they can hydrophobize proteins using soy protein, modified proteins, or any other ingredient during fabrication in the chemical loading process. These proteins can have positive characteristics when cross-linking stability with bioadhesive results in electrostatic, hydrophobic, or chemical bonding methods. To stabilize the carbo-protein matrix for bioadhesive substances like nanoemulsion, solid lipid nanoparticles, TiO2, or other related materials, they successfully stabilized the liquid-liquid nanoemulsion interface and solid surface. The nutritional stability, protection, detection, and control implementation of the nanocarrier system are nutritious (Chaturvedi & Dave, 2020; Hoque *et al.,* 2021 and Kareem *et al.,* 2024)

3.2 Liposomal nanoparticles:

They are a type of micelle nanocarrier since the structural orientation is similar to a micelle, but they produce a spherical vesicle with a double-bilayer coating and aqueous liquid inside. This nanocarrier acts as both fat and water-soluble and is useful for nutrients, incense, insecticides, and micronutrients. They provide higher biocompatibility, low toxicity, and high bioactivity in administration with low-dose drug responses. Liposomes are developed for the delivery of a hydrophobic and hydrophilic drug core to the interior of the lipid bilayer and the external part, gold nanoparticles, bacteria, and filtration similar to the environment of the donor. When developing liposomes, whey proteins, animal, plant phospholipids, soy emulsifying properties, or any related ingredients produce food-grade phytosome formulations (Lugani *et al.,* 2021 and Salama *et al.,* 2022).

The different types of nanomaterials working as carriers of nutraceuticals are: Micelles, liposomes, nanoemulsions (NEs), nanosuspensions, lipid nanocapsules (LNCPs), solid lipid nanoparticles (SLNPs), lipid nanocarriers (NLCs), and lipid-polymer hybrid nanoparticles (Chaturvedi & Dave, 2020).

Applications of Nanotechnologies in Dairy Science

Despite boon-like potentialities in dairy production, nanotechnologies may potentially be flourished. The vagueness in the long-term bio-safety studies and strict regulations across the world and their policies to assimilate nano-dairy emerge as serious limitations. The performed study throws light on several potential applications of nanotechnologies in dairy science and urges changing regulations and policies, and performing long-term comprehensive bio-safety studies of nano-dairy commodities to assert society's confidence to enjoy adequate benefits (Chaturvedi & Dave, 2020).

Nano-encapsulation, nano-emulsion, and nano-composite are different types of nanotechnologies that have reformed nanoscience widely and dairy products specifically. Nano-emulsification has cut off the usage of synthetic emulsifiers and their harmful effects from dairy formulations. Both nano-encapsulation and nano-composite technologies shield bioactive compounds like nutrients, antioxidants, antibiotics, probiotics, peptides, and fatty acids from the harsh conditions of the gastrointestinal environment and have explored efficient ways of conveying them into targeted commodities. Nanoparticles' potential is further extended to nano-sensors, nano-biosensors, and nano-controlled release systems for foodborne pathogen detection and elimination in the constantly evolving dairy industry. The other trending

applications of nanotechnologies are in nano-filtration creating a broad window for lactose-intolerance-challenged individuals to enjoy dairy food products (Salama *et al.,* 2022).

1. Nanoparticles in Milk Processing

In order to inhibit the growth and activities of undesirable microorganisms in foods, many investigators have turned to nanotechnology to develop new antimicrobials compared to commonly used man-made and natural compounds such as salts, added sugar, and acetic acid. Generally, in the field of nanotechnology, antimicrobial inorganic nanoparticles - such as silver (Ag), gold (Au), and copper (Cu) - or antimicrobial organic anti-infectious agents - such as quinoline-derived peptides, chitosan, and different forms of carbon - are being considered for active food packaging applications. These extremely low nano-molar concentration inorganic nanoparticles can provide superior benefits compared to the classical methods of protection through dilution, physico-chemical-mechanical barrier, and inhibitors of the matured cell membrane. Due to their high reactivity and small size of inorganic nanoparticles, they can penetrate and interact with very small cells, highlighting that these bioactive compounds are more toxic to pathogenic cells than human cells at these required low concentration rates (Lugani *et al.,* 2021; Jagtiani, 2022 and Singh *et al.,* 2021; Hoque *et al.,* 2021).

