



Nano-encapsulation and Probiotic Delivery: Emerging Strategies for Non-Dairy Functional Foods and Therapeutic Applications

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ABSTRACT

The growing demand for functional foods has led to the development of non-dairy probiotic products that cater to consumers with dietary restrictions or preferences. Nanoencapsulation has emerged as a promising strategy to enhance the stability, bioavailability, and targeted delivery of probiotics, particularly in challenging gastrointestinal environments. This review explores recent advances in nanoencapsulation techniques, focusing on their application in non-dairy matrices and their potential therapeutic roles. Gold nanoparticles (AuNPs) and magnetic nanoparticles (MNPs) have shown significant promise in biomedical applications due to their unique optical and magnetic properties. Their integration with probiotic strains such as *Lactobacillus fermentum* enables the creation of heterobimetallic systems capable of dual-functionality: photothermal therapy and magnetic hyperthermia. These systems demonstrate efficient heat generation under laser and magnetic field exposure, offering new avenues for oral cancer treatment strategies. The review also highlights the importance of encapsulation materials, including biopolymers and lipid-based carriers, and discusses the physicochemical factors that influence nanoparticle-probiotic interactions. Additionally, regulatory considerations and toxicological evaluations are addressed to ensure the safe incorporation of nanomaterials into food and therapeutic products. While current findings are promising, further studies are needed to optimize nanoparticle design, improve detection methods for bacterial viability, and ensure long-term safety. The potential of *Lactobacillus fermentum* as a drug carrier opens new possibilities for targeted delivery systems in gastrointestinal therapies, positioning nanoencapsulation as a key technology in the future of functional foods and biomedicine.

Keywords: Nanoencapsulation, probiotic delivery, gold nanoparticles (AuNPs), magnetic hyperthermia, *Lactobacillus fermentum*, non-dairy functional foods.

1. INTRODUCTION

Functional foods are enriched with probiotic microorganisms and bioactive compounds, commonly found in dairy and fermented products. Their consumption is especially recommended for vulnerable populations due to their potential role in promoting health (Prado, Parada et al. 2008, Cassani, Gomez-Zavaglia et al. 2020, Arratia-Quijada, Nuno et al. 2024). Among the most widely consumed probiotic products are milk-based beverages containing *Lactobacillus* strains. The efficacy and quality of these drinks largely depend on the concentration and viability of the bacteria they contain. Unfortunately, such details are typically disclosed only in promotional materials by manufacturers, which may not always be reliable. Moreover, there is a lack of comprehensive studies evaluating the actual bacterial content of these products, and traditional methods for



quantifying *Lactobacillus* are often complex and time-intensive (Di 2020). The growing demand for functional foods with live probiotics has spurred innovation in nondairy alternatives. These products aim to address the limitations associated with dairy, such as poor digestibility, allergic reactions, lactose intolerance, elevated cholesterol levels, and high saturated fat content. Additionally, they cater to diverse dietary preferences, which can significantly influence consumer health outcomes (Min, Bunt et al. 2019, Aspri, Papademas et al. 2020, Arratia-Quijada, Nuno et al. 2024). Integrating probiotics into functional foods faces multiple challenges that can be classified into four categories: (1) those inherent to the probiotic strain, (2) those associated with the manufacturing process, (3) those affected by storage conditions, and (4) those specific to the administration route (Champagne, Gardner et al. 2005, Tolve, Galgano et al. 2016, Arratia-Quijada, Nuno et al. 2024). To address these challenges, various strategies have been proposed, including the use of probiotic strains resistant to acid and bile, fermentation processes, the addition of micronutrients and prebiotic substrates, cold-chain storage, oxygen-barrier packaging, aseptic processing, and advanced encapsulation methods (Champagne, Gardner et al. 2005, Hosseini and Jafari 2020, Arratia-Quijada, Nuno et al. 2024). In recent years, microencapsulation and nanoencapsulation technologies have been increasingly applied to protect probiotic strains from harmful environmental factors such as pH fluctuations, exposure to light, moisture, oxygen, and heat. These techniques significantly enhance probiotic viability, bioavailability, functional performance, and nutritional benefits (Augustin and Hemar 2009, Hosseini and Jafari 2020, Arratia-Quijada, Nuno et al. 2024). Nanomedicine continues to expand the scope of cancer treatment options, offering innovative therapeutic pathways (Chen, Roy et al. 2016). Among these emerging approaches is the use of metallic nanoparticles, which possess unique optical and magnetic characteristics that make them promising candidates for targeted cancer therapies (Shang, Yang et al. 2014, Garcés, González et al. 2022). Specifically, gold nanoparticles (AuNPs) and superparamagnetic maghemite/magnetite nanoparticles (MNPs) are under investigation for their potential use in tumor-targeted hyperthermia therapies (Dung, Linh et al. 2021, Mekseriwattana, Guardia et al. 2022).

