Nano-Probiotics in Sustainable Aquaculture and Agriculture: Enhancing Productivity, Disease Management, and Environmental Safety

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ABSTRACT

Aquaculture, as a rapidly growing global industry, faces significant challenges from disease epidemics, water quality deterioration, and antibiotic overuse that accelerates antimicrobial resistance. Contemporary agricultural systems are principally oriented toward high-yield cultivation of cereal grains and other food crops through sustainable practices to meet the nutritional requirements of an expanding worldwide population. Nevertheless, intensive farming methods, excessive application of agrochemicals, and additional environmental influences lead to reduced soil fertility, ecological contamination, disturbance of soil biodiversity, increased pest resistance, and diminished agricultural productivity. Beneficial microorganisms, particularly probiotics, have emerged as ecologically sound and sustainable alternatives. These probiotics activate immune responses, reduce pathogen concentrations, improve digestive processes, and contribute to enhanced water quality. Unlike the singular action of antibiotics, probiotics operate through multiple mechanisms including competitive exclusion, immunomodulation, and production of antimicrobial substances. Nanotechnology applications are pervasive in daily human activities and numerous industrial sectors. The continuous advancement of nanotechnology is substantially transforming food technology, with broad applications across diverse specialized areas. Sophisticated nanotechnology can address these limitations by improving probiotic effectiveness through nano-encapsulation techniques, controlled release mechanisms, and enhanced bioavailability. This comprehensive review investigates the collaborative potential of probiotics and cutting-edge nanotechnology in tackling challenges within aquaculture and agricultural sectors. It emphasizes significant advancements in probiotic formulations, nano-enabled delivery platforms, and their collective effects on growth enhancement, disease prevention, stress mitigation, and ecological sustainability. The integration of probiotic technology with nanotechnology constitutes an innovative and transformative strategy for advancing sustainable practices in both aquaculture and agriculture.

Keywords: Nano-Probiotics, Sustainable Aquaculture, Nanobiofertilizer, Disease Management, Environmental Safety, Synergistic Effects.

1. INTRODUCTION

Aquaculture involves the controlled cultivation of economically significant aquatic species, including fish and shellfish. This method enhances production conditions to generate protein-rich food sources that are readily accessible (Gadhiya, Katariya et al. 2025; Iheanacho, Hornburg et al. 2025). The global significance of aquaculture has grown substantially as a result of the escalating depletion of wild fish stocks (Msangi, Kobayashi et al. 2013). Contemporary agricultural systems are largely dedicated to the high-yield cultivation of cereals and various food crops in a sustainable fashion, aiming to meet the nutritional requirements of a continuously expanding global population (Upadhayay, Maithani et al. 2023). Nonetheless, intensive farming methods, excessive application of agrochemicals, and additional environmental influences contribute to the reduction of soil fertility, environmental contamination, loss of soil biodiversity, development of pest resistance, and reduced agricultural productivity (Upadhayay, Singh et al. 2022). The move toward more intensive aquaculture practices has been linked to a higher incidence of bacterial infections, leading to greater dependence on antibiotics (Gostin and Meier 2023). Regional disparities in antibiotic application are notable; for example, Norway utilizes approximately 1 gram per metric ton of farmed fish, whereas Vietnam may employ over 700 grams per ton (Stephen, Mukherjee et al. 2023). The overuse of antibiotics compromises treatment effectiveness and disrupts the microbial equilibrium in aquatic settings, increasing the susceptibility of fish to opportunistic diseases (Asif, Chen et al. 2024). In response, the aquaculture sector has increasingly adopted chemical treatments and veterinary pharmaceuticals. However, persistent issues related to the long-term utilization of antimicrobial agents particularly concerning the durability and spread of antibiotic resistance genes continue to pose significant challenges (Jian, Zeng et al. 2021). Probiotics, or beneficial microorganisms, have emerged as sustainable and ecologically sound alternatives (Amenyogbe, Chen et al. 2020). These microorganisms bolster immune responses, reduce pathogen levels, improve digestive efficiency, and contribute to better water quality (Wang, Chuprom et al. 2020). Unlike antibiotics, which typically operate through a single mechanism, probiotics exhibit diverse modes of action, including competitive exclusion, immunomodulation, and the production of antimicrobial substances (Zorriehzahra, Delshad et al. 2016). Nanotechnology is now pervasive in daily life and numerous industrial sectors(Zomorodimanesh, Hosseinkhani et al. 2019, Zomorodimanesh, Razavi et al. 2024, Zomorodimanesh, Razavi et al. 2024). Its continued advancement is significantly reshaping food technology, with applications spanning the development of novel dietary supplements, improved food safety practices, strengthened biosecurity frameworks, sophisticated nano-delivery mechanisms for nutrients, and thorough nanotoxicological evaluations to ensure public health safety (Chau, Wu et al. 2007; Dwivedi, Pandey et al. 2014; He, Deng et al. 2019). The significance of microorganisms that promote plant growth, often referred to as "plant probiotics (PPs)," has received broad acknowledgment, and their application as biofertilizers is increasingly advocated to reduce the adverse impacts of agrochemicals (Sarbani and Yahaya 2022; Rai, Solanki et al. 2023). Owing to the advantageous attributes of both PPs and nanomaterials (NMs), these can be employed in combination to optimize benefits (Khati, Chaudhary et al. 2017; Khati, Parul et al. 2018; Agri, Chaudhary et al. 2021; Chaudhary, Chaudhary et al. 2021; Chaudhary, Khati et al. 2021). Nevertheless, the combined or synergistic application of NMs and PPs remains at an early stage but has demonstrated superior crop-modulating effects, including enhanced crop productivity, alleviation of environmental stresses (e.g., drought, salinity), restoration of soil fertility, and reinforcement of the bioeconomy (Kumari, Khati et al. 2021; Agri, Chaudhary et al. 2022; Akhtar, Ilyas et al. 2022).