Nanoparticles in milk processing have been widely used for the production of desirable functionalities in milk and milk-based products such as yoghurt, cheese, and cream. In many dairy-based product applications, these nanoparticles should not change the organoleptic quality while providing various functionalities compared to proteins or casein, which are currently being used in these applications. The case of nanoscale particles with a high surface volume ratio compared to the bulk material offers the opportunity to modify their properties, such as their antimicrobial activity, which is needed for many dairy applications, and emulsifying properties, more or less significantly by modifying their synthesis parameters. These electrostatically and sterically repulsed nanoparticles, with a lower tendency to aggregate compared to classic surfactant molecules, make increasingly available entirely new surface properties, effects such as the reduction of surface tension effects, which are small surfactant molecules (Chaturvedi & Dave, 2020; Jagtiani, 2022 and Jiya & Balogu, 2023)

2. Nanoencapsulation of Bioactive Compounds

Nowadays, nanoencapsulation has appeared as a powerful technique due to its increased bioavailability, controlled release, protection, and stabilization properties of bioactive compounds, such as vitamins, antioxidants, antimicrobials, probiotics, etc., by encapsulating them within a matrix of nano-scaled materials. Thus, nanoencapsulation, serves as a potential vector for the bioavailability of food bioactive substances, by improving solubility and lipidic physical-chemical properties, thus increasing the metabolic stability of unstable bioactive ingredients against light, heat, and pH, and decreasing organoleptic, toxic, and oxidative rancidity hazards from bioactive compounds, and promoting their gradual release to the target site, contributes to the effectiveness of the bioactive (Chaturvedi & Dave, 2020 and Lugani *et al.,* 2021).

Nanotechnology is today's science, which makes future dreams come true. The reason behind this statement is that nanotechnology provides the tools to create products, such as nano-sized particles, about 1 to 100 nm in size. From this point of view, nanoencapsulation can be defined as the embedding of a bioactive compound in an edible capping material, creating a wall surrounding the bioactive, and allowing it to perform the expected function, and preserving it in a product (Chaturvedi &

Dave, 2020; Singh *et al.,* 2021 and Sahoo *et al.,* 2022).

Benefits and Challenges

Nanocomposite films are more effective against microorganisms compared to the individual actions of nanoclays or other nanomaterials added to enhance the strength of products. Carriers with a lipid core and surfactant protect fats from the hydrolysis process of the small intestine, improve the release of fat-soluble vitamins and improve their functionality. The improvement of the stability and flow of emulsions is beneficial to the foaming and whipping of dairy products. The protection mechanisms of lipids can help preserve the intramuscular lipid oxidation of dairy products and improve their nutritional quality. Animal nutrition is also subject to the exploitation of some positive effects of nanotechnology, such as the improvement of the efficiency of feed utilization, the better health conditions of domestic animals and therefore the reduction of waste materials introduced through the diet. The welfare of domestic animals can also be improved through the use of nanotechnology, mainly concerning the monitoring of animal welfare and the identification of the most appropriate breeding and rearing conditions, with the prevention of diseases (Mustafa & Andreescu, 2020; Lugani *et al.,* 2021; Salama *et al.,* 2022 and Guleria *et al.,* 2023).

The potential of nanotechnology when applied to dairy products is extensive and impacts all fields, from animal nutrition and welfare to milk transformation and human nutrition. On one side, the dairy sector is the most important of the agri-food industry. However, the product lifecycle of dairy products shows a high level of losses of final products mainly due to the expiration date. The addition of nanomaterials seems to prevent and slow down microbial contamination on the one hand, and to add health-promoting features to dairy products on the other hand. Moreover, it seems to represent valid support concerning applied animal nutrition and animal welfare for the improvement of the rearing and productive data (Hoque *et al.,* 2021; Lugani *et al.,* 2021; Sahoo *et al.,* 2021 and Singh *et al.,* 2021).