This review presents a detailed exploration of nanosystems, highlighting their potential role in advancing innovative non-dairy probiotic formulations. It also outlines key considerations for selecting probiotic strains, examines various nano-carrier platforms and encapsulation strategies, and addresses the toxicological and safety aspects associated with nanoscale delivery systems.

2. Nano-encapsulation techniques for probiotics

Microbial nanoencapsulation has emerged as a promising strategy to improve probiotic viability by creating tailored microenvironments that support their stability and survival (Tolve, Galgano et al. 2016, Reque and Brandelli 2021). Encapsulation involves embedding probiotics as core materials or dispersing them within protective matrices such as coatings, membranes, shells, or wall materials to shield them from adverse environmental conditions (Nedovic, Kalusevic et al. 2011, Jafari 2017). A key challenge in this field is to engineer an effective delivery system that maintains the bioavailability and functional activity of probiotic strains, while also preserving the sensory qualities of food products, including taste, visual appeal, and texture (Dima, Assadpour et al. 2020). A probiotic nano-system is composed of two fundamental elements: a carrier typically a nanomaterial with at least one dimension in the nanometric range and the probiotic strain itself, which serves as the bioactive agent delivering health benefits to the host. The interaction and properties of these components determine the overall performance and behavior of the nano-system (Jafari 2017, Duarte, Mergulhão et al. 2021). Nano-systems significantly boost the survival of probiotics and enhance the quality of products mainly by reducing particle size. This downsizing improves water dispersibility, offers greater protection against chemical and biochemical degradation, and minimizes undesirable interactions with other food ingredients (Jafari 2017, Assadpour and Mahdi Jafari 2019). Successfully addressing these challenges depends on selecting the right encapsulation material and technique. Additional factors such as strain type, material concentration, particle size, and surface charge must also be tailored to the specific physicochemical properties of the food formulation (Delfanian and Sahari 2020). Encapsulation technologies, which are based on biotechnological principles, have been utilized in the food industry for an extended period. These techniques whether physical or chemical involve enclosing active substances within protective matrices that release their contents under controlled conditions. When performed at the nanoscale, this process is referred to as nanoencapsulation, which, like conventional encapsulation, aims to safeguard compounds from environmental stressors and ensure their targeted release (Nedovic, Kalusevic et al. 2011, Jafari 2017). A wide range of materials has been applied to encapsulate probiotic strains in food systems. Regardless of their source, be it