This review aims to provide a comprehensive examination of the synergistic use of probiotics and nanotechnology within aquaculture and agriculture. It will elaborate on the mechanisms of action, recent progress in nano-formulations, and the collective influence on health outcomes, alongside discussing the challenges and future prospects of this innovative strategy.

2. Probiotics and Nanotechnology in Aquaculture

Aquaculture, a rapidly growing global industry, faces significant challenges due to disease outbreaks, water quality deterioration, and antibiotic misuse, which exacerbate antimicrobial resistance (Blanchard, Watson et al. 2017). These issues stem from the accumulation of organic waste, such as deceased organisms, excrement, and uneaten feed, which emit toxic compounds like hydrogen sulfide and ammonia (Mallik, Pathak et al. 2024). Traditional disease management approaches relying on antibiotics and synthetic compounds are not only inefficient on a large scale but also contribute to environmental and health concerns (Kümmerer 2009). As a result, natural alternatives including immunostimulants, plant-based extracts, and prebiotics have been explored; however, their results are often inconsistent, and they may fail to tackle broader ecological challenges. Probiotics, or beneficial microbes, have emerged as sustainable and eco-friendly alternatives (Amenyogbe, Chen et al. 2020). Probiotics enhance immune responses, reduce pathogen levels, improve digestive processes, and contribute to better water quality (Wang, Chuprom et al. 2020). Unlike the singular action of antibiotics, probiotics operate through diverse mechanisms, including competitive exclusion, immunomodulation, and the production of antimicrobial compounds (Zorriehzahra, Delshad et al. 2016). Within aquaculture systems, they play a critical role in maintaining microbial equilibrium, reducing pathogenic loads, enhancing immune function, and supporting the growth and welfare of cultivated species (Nayak 2010). Probiotics offer comprehensive, sustainable solutions that improve both the health of aquatic organisms and their cultivation environments, in contrast to conventional unilateral disease management methods (Sihag and Sharma 2012). This review addresses current issues in aquaculture, the mechanisms of antibiotic resistance, and the diverse functionalities of probiotics. It also integrates recent findings regarding combinations with herbal remedies and nanoparticles, species-specific applications, and delivery techniques. Probiotics live microorganisms that confer health benefits to the host when administered in adequate amounts represent a promising alternative to antibiotics in aquaculture systems (Selvarajan and Mohanasrinivasan 2013). Microorganisms such as Lactobacillus, Bacillus, Enterococcus, and Saccharomyces species perform varied functions in enhancing the health of fish and shrimp (Kuebutornye, Abarike et al. 2019; Tran, Li et al. 2020). These beneficial microbes offer an ecological approach to diminishing the dependency on antibiotics in aquaculture (Ringø 2020; Ringø, Van Doan et al. 2020). Probiotics aid in strengthening immune function, digestion, feed conversion, and overall vitality in aquatic species (Nur 2019). Key benefits include: inhibiting pathogenic bacteria to prevent infections; synthesizing essential vitamins and fatty acids; enhancing digestive efficiency and nutrient uptake; stimulating immune responses; and modulating microbial communities to improve water quality (Selim and Reda 2015). Since the mid-1980s, probiotics have been successfully implemented in aquaculture (Fachri, Amoah et al. 2024). Their efficacy is attributed to the ability to enhance immune performance, support beneficial gut microbiota, and prevent disease outbreaks (Ringø 2020; Ringø, Van Doan et al. 2020). They improve intestinal health by generating antimicrobial substances such as bacteriocins, lysozyme, and organic acids, which suppress pathogen proliferation (Banerjee and Ray 2017). Additionally, they stabilize gut microbiota, mitigate stress-related health issues, and increase host resilience to heavy metal toxicity (Fachri, Amoah et al. 2024). Common sources of probiotics in aquaculture include algae, yeasts, and bacteria (Wang, Ran et al. 2019). Selecting probiotics based on host compatibility and administering appropriate doses are essential for maximizing benefits (Nayak 2010). Thus, probiotics contribute to fish health, operational productivity, and environmental sustainability in aquaculture by presenting a effective and practical substitute for antibiotics (Kwoji, Aiyegoro et al. 2021). Nanotechnology is extensively integrated into daily life and numerous sectors. Its continuous evolution is significantly transforming food technology, with applications extending to the development of novel nutritional supplements, improved food safety protocols, enhanced biosecurity measures, advanced nano-delivery systems for nutrient administration, and thorough nanotoxicological evaluations to ensure public health safety (Chau, Wu et al. 2007; Dwivedi, Pandey et al. 2014; He, Deng et al. 2019) .Nanotechnology facilitates the synthesis of nanoparticles ranging from 10 to 1000 nanometers in size, which exhibit increased surface area and enhanced bioavailability, thereby improving intestinal absorption and enabling more effective interactions with various biological components (Nel, Mädler et al. 2009; Tsai, Mao et al. 2016; Forouhar Vajargah, Imanpoor et al. 2019; Mohsenpour, Mousavi-Sabet et al. 2020; Rashidian, Lazado et al. 2021; Impellitteri, Multisanti et al. 2023; Rashidian, Mohammadi-Aloucheh et al. 2023). In this framework, nanoencapsulation within a protective nanoscale coating presents significant advantages and novel opportunities. The selection of nanocarrier types, encapsulation techniques, conditions, and formulations must be tailored according to the properties of the food matrix and the nature of the encapsulated substance (Assadpour and Mahdi Jafari 2019). Probiotics and paraprobiotics are recognized as safe dietary supplements that contribute to host health by promoting growth, providing essential nutrients, modulating microbial populations, strengthening immune function, improving feed efficiency, enhancing digestive enzyme activity, alleviating stress, ameliorating water quality, and controlling diseases (Selim and Reda 2015). Both probiotics and paraprobiotics represent sustainable and ecologically sound approaches for improving fish health and disease resistance, establishing them as fundamental elements in contemporary aquaculture practices (Nur 2019).