1. Enhanced Nutritional Value

Current research advances on the impact of nanotechnology on the dairy sector are summarized, showing that this technology is revolutionizing the food industry's future to improve the value of dairy foods, to gain high market shares through the development of new milk-based foods and nutraceutical products in a safe way, with controlled release, smart packaging, and rapid, accurate, and sensitive tools. The major concerns associated with nanotechnology applied in the dairy sector are the need for a common regulation with international harmonization and collaboration among all stakeholders, particularly communication between researchers and the public to promote the technology's transparency, safety, and sustainability (Anilakumar, 2021; Girigoswami *et al.,* 2021; Lugani *et al.,* 2021 and Jagtiani, 2022).

Food production in the world is continuously increasing to satisfy the demands of a growing human population. Traditional food sources are being overtaken by new and innovative foods, and milk is no exception. The dairy industry is producing new functional foods to attract consumers due to the direct association of milk and its derivatives with good health. New characterization strategies are available, and the use of new technologies may be essential to control and improve the quality of these foods. Nanotechnology, which can work at the nanometric scale, is revolutionizing the food sector/future. Despite the advantages of this recent technology, concerns about its potential risks have also arisen. This review summarizes the recent research advances in the development and study of nanomaterials applied in the dairy sector in terms of structure, characterization, valorization, and safety aspects (Lugani *et al.,* 2021; Guleria *et al.,* 2023 and Jiya & Balogu, 2023)

2. Improved Food Safety and Shelf Life

The quality of dairy products is impaired due to the high metabolic activity of microorganisms, the high moisture content, the neutral pH, the presence of essential nutrients, that is, proteins and sugars, and the availability of oxygen. There are reports of analytical methods used in the dairy sector in analyses of vitamins (B2, B12, D2/D3), adulteration by the presence of bovine milk in the presence of favourite milk, detection of milk pasteurization and infections in the uterine environment of cows. The inclusion of silver nanoparticles and gold nanoparticles performed by spraying and lyophilization in various dairy products contributed to the enhancement of the antimicrobial activity. Moreover the safety of the products concerning harmful microorganisms such as *Salmonella, Staphylococcus aureus, Escherichia coli, Bacillus coagulants, Listeria monocytogenes*, and other bacteria and microorganisms such as *Candida parapsilosis, L. innocua, L. ivanovii,* and *P. aeruginosa*, and the prolongation of the shelf life of the products (vessels of manual and automatic milking, butter packaging, Edam cheese whey protein coatings, infant formulas, and CampoMonte cheese). The combination of green and low-cost TiO2 nanoparticles and the use of the SrTiO3 photocatalyst allowed the reduction of the populations of contaminating bacteria (*L. innocua, S. Typhimurium, E. coli, and S. aureus*) in blocking and reducing the integrity of packaging films for Edam cheese, respectively (Mustafa & Andreescu, 2020; Madkour, 2021; Hoque *et al.,* 2021; Guleria *et al.,* 2023).

3. Regulatory and Safety Concerns

While recent studies have made progress on the fixation of nanoparticle exposure and localization, further research is still needed for in vivo studies to verify the real risk of or the unexpected toxicological or detrimental impact of nanoparticle exposure at all levels using different ecological models. Some nanoparticles, specifically antimicrobial ones, kill both microbial pathogens and "good" bacteria in our gut, and these nanoparticles may penetrate across the human GI tract according to some studies. Such general effects of engineered nano treatments may influence the health aspects of antimicrobial applications of dairy and other food nano treatments. So the use of nanotechnology to take care of dairy-related bacteria must precede safe use for oral intake (Lugani *et al.,* 2021; Hoque *et al.,* 2021; Salama *et al.,* 2022; Jagtiani, 2022 and Jiya & Balogu, 2023).

As with any novel technology, both perceived and real concerns pertaining to the health and safety aspects of nanotechnology have been raised. Many regulatory agencies in different countries define and regulate nanoparticles, nanostructures, and nanomaterials based on their size features with clear guidelines for their approval and use in food and food products. For promoting these novel materials to assure the Food and Drug Administration (FDA) and consumers about the safe use of nano-additives, formulated guidance standards are necessary for deciding if a foodstuff contains nano-sized additives. Pharmacology-based studies would help to take an approach toward the safe use of nanotechnology, including encapsulation of flavors, bioactive peptides, lipids, etc. Many of these studies have been conducted at lower levels of exposure to the target tissues. (Lugani *et al.,* 2021; Anilakumar, 2021; Salama *et al.,* 2022; Guleria *et al.,* 2023 and Jiya & Balogu, 2023).