natural or synthetic, materials used for nanoencapsulation must comply with food-grade standards and be selected from the Generally Recognized as Safe (GRAS) list. Typical examples encompass food biopolymers such as proteins and carbohydrates, fats, protein-carbohydrate copolymers, minerals, and surfactants. (Augustin and Hemar 2009, Tolve, Galgano et al. 2016). Two main approaches are used to synthesize nanoscale materials in the food sector: top-down methods, which are physical, and bottom-up methods, which are chemical. Nanoencapsulation processes can be categorized into physical, chemical, and biological techniques (Dhand, Dwivedi et al. 2015, Tulinski and Jurczyk 2017). Nanofibers are cylindrical structures with diameters less than 1000 nm and aspect ratios exceeding 50. These materials can be tailored for specific uses, including the encapsulation of probiotics. Their large surface area offers several advantages, such as high immobilization efficiency, enhanced protection, and minimal impact on the sensory properties of food products (Fung, Yuen et al. 2011, Jayani, Sanjeev et al. 2020). Among the most promising carriers for nanoencapsulation are lipid-based systems, which include nanoliposomes, nano emulsions, solid lipid nanoparticles, and nanostructured lipid carriers. These systems provide benefits such as targeted delivery, the ability to encapsulate both hydrophilic and lipophilic compounds, and scalability for industrial production using diverse materials (Khorasani, Danaei et al. 2018, Reque and Brandelli 2021). Polymeric systems are essential in the development of probiotic-based formulations for both food and non-food applications. These systems involve the use of polymers to form vesicular structures, where probiotic cells are enclosed within a reservoir protected by an outer shell. A wide variety of polymers are used for this purpose, including naturally derived ones like pectin, chitosan, guar gum, gellan gum, dextran, cyclodextrin, alginates, xanthan gum, whey protein, and inulin. Synthetic polymers such as Eudragit L 100, Eudragit S 100, Hydroxypropyl ethylcellulose phthalate 50 or 55, and cellulose acetate trimellitate are also commonly employed (Huq, Khan et al. 2013, Asgari, Pourjavadi et al. 2020).

Table 1. Comparative overview of nanoencapsulation techniques used in probiotic delivery.

Technique	Carrier Material	Advantages	Limitations	References
Nanoliposomes	Lipids	Targeted delivery, suitable for lipophilic compounds	Low stability under certain conditions	Khorasani et al., 2018; Reque & Brandelli, 2021
Nanoemulsions	Surfactants	Good water dispersibility, scalable production	Sensitive to pH and temperature	Augustin & Hemar, 2009; Tolve et al., 2016
Polymeric Systems	Natural/Synthetic Polymers	High protection, versatile formulation	Complex formulation process	Huq et al., 2013; Asgari et al., 2020

3. Gold nanoparticles as sensors and carriers

Recent advancements have positioned gold nanoparticles as a promising tool across disciplines such as chemistry, physics, and biology, largely due to their distinctive optical characteristics (Di 2020). A notable optical feature of gold nanoparticles is their ability to exhibit vivid red or blue hues, a phenomenon attributed to plasmon resonance (Eustis and El-Sayed 2006). Thanks to their exceptional optical and thermal properties, gold nanoparticles (Au NPs) have found widespread use in biological fields, including applications in labeling, targeted delivery, thermal therapy, and biosensing (Sperling, Gil et al. 2008). For instance, Au NPs are employed in highly sensitive immunoassays designed to detect specific antibodies, making them valuable tools for the early diagnosis of diseases such as cancer (Slagle and Ghosh 1996). The red or blue coloration of Au NPs, resulting from plasmon resonance, also enables visual comparison of nanoparticle concentrations based on color intensity (Eustis and El-Sayed 2006). This report introduces an innovative approach for quantifying bacterial colony-forming units (CFU) in probiotic milk beverages, utilizing gold nanoparticles (Au NPs) as both the core material and detection indicator. When coated with appropriate compounds, Au NPs can function as biosensors by binding to bacterial cells through electrostatic interactions (Di 2020). For example, cysteine-coated Au NPs are effective in detecting *E. coli* O157:H7; aptamer-functionalized Au NPs can identify *S. typhimurium*; antibody-linked Au NPs are suitable for detecting *Lactobacillus* spp. and *Staphylococcus aureus*; and polyethylenimine (PEI)-capped Au NPs serve as rapid biosensors for bacterial detection (Mocan, Matea et al. 2017). Despite these advancements, prior studies have not explored the use of Au NPs alone for bacterial



