

Nanozymes and Nanomaterials in Dairy Technology

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1. Introduction

1.1 Background:

Dairy Industry is a major sector of the economy that is challenged in the following way. Dairy industry can be relevant to the world food system, as it constitutes a significant source of such nutrients as protein, calcium, and vitamins, which are required to support the health of the population (Yesildemir et al., 2023). This addiction strains the needs of high quality and safety level between the dairy value chain and the raw milk to finished products. However, there are many issues in the industry that require technological improvements (Singh et al., 2023). Some of the dairy industry challenges include food safety threats (microbial contamination), (including E. coli and Salmonella), and chemical contamination (including antibiotics and pesticides), (Chowdhury et al., 2024) and (Yan et al., 2022). Another matter of concern is adulteration, and adding harmful chemicals (such as melamine) that intentionally aims at raising the protein amount is the misdemeanour that is potentially life-threatening (Alizadeh et al., 2023; Luo et al., 2017).

1.2 Disadvantages compared to Natural Enzymes.

To enhance quality, the industry needs to screen the spoilage and nutritional quality rapidly, precisely and cost-effectively. The majority of the traditional methods of analysis, e.g., chromatography, are not only slow but also costly, or impossibly fast to obtain speedy results (García-Miguel et al., 2016). There is also the need to continuously improve the efficiency of the

processing, minimize the effect of environmental degradation, and extend the shelf life of dairy products with a more advanced preservation and packing system (Singh et al., 2023).

Nanozymes and nanomaterials are the result of the human activity and development of technologies in medicine, biology, and biotechnology (Burzio et al., 2019).

The use of nanotechnology has emerged as one of the most significant solutions to solve such problems because the materials are used in the nanoscale (1 to 100 nm) (Hossain, 2024). The size and shape peculiarities of nanomaterials (NMs) enhance the reactivity of nanomaterials, their surface area, and conductivity, thus, they can be used in advanced sensing and catalytic applications (Atanda et al., 2025).

An example of this type of nanomaterial is nanozymes which are man-made materials (e.g., metal oxides and noble metals) with the catalytic activity of an enzyme (e.g., peroxidase or oxidase) but not a natural protein (Singh et al., 2023). There are numerous benefits of nanozymes over natural enzymes, such as expensive, lacks stability (He et al., 2020), and is powerful, scalable, and assuring diagnostic agents. Intelligent, effective and sustainable dairy technology can be impacted in a drastic manner by nanomaterials with nanozymes.

1.3 Objectives of this Review.

Even though the existing literature has covered the individual uses of nanotechnology in the dairy science field, there remains a gap that needs to be filled by a comprehensive review of the collective potential of nanomaterials and nanoenzymes in different uses, such as the optimization of the processing to safety diagnostics (Hossain, 2024; Singh et al., 2023).

The review will focus on offering a systematic and concise review of the most recent findings on application of nanomaterials and nanozymes in dairy technology. It will specifically investigate the work of them in the following: 1) quality improvement and preservation (packaging and processing) and 2) food safety and diagnostics (pathogen and contaminant detection) (Chowdhury et al., 2024). Furthermore, such crucial aspects of the review will include safety concerns, regulatory concerns, and the viability of the market that guarantee the successful commercialization (Singh et al., 2023)..

2. Introduction to Nanozymes and Nanomaterials.

The dairy business relies on nanotechnology on the basis of the distinctive chemical and physical characteristics that chemicals acquire once they are diminished to the scale of 1 -100 nanometers (Atanda et al., 2025). This is due to the fact that at this nanoscale, several special effects (such as quantum effects and very high surface area-to-volume ratio) can be achieved (Hossain, 2024). This set of features is utilized strategically to improve the functions of catalysis, sensing, and encapsulation, and ultimately raise the degree of functionality and efficiency of various dairy applications (Singh et al., 2023).

As shown below, nanomaterials are categorized under different groups.

The nanomaterials (NMs) utilized in food science and food manufacturing especially dairy technology can be classified widely, according to their chemical composition and structure. This classification is significant due to its impact on their behavior, stability, and many applications, such as senses, packaging, and direct incorporation into the food products (Atanda et al., 2025).

Carbon-Based Nanomaterials

This category includes the Carbon Nanotubes (CNTs), Graphene and Carbon Dots (CDs). These materials have been distinguished by their high electrical conductivity, mechanical strength and massive and conveniently large surface areas. They are the most preferable transducers of the dairy diagnostics because the electrochemical biosensors have been developed to sense the presence of the pathogens or the contaminants (Hossain, 2024).