Future Directions and Research Opportunities

Based on increased consumer fears about synthetic preservative use, the most promising approach has been the implementation of nanopackaging technologies in the active, intelligent, and nonmigrating antimicrobial type. In this matter, a specific distribution model of synergistic antimicrobial agents in active modified atmosphere packaging for cheese from waste whey was designed to address the loss of youth freshness. Given the

heterogeneity of the tasks and consumer preferences, alternative packaging solutions led to further research through chilling and freezing under continuous or discontinuous conditions. However, some limitations that could compromise the suitability of nanomaterials in food applications have to be addressed (Lugani *et al.,* 2021; Anilakumar, 2021; Sahoo *et al.,* 2021; Guleria *et al.,* 2023).

To capitalize on the potential that nanotechnologies and nanomaterials promise for the dairy industry in a sustainable, commercially viable, and socially responsible manner, it will be important to overcome current limitations and answer open questions for research and investment stakeholders. Moreover, consensus must be achieved on the mechanisms needed to validate, characterize, and communicate information regarding food-grade food components, generally regarded as safe, to consumers. An important starting point will be the development of the best handling and full, effective, economically viable, and sustainable packaging solutions that keep the desired features of dairy-based products and ingredients throughout manufacture, distribution, cooking, and storage and still maintain brand market attractiveness (Hasan *et al.,* 2020; Mustafa & Andreescu, 2020; Anilakumar, 2021 and Guleria *et al.,* 2023)

1. Emerging Trends in Nanotechnology Research

This review represents and comprehends different scientific research and manuscripts present in milk-related topics like dairy products, technological processes, fortifications, and storage. As exploratory research, we adopted the descriptive scientific method, which selects, explains, and classifies information through scientific manuscripts and literature reviews. Current worldwide scientific trends regarding nanotechnologies in dairy product quality are presented. Data available indicate nanotechnology is an increasing research field related to food and dairy in its broadest concept (Saadi *et al.,* 2022). The actual state of this research shows that still there is a lot to explore and more scientific efforts should be made to assess eventual risks associated with nanotechnology and nanotoxicology. (Anilakumar, 2021; Lugani *et al.,* 2021; Hoque *et al.,* 2021; Salama & Bhattacharya, 2022 and Al-Bedrani *et al.,* 2023)

The impact of nanotechnology in recent decades is immense due to its ability to revolutionize several fields of science and technology. Nanofood is not revolutionary, and only a few products are ready to be commercialized. The main nanotechnology research is performed in curcumin, omega 3, carotenoids, vaccinium, and pectin. Nanoparticles behave differently in organic foods due to the presence of vitamins, phenolic compounds, and oils. In nutritional areas, active packaging containing Fe3O4 nanoparticles and honey-containing propolis nanoparticles is studied. Controlled release, sensorial characteristics, and protein stability are issues that require further research. The main consumer's concern about nano-technology is safety. Meat technology research related to nanotechnology applied in product quality, as well as smart packaging to increase consumer shelf-life, is increasing in dairy production (Anilakumar, 2021; Sahu *et al.,* 2022; Naskar *et al.,* 2022).

2. Potential Innovations in Dairy Products

Finally, we mention the potential of non-thermal technologies that would certainly profit from the development of nano-tools. (Chaturvedi & Dave, 2020; Salama *et al.,* 2022 and Ashique *et al.,* 2023)

Moreover, all the thermally driven cheese elaboration processes could be quickly monitored with new in-situ tools based on evanescent waves (EW). With the recently developed Japanese hyperdivergent seconds-asymptotic expansion and the above-mentioned path-defects perspective, one could think to perform a quantitative series of experiments in order to better understand the possible interference of the subgroup of evanescent wave physical paths with nucleating bacterial and mold spores

(Mandal and Ray, 2020; Chaturvedi & Dave, 2020; Hoque *et al.,* 2021; Lugani *et al.,* 2021 and Salama *et al.,* 2022)

Cheese is an interesting 3D-structured soft-matter system. Its rheology depends not only on composition but also on its hierarchical structure, which is a result of a complex dynamic related to the separation of the whey from the curd. Modelling this process from the evolution of curd nano-structure would help to build predictive tools for the texture properties of cheese (Lugani *et al.,* 2021; Anilakumar, 2021; Salama & Bhattacharya, 2022).