detection, nor have they examined their interactions with probiotic strains in depth. This study offers a fresh perspective by employing Au NPs to detect *Lactobacillus* bacteria through their aggregation behavior. The adhesion of Au NPs to bacterial cells enables a correlation between nanoparticle quantity and bacterial count. By analyzing the color intensity of the resulting mixture, a quick and straightforward estimation of CFU in probiotic milk drinks becomes possible. The proposed method allows for rapid (15–16 times faster than traditional colony counting) and convenient testing without the need for sterile conditions, and holds promise for broader applications (Di 2020). In the context of photothermal therapy, gold nanoparticles have garnered significant attention (Weintraub 2013). Their ability to absorb light ranging from visible to near-infrared (NIR) wavelengths is attributed to surface plasmon resonance (SPR), which subsequently generates heat (González, Garcés et al. 2019). The specific wavelength at which Surface Plasmon Resonance (SPR) occurs is significantly influenced by the size, shape, and aggregation state of the nanoparticles (Alrahili, Peroor et al. 2020). In clinical settings, AuNPs with SPR tuned to the NIR spectrum are particularly valuable, as NIR light penetrates deeper into biological tissues compared to other wavelengths (Nehl, Liao et al. 2006, Liu, Kangas et al. 2020). Near-infrared (NIR) absorbing gold nanoparticles (AuNPs) often exhibit anisotropic shapes, such as rods and prisms, as well as certain aggregated forms (Bhattacharya and Mukherjee 2008). Gold nanoprisms (AuNPR) and gold nanorods (AuNR) were synthesized according to established protocols and were individually incubated with Lactoferrin (Lf) strains (Nikoobakht and El-Sayed 2003, Pelaz, Grazu et al. 2012, Garcés, González et al. 2022). The resulting bacterial samples treated with AuNPR and AuNR were analyzed using High-Angle Annular Dark Field Scanning Transmission Electron Microscopy (HAADF-STEM) and Energy Dispersive X-ray Spectroscopy (EDX) techniques. Observations revealed that aggregated nanoprisms and smaller spherical AuNPs adhered to the native extracellular polymeric substances (EPS) of the probiotic bacteria, with a relatively uniform distribution across the bacterial surface. Spectral analysis showed a redshift in the absorbance peak of the AuNPR-bacteria complex to approximately 1100 nm, compared to 935 nm for isolated AuNPRs likely due to localized aggregation on the bacterial surface. The efficiency of photothermal conversion was evaluated under 1064 nm laser irradiation for a duration of 5 minutes. At a bacterial concentration of 2 mg/mL, the AuNPR-bacteria system exhibited a temperature increase of 24 °C, while the AuNR-bacteria system, under the same conditions, resulted in a mere 6 °C rise. This discrepancy was attributed to the higher gold nanoparticle content in the AuNPR-bacteria sample (20% w/w or 200 mg Au/g) compared to the AuNR-bacteria sample (3% w/w or 30 mg Au/g). Additional heating curve experiments were conducted using equal Au concentrations (0.05 mg Au/mL). Under these circumstances, both systems exhibited similar outcomes, with specific absorption rates (SAR) recorded at 193 kW/g Au for AuNPR and 190 kW/g Au for AuNR-bacteria. These findings confirm that the nanoparticle loading level within the bacterial matrix plays a critical role in heat generation. Overall, the data validated the potential of AuNPR-bacteria complexes as effective agents for photothermal applications (Garcés, González et al. 2022).

4. Synergistic applications: combining magnetic and optical properties

Probiotic bacteria have been investigated as vehicles for metallic nanoparticles to develop innovative oral agents for hyperthermia-based cancer treatments. Two distinct synthesis strategies were employed to develop these therapeutic systems. In the first method, *Lactobacillus fermentum* was simultaneously loaded with magnetic nanoparticles (MNPs) and gold nanoparticles (AuNPs) of varying shapes, resulting in a composite system (AuNP+MNP-bacteria) where both nanoparticle types were embedded within the same layer of bacterial exopolysaccharides (EPS). In contrast, the second strategy employed a sequential loading method: AuNPs were initially attached to the probiotic to create AuNP-bacteria, followed by the incorporation of MNPs within EPS, resulting in a layered structure (AuNP-bacteria-EPS-MNP) where each type of nanoparticle is localized in separate EPS layers. This second approach, which leverages EPS-to-EPS recognition for layer-by-layer assembly on the bacterial surface, had not been previously reported. Both systems AuNP+MNP-bacteria and AuNP-bacteria-EPS-MNP were characterized using scanning electron microscopy (SEM), transmission electron microscopy (TEM), and UV-visible spectroscopy. Their potential as agents for magnetic hyperthermia and photothermal therapy was evaluated by measuring heat generation under alternating magnetic fields and near-infrared (NIR) laser exposure. In the initial strategy, Au nanoprisms (AuNPRs) were combined with MNPs and subsequently introduced directly to *L. fermentum*. HAADF-STEM and EDX analyses confirmed the incorporation of both nanoparticle types. MNPs were uniformly distributed across the native EPS layer, while gold aggregates appeared sporadically. This formulation, referred to as AuNPR+MNP-bacteria, exhibited a UV-vis absorbance peak shifted to 1100 nm lower than that of free AuNPRs and similar