Table 1: Overview of Key Aspects in Probiotics and Nanotechnology for Aquaculture.

Category	**Key Points / Examples**	**Mechanisms / Benefits**	**Selected References**
Challenges in Aquaculture	Disease outbreaks, water quality deterioration, antibiotic misuse (AMR).	Accumulation of organic waste (e.g., H_2S, NH_3); inefficiency of synthetic compounds.	(Blanchard et al., 2017); (Mallik et al., 2024); (Kümmerer, 2009)

Probiotic Microorganisms	Lactobacillus, Bacillus, Enterococcus, Saccharomyces, algae, yeasts.	Competitive exclusion, immunomodulation, production of antimicrobial compounds (bacteriocins, lysozyme, organic acids).	(Kuebutornye et al., 2019); (Tran et al., 2020); (Wang et al., 2019)
Benefits of Probiotics	1. Inhibit pathogens 2. Synthesize vitamins & fatty acids 3. Enhance digestion & nutrient uptake 4. Stimulate immune responses 5. Improve water quality	Strengthen immune function, improve feed conversion, stabilize gut microbiota, increase resilience to stress and heavy metal toxicity.	(Selim & Reda, 2015); (Banerjee & Ray, 2017); (Fachri et al., 2024)
Role of Nanotechnology	Nano-encapsulation, nano-delivery systems for nutrients and probiotics.	Enhances bioavailability, intestinal absorption, and targeted delivery; allows controlled release.	(Assadpour & Jafari, 2019); (Nel et al., 2009); (He et al., 2019)
Application & Selection	Based on host compatibility and appropriate dosage. Administered via feed or water.	Essential for maximizing benefits; ensures efficacy and sustainability.	(Nayak, 2010); (Ringø, 2020)