To continue with the example of yoghurt, the distribution in the product of the probiotic bacterial strains can be very irregular due to the presence of settled fruits and bubble-free zones around them. The phenomenon of most-probable-path is present in many biological systems where the provision of a few favorable paths for the good (for instance the human voice) creates the conditions for some destructive resonance effect, as most of the available energy will follow the same path (Saadi *et al.,* 2019; Anilakumar, 2021; Hoque *et al.,* 2021 and Lugani *et al.,* 2021).

The formulation of dairy products presents interesting challenges, which could be partially solved by using current knowledge in nano-sciences. For instance, physical interactions in conventional yoghurt are greatly limited by the presence of a 3D structure built from the gelation of proteins. This gelation could be tunable at a molecular scale to control the final properties of the product, improving interaction with gut biology or suppressing the settling of fruits (Lugani *et al.,* 2021; Salama *et al.,* 2022)

Summary of Key Findings

The three examples given above illustrate that EPS will probably be of value in a range of foods. After high hydrostatic pressure treatment, EPS-unloaded mayonnaises display better stability against centrifugation and temperature, better preservation of sensory traits, and a smoother consistency, which may benefit some consumer groups. Such condiments gain interest in fresh salads and different types of sandwiches. The EPS effect was studied by the group of Yang and Li, 2009. Samples of EPS-containing cold-pressed acidified wasabi oil-loaded whey protein isolate were examined with droplet sizes that remained smaller for longer and did not increase as much as the temperatures of 20 and 5 ^{o}C, peaking at 260 and 650 mg/l, and for 40 and 80 ^{o}C at 1780 and 1330 mg/lans, and emulsions were almond-based through treatment with single-phase ethanolic glycerin, and glycerin-treated and plain samples exhibit WPI nanoparticles, and emulsification, therefore, being dependent on EPS for stabilization. EPS-coated whey protein isolate nanoparticles are also synthesized using EPS with an α-carbohydrate and β-peelemulsion property that depends on EPS incorporation. Thus, WPI nanoparticles stabilized with EPS might offer potential as food emulsifiers or edible food coatings (Chaturvedi & Dave, 2020; Nile *et al.,* 2020 and Lugani et al.,2021)

In summary, EPS shows promise as an innovative emulsifier in the preparation of food emulsions and nanoencapsulations. They possess bioactive properties, are available at low cost, are relatively easy to extract, and are considered edible by the food industry. The presence of EPS has been proven to enhance the stability of food emulsions by forming a more consistent film network that strengthens the oil-water interface. In nanoemulsions, EPS has been shown to prevent Ostwald ripening and produce smaller droplets. EPS is not a fat-loving component but a water-loving component of WPI, and it stabilizes the nanodroplets by being present on the nanodroplet surface. This makes EPS suitable for specific applications in fat food oppression and encapsulation, where droplets with very small diameters such as bitter fighters, aromatics, and/or essential oils are crucial. EPS WH1, while not removing the thickening properties of WPI, markedly enhances the thickening

measurements of the WPI-stabilized nanoemulsion, 2000 times, as evaluated by Nooshkam et al., 2023. Moreover, EPS is suitable for generating WPI- and oil-laden materials such as butter and cream gel products. Water-weighted EPS does not affect the mechanical properties of the fat matrix after hydration, impregnation, and drying (Chaturvedi & Dave, 2020; Mandal and Ray 2020; Nile *et al.,* 2020 and Anilakumar, 2021).

Implications for the Dairy Industry

The packaging of dairy products with some nanocomposites tends to improve shelf life, organoleptic properties, and physical properties, as antimicrobials and the application of modified atmosphere packaging can be carried out. On the other hand, the activation of milk and/or dairy manufactured products with nanosystems can be used as tools for the development of enriched dairy products which may respond to current consumer demands, enabling the creation of new ingredients and ultimately new products. Since milk proteins mainly lead to the process of emulsification, the open window and stability of the created structure can be accurately controlled (Verma and Pandey 2021; Puttasiddaiah *et al.*, 2022).