Metal Oxides

Some of the notable representatives of such metal oxides include Fe₃O₄ (Iron Oxide), ZnO (Zinc Oxide) and TiO₂ (Titanium Dioxide). The resources are valued in accordance with their versatile nature. ZnO and TiO₂ are the ones that are specially known to have photocatalytic and good antimicrobial qualities, which makes them the most ideal materials to utilize in packaging (Singh et al., 2023). Moreover, Fe₃O₄ possesses superparamagnet properties, and it is possible to efficiently and quickly separate and pre-concentrate targets, such as bacterial cells or chemical residues, on complex milk samples using Magnetic Solid-Phase Extraction (MSPE) (Wang et al., 2023; Zhang et al., 2022).

Metallic and Polymeric Nanomaterials.

Noble metals have been found to be NPs with distinct Surface Plasmon Resonance (SPR) characteristics that have played a pivotal role in highly sensitive optical biosensors and notably in colorimetric detection (Shameer et al., 2025). Moreover, AgNPs are potentially potent antimalarial agents that are broad spectrum (Singh et al., 2023).

Polymeric nanomaterials, polymeric liposomes and polymeric micelles have become popular in practice as nano-capsules due to their biocompatibility and the fact that they can be used as stable nano-capsules. These nano-capsules are essential in the preservation of fragile nutrients (e.g. vitamins and polyunsaturated fatty acids) during food processing, and thus, increasing their bioavailability in dairy products (Singh et al., 2023).

2.2 Introduction to Nanozymes

Nanozymes are artificial nanomaterials and these are artificial materials that have inherent catalytic characteristics and resemble the workings of natural enzymes. Such properties can be normally linked to defects within the crystal lattice, surface area effects and differences in valence state, and this provides alternatives to the limitations commonly encountered by biological enzymes (Singh et al., 2023).

Mechanism of Action

Nanoenzymes tend to behave in a similar manner as natural enzymes having peroxidase-like, catalase-like, and oxidase-like reactions. In the example, certain metal oxide nanozymes such as Fe₃O₄ and CeO₂ can cause the breakdown of hydrogen peroxide (H₂O₂) and resemble the ability of the natural peroxidase enzymes (He et al., 2020). The outcome of this catalytic process is reactive oxygen species (e.g., hydroxyl radicals, •OH) and is able to oxidise a chromogenic substrate to provide a detectable colour change (e.g. TMB). Very sensitive colorimetric tests, which are used in dairy diagnostics, are based on such an idea (Ensafi et al., 2021).



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Disadvantages compared to Natural Enzymes.

A range of important operational and economic benefits predetermines the substitution of natural enzymes with nanozymes (Singh et al., 2023):

Enhanced Stability: Nanozymes are very stable to denaturing forces as compared to other protein-based enzymes; therefore, they retain their catalytic activity under harsh conditions, e.g. high temperatures, low and high pHs, and organic solvents. This reliability ensures that the industry will have long life and be stable (He et al., 2020).

Scalability and Cost-Effectiveness: Nanozymes can be made using standard, scalable and low cost chemical methods (e.g. co-precipitation and hydrothermal synthesis). The method eliminates the costly and difficult purification procedures that may be necessary in order to generate natural

enzymes and nanozymes are therefore optimal in a large-scale industrial context (Ensafi et al., 2021).

Tunable Properties: Kinetic properties and specificity Nanozymes can be tuned in terms of controlled synthesis parameters (e.g., size, shape and composition) and surface engineering (e.g., ligand capping). This customization capability enables certain design approaches to be crafted based on the needs of the use, which gets streamlined whenever creating the particular analyte (Singh et al., 2023).

2.3 Significant Substances in dairy technology.

Various nanomaterials attract the dairy industry because of the following functionalities that have been chosen:

Fe₃O₄ (Iron Oxide Np)

The primary characteristic of Fe₃O₄ nanoparticles is the high saturation magnetization (M_{3n}) and excellent superparamagnetism (Zhang et al., 2022). This magnetic characteristic enables the target analytes or microorganisms to purify rapidly and without reagents and by means of an external magnetic field and complex samples (Wang et al., 2023). Furthermore, the surfaces of these nanoparticles can also be easily functionalized, and it can serve as a selective adsorbent to chemical contaminants including melamine or pesticides and as nanozyme to produce signals (Singh et al., 2023).