to AuNPR-bacteria(Garcés, González et al. 2022). In the second strategy, a stepwise assembly was used: AuNPR-bacteria were first prepared, followed by the addition of an EPS-MNP layer. EPS-MNPs were synthesized by isolating EPS from *L. fermentum* and loading it with MNPs, based on previously established protocols(González, Garcés et al. 2019). The goal was to exploit EPS-EPS recognition, allowing the native EPS of AuNPR-bacteria to interact with the MNP-loaded EPS, forming a bilayer structure. This arrangement, known as AuNPR-bacteria-EPS-MNP, illustrates the positioning of AuNPRs and MNPs within separate EPS layers. HAADF-STEM-EDX analysis verified the partial adhesion of EPS-MNPs to the surface of AuNPR-bacteria, thereby confirming the bilayer structure. Upon assessing the thermal characteristics of the layer-by-layer assembled system, AuNPR-bacteria-EPS-MNP exhibited an absorbance peak around 1100 nm in the UV-vis spectrum, which closely matched that of the AuNPR-bacteria formulation. The heating efficiency of both heterobimetallic systems AuNPR+MNP-bacteria (synthesized in a single step) and AuNPR-bacteria-EPS-MNP (assembled sequentially)—was assessed using identical bacterial concentrations (2 mg/mL) under 1064 nm laser irradiation for 5 minutes. The observed temperature elevations were 25 °C for the AuNPR+MNP-bacteria combination and 19 °C for the AuNPR-bacteria-EPS-MNP, which is similar to the 24 °C increase noted in the AuNPR-bacteria sample. While AuNPRs were likely the primary contributors to heat generation, the MNP-bacteria system also showed measurable absorption at 1064 nm. However, its thermal output was 3.4 times lower than that of the heterobimetallic systems under identical conditions. To quantify thermal performance, specific absorption rate (SAR) values were calculated based on gold content alone. The SAR values were 125.4 kW/g Au for AuNPR+MNP-bacteria and 87.4 kW/g Au for AuNPR-bacteria-EPS-MNP both lower than the 193 kW/g Au recorded for AuNPR-bacteria. Nonetheless, the observed temperature elevations confirmed the potential of both heterobimetallic systems for photothermal therapy applications. Given that both systems also incorporate magnetic nanoparticles, their performance under magnetic hyperthermia conditions was examined. Samples were exposed to a high-frequency alternating magnetic field for 5 minutes, resulting in temperature increases of 2.6 °C, 3 °C, 5 °C, and 7 °C for AuNPR-bacteria-EPS-MNP, AuNPR+MNP-bacteria, MNP-bacteria, and MNP, respectively. The corresponding SAR values were 80, 117, 185, and 463 W/g Fe. While MNPs alone resulted in the most significant temperature increase, a direct comparison with systems containing bacteria is complicated due to inherent differences in sample composition. The comparatively higher SAR of MNP-bacteria, in relation to the heterobimetallic systems, can be ascribed to increased aggregation of the nanoparticles. Despite modest temperature increases, these findings underscore the dual functionality of AuNPR+MNP-bacteria and AuNPR-bacteria-EPS-MNP as agents for both magnetic hyperthermia and photothermal therapy(Garcés, González et al. 2022). *Lactobacillus fermentum* has previously been identified as a viable oral drug delivery vehicle, capable of surviving gastric conditions and transporting therapeutic agents to the intestines. It is already marketed as a gut microbiota-supporting supplement. Building on this foundation, the current results pave the way for innovative treatment strategies targeting gastric diseases, including the use of these newly developed heterobimetallic AuNP/MNP-bacteria systems as oral agents for cancer therapy via magnetic hyperthermia and photothermal mechanisms(Nikoobakht and El-Sayed 2003, Martín, Rodríguez-Nogales et al. 2016, Martín Marcos 2016, Garcés, Rodríguez-Nogales et al. 2018).