3. Probiotics and Nanotechnology in Agriculture

Contemporary agricultural systems are chiefly oriented toward the high-yield cultivation of cereals and other food crops through sustainable practices to meet the nutritional needs of a continuously growing global population. Nonetheless, intensive farming methods, excessive application of agrochemicals, and additional environmental factors lead to diminished soil fertility, environmental contamination, disruption of soil biodiversity, development of pest resistance, and reduced agricultural productivity (Upadhayay, Chitara et al. 2023). Consequently, researchers are increasingly directing attention toward eco-friendly and safer fertilization techniques to achieve agricultural sustainability (Agri, Chaudhary et al. 2021; Elnahal, El-Saadony et al. 2022). Indeed, the role of plant growth-promoting microorganisms, commonly designated as "plant probiotics (PPs)," has attained broad acceptance, and their deployment as biofertilizers is being vigorously encouraged to counteract the detrimental effects of agrochemicals (Upadhayay, Chitara et al. 2023). Functioning as bio-elicitors, PPs stimulate plant development and colonize either soil or plant tissues when applied to soil, seeds, or plant surfaces, serving as an alternative strategy to reduce reliance on intensive agrochemical use (Sarbani and Yahaya 2022; Rai, Solanki et al. 2023). In recent years, the adoption of nanotechnology has also instigated a transformation in agriculture through the implementation of diverse nanomaterials (NMs) or nano-fertilizers to enhance crop yield (Neme, Nafady et al. 2021). Considering the favorable characteristics of both PPs and NMs, their combined application can be employed to optimize agricultural benefits. However, the utilization of NM and PP combinations, or their synergistic use, remains in nascent stages but has demonstrated superior crop-regulating outcomes, including increased productivity, amelioration of environmental stressors (e.g., drought, salinity), rejuvenation of soil fertility, and reinforcement of the bioeconomy (Upadhayay, Chitara et al. 2023). Furthermore, a thorough evaluation of nanomaterials is imperative prior to their implementation (Shahzad, Ullah et al. 2021). The agricultural sector is considerably influenced by climate change, where

escalating occurrences of abiotic stresses such as drought, salinity, cold, and flooding, along with biotic stresses (including infestations by pathogens like bacteria, fungi, oomycetes, nematodes, and herbivores), adversely affect farming output (Shahzad, Ullah et al. 2021; Upadhayay, Chitara et al. 2023). Additionally, although agrochemicals substantially boosted crop yields over recent decades, the detrimental consequences of excessive chemical fertilizer application have become increasingly evident (Lin, Lin et al. 2019; Upadhayay, Singh et al. 2022). This has resulted in soil quality deterioration, disruption of soil microbial ecosystems, pollution of soil and aquatic systems, and adverse human health impacts due to pesticide and herbicide residues (Singh, Singh et al. 2020; Tripathi, Srivastava et al. 2020; Boregowda, Jogigowda et al. 2022). Moreover, the shift toward organic farming, particularly through the use of biofertilizers, has offered an environmentally sustainable substitute for chemical-dependent agriculture, while simultaneously enhancing crop production and soil health (Asghar, Akça et al. 2022; Elnahal, El-Saadony et al. 2022). The term "plant probiotics (PPs)" refers to a specific group of microbial strains that meet all essential criteria to be classified as biofertilizers, influencing plant growth through direct and indirect mechanisms (microorganisms demonstrating beneficial effects on plant growth and yield) (Sarbani and Yahaya 2022; Rai, Solanki et al. 2023). The rhizosphere and internal plant tissues each constitute unique centers for distinct microbial communities, known as the rhizomicrobiome and endophytomicrobiome, respectively (Jiang, Zhang et al. 2022; Jiang, Li et al. 2022; Pandey, Jain et al. 2022). This microbiome represents a valuable reservoir of plant probiotics owing to its diverse capabilities, including nutrient solubilization, nitrogen fixation, synthesis of plant hormones [such as indole-3-acetic acid (IAA)], ammonia, anti-pathogenic compounds, hydrogen cyanide (HCN), exopolysaccharides, siderophores, and lytic enzymes (Mathur, Koul et al. 2019; Nazli, Mustafa et al. 2020; Kashyap, Manzar et al. 2021; Abdelkhalek, El-Gendi et al. 2022; Khan, Singh et al. 2022; Latif, Bukhari et al. 2022; Mushtaq, Nazir et al. 2022; Reddy, Reddy et al. 2022; Upadhayay, Singh et al. 2022). Plant probiotics facilitate nutrient acquisition and shield plants from environmental challenges, including both biotic and abiotic stresses, while also enhancing overall plant vitality (Kenawy, Abo-Zaid et al. 2021; Pandey, Jain et al. 2022). Plant probiotics with diverse growth-promoting attributes deliver benefits such as increased agricultural productivity and enhanced food security (Arif, Batool et al. 2020; Ghoghari, Bharwad et al. 2022). In modern agriculture, the application of nanotechnology is attracting growing interest, especially within developing nations (Neme, Nafady et al. 2021). Owing to their enhanced surface area and solubility, nanomaterials are considered superior to conventional agrochemicals when utilized as nano-fertilizers in farming practices (Fen, Rashid et al. 2022).
Nano-fertilizers augment nutrient absorption efficiency in plants, mitigate the adverse impacts of environmental stressors, and elevate crop yields (Guleria, Thakur et al. 2023). It is feasible to employ a combination of specific plant probiotics that have demonstrated compatibility with targeted nanoparticles (Khati, Chaudhary et al. 2017; Khati, Parul et al. 2018; Agri, Chaudhary et al. 2021; Chaudhary, Chaudhary et al. 2021; Chaudhary, Khati et al. 2021). The integration of NMs and PPs holds considerable potential for sustainable agriculture as a preferable alternative to agrochemicals and is emerging as a prominent concept within the agricultural industry (Kumari, Khati et al. 2021; Agri, Chaudhary et al. 2022; Akhtar, Ilyas et al. 2022). This efficient fertilization strategy can be favored over chemical-based methods due to its superior resource utilization, sustained and gradual nutrient release, ability to increase crop productivity with reduced fertilizer quantities, and minimal negative effects on soil (Kumari, Khati et al. 2021). Furthermore, the application of NMs and PPs is economically viable and presents lower environmental toxicity. According to existing literature, the combination of NMs and PPs can be termed a "nanobiofertilizer (NBF)" since it harnesses the efficacy of both components and facilitates slow, controlled nutrient release, improves nutrient use efficiency, and leads to substantial improvements in crop yield (Kumari, Khati et al. 2021). The microbial component of this mixture benefits the plant system through a wide range of growth-promoting properties, including nutrient solubilization, nitrogen fixation, production of plant hormones, exopolysaccharides (EPS), siderophores, and anti-pathogenic compounds (Kumari, Khati et al. 2021). The influence of the effective microbial constituent is reflected in enhanced soil fertility, functional enzymatic activities, NPK content, organic carbon levels, and soil microbial biomass (Kumari, Khati et al. 2021). Conversely, the second and highly effective segment, "NMs," maximizes benefits and supports plant growth through controlled and sustained nutrient release, reduction in soil nutrient fixation, increased nutrient bioavailability, enhanced plant tolerance to environmental stress, and protection against pests (Kumari, Khati et al. 2021). The combination of nanomaterials and plant probiotics can be administered to plants through multiple methods, including seed treatment, seedling treatment, foliar spray, soil application, and other techniques (Kumari, Khati et al. 2021).
Progress in nanotechnology has further enabled the encapsulation of plant probiotic strains within suitable nanomaterials, or the co-encapsulation of both nanomaterials (NMs) and plant probiotics (PPs) into an