AuNPs (Gold Nanoparticles)

The extraordinary nature of the optical properties of gold nanoparticles basing on the size of the gold core as well as the dielectric surrounding the core. These properties are employed by them to develop highly sensitive colorimetric and Surface-Enhanced Raman Spectroscopy (SERS) biosensors (Shameer et al., 2025). Lateral flow assays based on GauNPs can also be performed on paper that can be laterally used in dairy safety to observe the presence of a pathogen or contaminant with the visual eye (Hossain, 2024).

CeO₂ (Cerium Dioxide)

Cerium dioxide is regarded as one of the most significant nanozymes as these variations between the Ce³⁺ and Ce⁴⁺ oxidation states can be made without significant complications (He et al., 2020). This ambivalent condition renders it good intrinsic oxidase, peroxidase and catalase like activity. Also, CeO₂ is a powerful antioxidant of reactive oxygen species (ROS) (Singh et al., 2023), which is an important attribute that might be applied to reduce the oxidative stress level and improve the quality and the stability of lipid-rich dairy products.

Applications and Quality Improvement of dairy Processing.

In the dairy industry, nanomaterials and nanozymes have been applied in the dairy industry in the diagnosis, processing, preservation, and formulation of products. Nanotechnology has proposed alternative modalities of improving the physical stability, microbiological and nutritional dairy products (Han et al., 2025).

3.1 Increasing Preservation and Shelf Life.

The other essential economic and safety issue in the industry is the way to increase the shelf life of the perishable dairy products. Nanomaterials play a significant role in this objective in innovative packaging and direct antimicrobial activities (Donkor et al., 2025).

Packaging: Nanotechnology: Nanocoatings and Nanofibers.

Nanomaterials are used to produce food contact material to create better nanocoatings and nanofibers that have excellent barrier properties compared to regular polymers (Vasile et al., 2018).

Gas Permeability Control: By incorporating nanomaterials with high aspect ratio, e.g. nanoclay or graphene oxide (GO) into polymer matrices, road network to gaseous molecules (e.g., O₂, CO₂ and water vapor) is formed in a complex way. The advantageous impact of this is the reduction of the rate of the oxidative spoilage of fats (rancidity) and texture loss (dryness, excessive moisture uptake) of such products as cheese and powdered milk (Sankaranarayan et al., 2025).

Antimicrobial Release Systems: Nanoparticles can be used to provide a high-affinity antimicrobial. The possibility of silver nanoparticles (AgNPs) to release silver ions (Ag⁺) in a controlled condition and, consequently, avoiding the development of spoilage microorganisms and pathogens on the surfaces of the products has been given a lot of attention. In addition to that, natural essential oils or bacteriocins can be loaded into the electrospun nanofibers and used as a functional insert or wrapper in packaging (Sati et al., 2025).

Intelligent and Active Packaging Systems.

Nanomaterials contribute significantly in production of smart.

packaging technologies:

Active Packaging: This is an active application of change within the inner environment of the packaging with the aim of enhancing the product quality. It exploits nano-adsorbents, the carbon nanotubes, to adsorb volatile off-flavor compounds or adds oxygen scavengers to the film to contribute to the preservation of freshness over longer storing periods (Singh et al., 2023).

Smart Packaging: It is the system that controls the state of food and transfers the data about the food quality to the consumers. Indicatively, nanosensors, e.g. pH-sensitive quantum dots or colorimetric nanozyme-based arrays, can detect a specific amount of microbial metabolites (e.g. volatile organic compounds or amines) that are indicative of spoilage. The consumers are notified by a visible shift in color or signal on the outer label of any potential degradation of the product without the necessity to break open the package (Mani et al., 2025).

3.2 Improvement of Characteristic Properties.

Nanotechnology allows manipulation of physical and chemical traits of dairy components in very finer details that results in excellent functional traits, nutrition, and new-fangled textual experiences (Kaptan et al., 2025).

Bioavailability of Nutrient and Encapsulation.

Dairy products are good vectors of vital, albeit, most of the time unstable nutrients. Nanomaterials stabilize these functional ingredients.