5. Challenges and future perspectives

Despite its promising potential, this method faces certain limitations. A key drawback is its incompatibility with all probiotic milk formulations. For example, the Meiji probiotic milk drink contains bacterial strains likely *Streptococcus thermophilus* that do not exhibit interaction with gold nanoparticles (Au NPs), rendering the technique ineffective for CFU estimation in such products. To broaden the applicability of this approach across various probiotic beverages and other *Lactobacillus*-containing items, procedural refinements and material modifications are necessary. Future research should focus on evaluating the method's feasibility for diverse probiotic matrices and simplifying its operational steps to enhance usability. Critical factors such as the morphology and size of Au NPs, the composition of the growth medium, and the underlying mechanisms of nanoparticle-bacteria binding warrant deeper investigation. Moreover, essential analytical parameters including detection limits, linear response range, and test selectivity must be clearly defined to optimize the method's performance (Di 2020). While nanometric systems offer significant advantages, their widespread adoption may be constrained by potential health risks. Ensuring food safety requires a thorough understanding of the physicochemical properties and toxicological profiles of nanomaterials. Comprehensive studies are needed to elucidate the molecular interactions between these nano systems and biological entities. Although



numerous *in vitro* and *in vivo* assessments have been conducted, conflicting results highlight the need for further investigation. A robust and informed design strategy grounded in detailed knowledge of nanomaterial behavior and biological compatibility is essential. Rigorous testing using both *in vitro* and *in vivo* models is critical to identify possible toxic responses, confirm biocompatibility, and mitigate health risks prior to integrating nanomaterials into probiotic food products (Singh, Manshian et al. 2009, Liu, Zhu et al. 2022, Onyeaka, Passaretti et al. 2022). Toxicological evaluation of nanomaterials must be closely aligned with their regulatory oversight in the food industry. Currently, the U.S. Food and Drug Administration (FDA) oversees the use of nanoparticles in food packaging and mandates manufacturers to disclose their use as additives via the Food Contact Notification (FCN) system. In the European Union, the European Commission enforces similar regulations under EC 1935/2004 to ensure consumer safety in food packaging applications. Nonetheless, broader regulatory frameworks are needed when nanomaterials are incorporated directly into food or nutraceutical products, as they may pose health risks to the general population. Legislation should comprehensively address how nanomaterials are absorbed throughout the food chain, their potential interactions with other ingredients or microorganisms, and their environmental impact during processing and disposal. The short- and long-term consequences of exposure to nanomaterials remain a pressing concern for both scientific and regulatory communities. A deep understanding of emerging nanotechnologies is essential for crafting effective policies and safety standards that protect both industry workers and consumers (Sodano 2018, Ranjan, Dasgupta et al. 2019, Zomorodimanesh, Hosseinkhani et al. 2019, Onyeaka, Passaretti et al. 2022, Zomorodimanesh, Razavi et al. 2024, Zomorodimanesh, Razavi et al. 2024). Given that *Lactobacillus fermentum* is already marketed as an oral supplement that supports gut microbiota, its regulatory approval as a drug delivery vehicle is increasingly plausible (Maldonado, Cañabate et al. 2012). Moreover, this probiotic has demonstrated the ability to safely transport nanoparticles through the gastric environment into the intestines, reinforcing its potential as a nanocarrier (Martín, Rodríguez-Nogales et al. 2016, Martín Marcos 2016, Garcés, Rodríguez-Nogales et al. 2018). Consequently, the findings of this study advocate for further investigation into these heterobimetallic systems as oral therapeutic agents for gastrointestinal tumors, particularly through dual-action magnetic hyperthermia and photothermal therapy (Garcés, González et al. 2022).