appropriate carrier medium, contingent upon experimental design (Panichikkal, Thomas et al. 2019; Panichikkal, Prathap et al. 2021; Akhtar, Ilyas et al. 2022; Moradi Pour, Saberi Riseh et al. 2022). This approach ensures the preservation of efficacy and extended shelf life of the microbial constituents (PPs), alongside facilitating a regulated and sustained release of both NMs and PPs (Panichikkal, Thomas et al. 2019; Panichikkal, Prathap et al. 2021; Akhtar, Ilyas et al. 2022). This dual strategy enhances nutrient accessibility directly via nanomaterials, while concurrently promoting plant development through efficient microbial intervention. The application of such optimized combinations of NMs and PPs holds considerable promise for transformative impacts in agriculture, ultimately contributing to sustainable agricultural outputs and enhanced food security (Kumari, Khati et al. 2021; Agri, Chaudhary et al. 2022; Akhtar, Ilyas et al. 2022).

Table 2: Synergistic Application of Nanomaterials (NMs) and Plant Probiotics (PPs) in Sustainable Agriculture.

Concept / Component	Description / Function	Key Benefits / Mechanisms	Selected References
Challenges in Modern Agriculture	Intensive farming, agrochemical overuse, climate change stresses (abiotic & biotic).	Leads to soil degradation, biodiversity loss, pollution, and reduced productivity.	(Upadhayay et al., 2023); (Shahzad et al., 2021)
Plant Probiotics (PPs)	Beneficial microbes (biofertilizers) e.g., rhizobacteria, endophytes.	Nutrient solubilization, N-fixation, phytohormone (e.g., IAA) production, pathogen inhibition, stress tolerance.	(Sarbani & Yahaya, 2022); (Rai et al., 2023); (Kashyap et al., 2021)
Nanomaterials (NMs) / Nano-Fertilizers	Synthetic or natural particles (1-100 nm) used as nutrient carriers.	High surface area, controlled release, improved nutrient uptake, reduced nutrient fixation in soil.	(Neme et al., 2021); (Fen et al., 2022); (Guleria et al., 2023)
Synergistic Combination (Nanobiofertilizer - NBF)	Integration of NMs and PPs into a single formulation.	**PPs:** Enhance soil health & plant growth via microbial activity. **NMs:** Improve nutrient delivery & efficiency. **Together:** Controlled release, increased stress resilience, higher yield.	(Kumari et al., 2021); (Agri et al., 2022); (Akhtar et al., 2022)
Application Methods	Methods to administer NBFs to crops.	Seed treatment, seedling treatment, foliar spray, soil application.	(Kumari et al., 2021)
Advantages over Agrochemicals	Benefits of using NBFs compared to traditional chemicals.	Reduced environmental toxicity, improved soil health, economic viability, enhanced food security.	(Kumari et al., 2021); (Elnahal et al., 2022)