Protection and Stability: Sensitive nutrients such as fat-soluble vitamins ("A" , "D" , "E") and volatile polyunsaturated fatty acids (PUFAs) are entrapped in polymeric nanoparticles (e.g., chitosan) and nano-liposomes. This encapsulation can guarantee the safety of those molecules against unfavorable conditions of processing (e.g. pasteurization) and oxidative degradation in the course of storage (Mankan et al.,2025).

Improved Bioavailability: Dissolving the nutrients in the liquid part of the milk: the smaller the nutrient and biocompatible shell it is (ex: protein-polysaccharide complexes), the better it will be absorbed in the digestive tract and nutritional bioavailability(Yudishter et al.,2025).

New Low-fat products and New Dairy Textures.

Nanotechnology provides opportunities to alter the texture and rheological properties of dairy preparations and in particular produce healthier preparations.

Fat Mimetics: The loss of fat normally gives the mouth the unwanted feel and touch. Nanotechnology can be employed to come up with nanostructured fat replacers or protein nanoparticles that mimic rheology and lubrication properties of fat droplets. It may also be applied to produce dairy products (e.g., yogurt, ice cream) that have desirable textures and viscosities and

sensorial properties with reduced fat content (Kew et al., 2025).

Structured Delivery Systems: There are numerous approaches that can be applied to alter the aggregation characteristics of milk proteins, such as nanostructuring milk proteins (like casein micelles), which will provide more control over the ultimate product microstructure. It is used to produce new products with a property that is customized, e.g., higher gel strength in yogurts or higher emulsification stability in cream-based beverages (Sadiq et al., 2021).

4. Nanomaterials/ Nanozymes in Diagnostics of dairy.

The production of fast, high sensitive and cheap analytical equipment that is claimed to be food safety is one of the applications of nanotechnology in the dairy industry. The biosensors of the next generation are founded on nanomaterials and nanozymes that can identify chemical adulterants, contaminants, microbial pathogens (Perumal, 2019).

The method used to identify the adulterants and contaminants will be as follows.

The trace chemical pollutants (including heavy metals and pesticides) and the intentional nitrogen-containing adulterants (such as melamine and urea) are also extremely difficult to detect and require complex pre-concentration and sensing technologies (Griesche et al., 2022).

Nanomaterials as Viable Sensing Surveys.

The other significant impact of nanomaterials is on sensor performance, which increases the electrochemical surface area of actual operation or multiplies optical signals.

Optical and electrochemical sensors.

Electrochemical sensor modifiers are also nanostructures (carbon nanotubes (CNTs) and graphene), which are used to enhance the rates of electron transfers and low limits of detection (LOD) of numerous heavy metals (e.g., Pb^{2+} , Cd^{2+}) and pesticides residues against electrochemical sensors. Optical detection (Gold Nanoparticles, AuNPs and Quantum Dots, QDs) is also applicable, with QDs potentially being engineered to possess fluorescence characteristics and modified to carry recognition bait (e.g. aptamers) to detect an analyte, like aflatoxins, in a highly selective and sensitive way (Li et al., 2013).

Melamine Detection

During the melamine crisis, nanomaterials were significant in two respects:

MSPE Pre-concentration Magnetic Iron oxide nanoparticles (Fe_3O_4) can undergo surface-functionalization to selectively pull down melamine in complex milk matrices, and then magnetic separation and elution can be quickly conducted, which causes reduced interference of the matrix (Zhang et al., 2023).

AuNP Aggregation: The aggregation of the AuNPs can be triggered by various nitrogen groups in melamine and the transformation between the red and blue color of the aggregate particle can be observed, and hence the detection can be achieved within minutes (Lodha et al., 2013).

Nanozyme-Based Biosensors

The nanozyme-based biosensors are developed to identify the existence of toxins and contaminants.

Colorimetric and Fluorometric Detection: nanozymes have been common substitutes in these assays of natural peroxidases. An example of such an enzyme is 3 4and 2 nanozymes catalyzing the oxidation of a substrate in the presence of an analyte (or its inhibitor). This principle can also be applied in the identification of pollutants like the organophosphate pesticides that inhibit specific enzymes because the nanozyme would act as a downstream reporter(Attar et al., 2019).

4.2 Pathogen Detection

The detection of pathogenic bacteria (e.g., *E. coli* O157:H7, *Salmonella*) in the raw milk must be very fast and precisely. The nanotechnology is useful to circumvent the problem of poor initial concentrations of pathogens and the complexity of matrix (Shanker et al., 2019).