Nanotechnologies can have several implications in dairy science as they could be successfully applied throughout the production chain from farming to food processing, packing, distribution, and retailing. Recent advancements in nanosciences and nanotechnologies have allowed the development of many new materials and devices with applications in food science. The dairy products market increasingly demands products with higher added value since functional ingredients beneficial to health are being searched. Regulators also support such innovations to promote the advances for the consumers as long as products are correctly labelled and correct legislation is applied. Encapsulation offers many opportunities for the food industry, which in particular can be advantageously used in coffee creamer powders, in the production of cheese flavors, and in micellar casein characteristics, among other products (Lugani *et al.,* 2021; Anilakumar, 2021; Sahoo *et al.,* 2021; Naskar *et al.,* 2022 and Salama *et al.,* 2022)

CONCLUSION

It is vital for the future of the rapidly expanding dairy industry to constantly adopt new technologies to keep abreast of the spiralling demand for healthy nutrition at affordable prices, avoiding waste and with minimal adverse environmental impact. The present paper looked at recent developments in nanoscience and nanotechnology and tried to match them with the supply chain of the dairy industry, starting with the primary producer. Based on a modified SWOT analysis, the likely most important growth areas for nanotechnology applications in the dairy field were discussed. From this, consumers should soon be able to benefit not only from the improved taste and flavor of dairy products but also select for their differing nutritional and health benefits. While allowing the greater production of safe, healthier, and tastier food, the innovative use of nanotechnologies should also enhance the sustainability of the complete dairy industry.

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تأثير تقنيات النانو في علوم الأغذية والألبان: مراجعة

[1]روى عادل حامد، [1]ميعاد وليد سعدالله، [1]رقية فؤاد لافي، [2,3]علي محمد سعدي

[1] قسم علوم الأغذية ، كلية الزراعة والغابات ، جامعة الموصل ، الموصل ، العراق
[2] قسم تقنيات التخدير ، المعهد التقني الطبي الموصل ، الجامعة التقنية الشمالية ، الموصل ، العراق.
[3] الكلية التقنية الزراعية ، الجامعة التقنية الشمالية ، العراق

Email: ali.mohammed@ntu.edu.iq Assiut University web-site: www.aun.edu.eg

سيؤدي الاستخدام الواسع النطاق لتكنولوجيا النانو قريبا إلى تحول جذري في صناعات الأغذية والألبان. تعد مواد التعبئة والتغليف الجديدة ذات الخصائص الميكانيكية والحاجزة والمضادة للبكتيريا المحسنة من بين الاستخدامات الممكنة، وكذلك المواد الملامسة للأغذية المحسنة، والعمر الافتراضي الأطول لمنتجات الألبان والمواد الغذائية، وطرق المعالجة عالية الجودة. كان هناك ارتفاع حديث في الأبحاث حول إمكانية استخدام تقنية النانو لتغليف ونقل المركبات النشطة بيولوجيا، وتحسين الصفات الحسية للأغذية، وتضمين الهياكل النانوية المضادة للميكروبات في التعبئة والتغليف، من بين استخدامات أخرى. تتمتع تقنية النانو بالقدرة على تعزيز خصائص النقل والذوبان والامتصاص الخلوي للمواد الكيميائية النشطة بيولوجيا عن طريق تقليل حجم جسيماتها. يجب تهدئة مخاوف المستهلكين بشأن الضرر المحتمل على صحة الإنسان من أنظمة التوصيل القائمة على تكنولوجيا النانو قبل أن يتم تنفيذ هذه الأنظمة تجاريا. مع التركيز على التطبيقات ذات الاحتمالية الأعلى للتسويق قريبا، تقدم هذه المقالة نظرة عامة شاملة على استخدام تقنية النانو في الأنظمة المتعلقة بالأغذية والألبان.

الكلمات المفتاحية: تقنية النانو ، علوم الأغذية ، علوم الألبان