4. Synergistic Effects of Probiotics and Nanoparticles

Nanotechnology finds broad application in daily life and numerous other sectors. The continuous evolution of nanotechnology is substantially influencing food technology, with widespread use in diverse areas. These encompass the development of novel dietary supplements, the implementation of improved food safety protocols via advanced methods, the reinforcement of biosecurity measures, the design of sophisticated nano-delivery mechanisms for efficient nutrient dissemination, and the execution of thorough nanotoxicity evaluations to safeguard consumer health (Vijayaram, Razafindralambo et al. 2024). The domain of nanotechnology incorporates various nanoparticles and bionanomaterials, including viruses, plasmids, and

protein-based nanoparticles, which are actively employed. Such materials function not only as catalysts for direct pollutant degradation but are also instrumental in promoting the proliferation of microorganisms that detoxify hazardous compounds. A prominent example involves multi-wall carbon nanotubes (MWCNTs), which are designed to adsorb oil and heavy metal hydrocarbons. This advancement has been applied to assist microbial populations in Antarctica that are adept at degrading petroleum-based contaminants (Vijayaram, Tsigkou et al. 2023; Vijayaram, Razafindralambo et al. 2024). Additionally, nanotechnology is valuable for enhancing the bioavailability, stability, absorption, and controlled release of nutrients and nutraceuticals. Its implementations yield beneficial health effects in nutraceuticals by enabling encapsulation, precise targeted delivery, and release from nanoformulations. Furthermore, it presents a range of significant benefits, including the use of biodegradable and eco-friendly nanocarriers for nutraceutical encapsulation. This methodology reflects a dedication to sustainability and augments the body’s nutrient assimilation efficiency. In addition, nanotechnology introduces therapeutic advantages that may transform multiple dimensions of health and well-being (Durazzo, Nazhand et al. 2020). Nanotechnology enables the production of nanoparticles measuring between 10 and 1000 nm, which possess increased surface area and enhance the bioavailability and intestinal absorption of these tiny structures, as well as facilitate greater interaction with diverse components. Within this framework, nanoencapsulation using a protective nanoscale coating may provide significant benefits and innovative possibilities. The selection of nanocarrier types, nanoencapsulation methods, conditions, and formulations must be aligned with the properties of the food matrix and the nature of the encapsulated material (Vijayaram, Razafindralambo et al. 2024). The term "nanoprobiotics" denotes probiotics that are coated with nanoparticles, and this developing area focuses on merging nanoscience concepts with probiotic applications (Bhargavi, Ramachandra et al. 2021). Both conventional probiotics and their nano-enhanced versions are increasingly used to counteract the adverse effects of cadmium-induced toxicity in Wistar rats. Moreover, studies indicate that nano probiotics and probiotic supplements may offer a safe and effective strategy to combat heavy metal toxicity and oxidative stress in these animals (Al-Enazi, Virk et al. 2020). For example, nanoparticle-coated probiotics have shown potential in alleviating neuroinflammation and have also yielded better results in enhancing cancer immunotherapy functions (Hu, Wu et al. 2015). The use of nanoparticle-coated probiotics introduces a novel targeted delivery technique focused on the intestinal mucosa. This method aids in reducing harmful agents while simultaneously supporting therapeutic components. For instance, dietary inclusion of nanoparticle-coated probiotics, specifically Bacillus amyloliquefaciens coated nanoparticles (BANPs) at a 5% concentration, has shown a significant decrease in intestinal damage from DSS-induced colitis. Also, BANPs have markedly improved recovery relative to unencapsulated B. amyloliquefaciens. These results strongly support the successful therapeutic use of BANPs for mitigating colitis (Alkushi, Abdelfattah-Hassan et al. 2022). Selenium is an essential micronutrient for higher animals and humans (Klasing 1998; Eisler 2000). Its main biological importance is linked to key functional elements in selenoenzymes, such as glutathione peroxidase (GPx) and thioredoxin reductase (TrxR). Multiple studies have emphasized the superior effectiveness of selenium nanoparticles in reducing acute toxicity compared to conventional forms like selenite, selenomethionine, and methyl selenocysteine, especially in increasing selenoenzyme activity in mice and rats (Wang, Zhang et al. 2007; Zhang, Wang et al. 2008). As an example, dietary inclusion of selenium nanoparticles (0.3%) coated with the probiotic Aspergillus awamori (0.05%) resulted significant improvements over 12 days in the growth performance of chicks. This supplementation induced favorable changes in the skeletal muscle fatty acid composition, α-tocopherol levels, and general meat quality. The use of nanoprobiotics has been shown to support better growth performance and meat quality in chicks, according to earlier research (Saleh 2014). Furthermore, the integration of selenium-enriched probiotics incorporating lactic acid bacteria and bifidobacterium strains has resulted in a spectrum of beneficial outcomes. These include antioxidative, anti-pathogenic, anti-inflammatory, anticarcinogenic, and antimutagenic properties (Pophaly, Singh et al. 2014). In poultry nutrition, the combined application of probiotics including Bifidobacterium animalis VKB, Lactobacillus casei IMVB-7280, and B. animalis VKL (Probifilact), together with spherical selenium nanoparticles measuring 7–60 nm, has demonstrated significant advantages. This synergistic approach resulted in enhanced biochemical parameters, increased body weight gain, improved feed conversion efficiency, and higher livestock survival rates. Recent investigations have highlighted the superior responsiveness of nanoprobiotics compared to conventional sodium selenite (Bityutskyy, Tsekhmistrenko et al. 2019). Zinc supplementation represents an essential mineral component in poultry feed, playing critical biological roles in animal physiology. Zinc is particularly vital for immune system functionality and intestinal development in chicks (Hu, Qian et al. 2013; Bityutskyy, Tsekhmistrenko et al. 2019). Dietary incorporation of zinc oxide nanoparticles (50 ppm) combined with probiotic supplementation (1 g) substantially improved poultry and livestock health, along with the quality of animal products including meat, milk, eggs, wool, and leather. Nanoprobiotic combinations have proven particularly effective in reducing mycotoxin contamination in poultry feed, with these dietary additives being established as safe and economically viable for administration over five-week periods (Sayed-ElAhl, Hassan et al. 2022; Ghafarifarsani, Hoseinifar et al. 2024). Probiotic Lactobacillus plantarum facilitates the synthesis of zinc oxide nanoparticles ranging from 7 to 19 nm, with biogenic nanoparticle production being environmentally sustainable, non-toxic, cost-effective, and scalable. Probiotic-mediated nanoparticle synthesis is generally recognized as safe (GRAS) and demonstrates superior efficacy compared to alternative biological methodologies (Selvarajan and Mohanasrinivasan 2013).