Table 2. Regulatory guidelines and challenges for nanomaterials in the food industry.

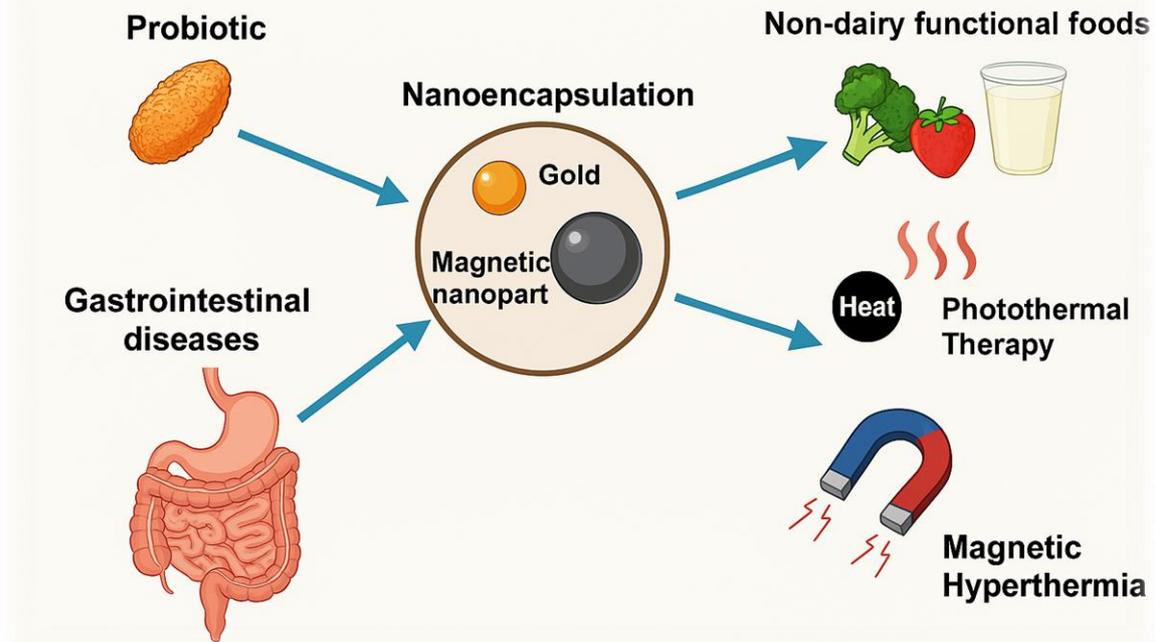
Regulatory Body	Scope of Oversight	Requirements	Challenges	References
FDA (USA)	Food packaging and additives	Notification via FCN system	Limited coverage for in-product nanoparticles	Sodano, 2018; Ranjan et al., 2019
EC (Europe)	Food contact materials	Compliance with EC 1935/2004	Need for updated guidelines for edible nanomaterials	Onyeaka et al., 2022
WHO	Public health	Long-term toxicity evaluation	Contradictory results in <i>in vivo</i> studies	Singh et al., 2009; Liu et al., 2022

6. Conclusion

The integration of nanoencapsulation technologies with probiotic delivery systems particularly in non-dairy matrices offers a transformative approach to functional food development and therapeutic applications. By leveraging the unique properties of gold and magnetic nanoparticles, novel heterobimetallic systems have been designed that not only enhance probiotic stability and bioavailability but also enable dual-functionality in cancer treatment through photothermal and magnetic hyperthermia mechanisms. The use of *Lactobacillus fermentum* as a biological carrier introduces a biocompatible and efficient platform for oral drug delivery, capable of surviving gastrointestinal conditions and targeting intestinal tissues. These findings open new avenues for the development of multifunctional probiotic-based therapies, especially in the context of gastric diseases and tumor management. However, the safety, regulatory, and toxicological aspects of nanomaterials must be thoroughly addressed before their widespread application in food and medicine. Future research should focus on optimizing nanoparticle design, simplifying detection methods, and ensuring long-term biocompatibility. Overall, this review highlights the promising potential of nanoencapsulation strategies in advancing both nutritional science and biomedical innovation.



Graphical Abstract



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