Separations and Pre-concentration using Magnetic Nanomaterials:

In this case, high efficiency of Magnetic Solid-Phase Extraction (MSPE) is required. Particles of nanoparticles can be coated with specific capture agents (e.g. antibodies or bacteriophages) by using surface antigens of pathogens Fe_3O_4 . These functionalized magnetic nanoparticles bind the targeted bacteria, hence, is thus isolated fast and this leads to 100-1000 fold pre-concentration of large quantities of milk under external magnetic field. This technique is highly useful in reducing the time that the next detection is supposed to take and reduces the disturbance of matrix (Kapsi et al., 2025).

Nanozyme-Based Assays Bacterial By-products.

Tests made to detect bacterial metabolites or enzymes can be carried out using nanozymes. Indicatively, the presence of odd bacterial enzymes can cause liberation of H_2O_2 active production or usage, which, in turn, impacts the functionality of an Fe_3O_4 or CeO_2 nanozyme reporters structure. This cascade amplification allows the quick and sensitive detecting of the living pathogens basing on the enzymatic activity without the time-consuming steps of culture (Lyu et al., 2021).

6. Conclusion and Future Projections.

6.1 Emerging Trends

The nanomaterials and nanozymes Dairy technology is an emerging discipline that is slowly picking up pace in terms of the materials science and their computational technologies. The most significant trends will have an effect on the next generation of applications (Ai et al., 2020).

- Integrated Nanodevices and Microfluidics Future diagnostic systems Future diagnostic systems have the potential to evolve into integrated lab-on-a-chip (LOC) and microfluidics systems. Such microfluidic applications will integrate sample clean-up and Magnetic Solid-Phase exaction (MSPE) with Fe_3O_4 nanoparticle and signal amplification capability of nanozyme biosensors on a single, disposable chip. This will facilitate the high throughput, automated, and speedy on-site analysis of different contaminants (Tennico et al., 2010).
- Connection to Artificial Intelligence (AI): Nanosensors are very sensitive and hence generate big data (e.g. electrochemical responses, spectral responses). The diagnostic accuracy will be improved with the combination of the nanosensors with the Artificial Intelligence (AI) and the Machine Learning (ML) algorithms. Artificial intelligence can be used to analyze the complex sensor data, correct the matrix effects, identify the subtle patterns indicating early spoilage, and make much more accurate predictions of the shelf-life than the human judgment (Yin, 2025).
- Development of eco-friendly and Green Nano-materials: The use of environmentally and sustainably friendly approaches to the development of nanomaterials is becoming increasingly popular. This requires the use of biological templates (such as plant extracts or microorganisms) in the preparation of nanoparticles with a view of lessening chemical toxic waste. More so, the food-grade and entirely biodegradable nanomaterials are being prepared to address the anxieties of the long-term consequences of the environment, especially when nanomaterials are in direct contact with food (Noah et al., 2025).
- Molecularly Imprinted Nanozymes (MINs): very selective Nanozymes that integrate the characteristics of stabilization of nanozymes and recognition characteristics of molecularly imprinted polymers (MIPs). It is also possible to design MINs, which will be catalytically

active against target molecules (melamine or special antibiotics) and, consequently, incredibly selective and minimize the number of false positives in complex dairy samples (Zhou et al., 2023).

6.2 Conclusion

This general summary points to the radical opportunities of nanomaterials and nanozymes application to dairy value chain. The solution to any contemporary problem is nanotechnology, be it the enhancement of the quality of the nutritional value and the time of products preservation, or the health of the population because of the potential of rapid diagnostics.

The significant accomplishments, which have been discussed, include:

There was the critical point of separation of contaminants and pathogens by nanoparticles (Fe_3O_4) to ease the process of preparing a sample.

The nanozyme efficiency (Fe_3O_4 , CeO_2) as valuable, stable, and cheap substitutes of natural enzymes to produce signals to be applied in biosensing.

The necessity of using nanomaterials (AgNPs, nanoclay) in active and intelligent packaging system to control spoilage and to measure freshness.

However, the industry encounters acute toxicological and regulatory challenges to be conquered to achieve prevalence in the industry. Standardized synthesis protocols, long term safety data and scalability (cost-effective) are the major focal points of future research. The future of Dairy industry will be that of smarter food processing and quality control and better food safety through continued advancement in the further application of nanomaterials and nanoenzymes as a synergistic system.

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