Table 3: Synergistic Applications and Effects of Nanoprobiotics.

Application Area	**Nanoparticle Type**	**Probiotic / Organism**	**Key Findings / Synergistic Effects**	**Selected References**
Environmental Remediation	Multi-Wall Carbon Nanotubes (MWCNTs)	Petroleum-degrading microbes	Adsorb oil & heavy metals; enhance microbial degradation of pollutants in Antarctica.	(Vijayaram et al., 2023, 2024)
Therapeutic Delivery (General)	Nanocoating (e.g., for targeted delivery)	General Probiotics	Enhanced bioavailability; targeted delivery to intestinal mucosa; reduced heavy metal toxicity (Cd) in Wistar rats.	(Bhargavi et al., 2021); (Al-Enazi et al., 2020)
Specific Disease Treatment	Nanoparticle coating (BANPs)	Bacillus amyloliquefaciens	Significant reduction in DSS-induced colitis damage; improved recovery compared to non-encapsulated probiotics.	(Alkushi et al., 2022)
Animal Nutrition & Health (Selenium)	Selenium Nanoparticles (SeNPs)	Aspergillus awamori	Improved growth performance, meat quality, and muscle composition in broiler chicks.	(Saleh, 2014)
Animal Nutrition & Health (Selenium)	Selenium Nanoparticles (SeNPs)	Lactic acid bacteria & Bifidobacterium	Antioxidative, anti-pathogenic, anti-inflammatory, anticarcinogenic properties.	(Pophaly et al., 2014)
Animal Nutrition & Health (Selenium)	Spherical SeNPs (7-60 nm)	Bifidobacterium animalis, Lactobacillus casei	Enhanced biochemical parameters, body weight gain, feed efficiency, and survival rates in poultry. Superior to sodium selenite.	(Bityutskyy et al., 2019)
Animal Nutrition & Health (Zinc)	Zinc Oxide	General Probiotic Supplement	Improved poultry/livestock health; enhanced	(Sayed-ElAhl et al., 2022);

	Nanoparticles (ZnO NPs)		quality of meat, milk, eggs; reduced mycotoxin contamination.	(Ghafarifarsani et al., 2024)
Green Synthesis	Zinc Oxide Nanoparticles (ZnO NPs)	Lactobacillus plantarum (Synthesizer)	Environmentally sustainable, non-toxic, cost-effective synthesis of NPs (7-19 nm); GRAS status.	(Selvarajan & Mohanasrinivasan, 2013)

5. Challenges, Safety, and Future Perspectives

The intensification of aquaculture practices has correlated with increased incidence of bacterial diseases and consequent antibiotic usage, fostering antimicrobial resistance (AMR) while creating environmental contamination and residue accumulation issues (Gostin and Meier 2023). While probiotics present a sustainable long-term approach for disease prevention and growth enhancement in aquaculture, several implementation challenges persist. Strain specificity constitutes a major obstacle, as probiotic efficacy varies across species and environmental contexts, necessitating meticulous strain selection protocols (Arora and Baldi 2017). Additionally, standardization and formulation aspects including dosage determination, stability assurance, and shelf-life optimization require significant attention (Ahmed, Prajapati et al. 2024). Probiotic stability remains crucial for functional effectiveness, with environmental factors including temperature fluctuations, moisture exposure, and oxygen sensitivity affecting microbial viability (Terpou, Papadaki et al. 2019). Stability enhancement strategies incorporating stabilizers, encapsulation technologies, and optimized storage conditions are essential for maintaining probiotic viability until administration (Sun, Yin et al. 2023). Host specificity presents another challenge, wherein probiotic strains effective in one fish species may demonstrate limited efficacy in others (Fontana, Bermudez-Brito et al. 2013). Consequently, research initiatives should focus on identifying either broad-spectrum probiotic strains or developing species-specific formulations tailored to distinct aquatic microbiomes (Das, Pradhan et al. 2022). Regulatory heterogeneity across regions presents additional complications for probiotic and paraprobiotic application in aquaculture (Lulijwa, Rupia et al. 2020). Proactive engagement with regulatory bodies, continuous monitoring of guideline updates, and generation of scientific evidence regarding safety and efficacy are imperative for regulatory compliance and approval (Fachri, Amoah et al. 2024). Establishing internationally harmonized regulatory frameworks is essential for ensuring safe and effective probiotic implementation across diverse aquaculture systems (Arora and Baldi 2017). Environmental concerns regarding probiotic release into aquatic ecosystems including potential ecological disruptions and resistance development require addressing (Hancz 2022). Risk mitigation involves implementing optimized management practices such as targeted delivery systems and environmental monitoring protocols. Responsible probiotic application, combined with strict adherence to environmental regulations, is critical. Although paraprobiotics may present reduced environmental risks due to their inactivated state, their long-term ecological impacts warrant further investigation (Fachri, Amoah et al. 2024).
From a safety standpoint, paraprobiotics defined as inactivated microbial cells offer a safer alternative to live probiotics, particularly in scenarios where viable microorganisms might pose risks (Taverniti and Guglielmetti 2011; Monteiro, Schnorr et al. 2023). They maintain immunomodulatory capabilities, bioactive compound production, and gut health improvement similar to live probiotics, while avoiding risks associated with live bacteria such as genetic transfer or environmental persistence (Taverniti and Guglielmetti 2011). Thermal inactivation represents the most prevalent processing method, proving safer than alternative techniques like UV inactivation in certain applications (Choudhury and Kamilya 2019; Tran, Yang et al. 2022). Future research directions should prioritize combination therapies, investigating synergistic interactions between probiotics and prebiotics, phytogenic extracts, and nanoparticles (Vijayaram, Razafindralambo et al. 2024; Vijayaram, Sinha et al. 2024). Nanotechnology integration has revolutionized agricultural and aquaculture practices, with combined applications of nanomaterials (NMs) and plant probiotics (PPs) offering sustainable alternatives to conventional agrochemicals (Kumari and Singh 2020; Agri, Chaudhary et al. 2022; Akhtar, Ilyas et al. 2022).
This integrated NM-PP combination, termed "nanobiofertilizer (NBF)," leverages the advantages of both components through controlled nutrient release mechanisms, improved nutrient utilization efficiency, and substantial crop yield enhancement (Kumari and Singh 2020). Such integrated approaches hold transformative potential for agricultural sectors, ultimately contributing to sustainable production systems and food security (Kumari, Khati et al. 2021; Agri, Chaudhary et al. 2022; Akhtar, Ilyas et al. 2022). Long-term field validation

trials are indispensable for translating laboratory successes to commercial-scale applications across diverse environmental conditions (Grumet, Tromp et al. 2020). Emerging technologies including genomics, metabolomics, and nanobiotechnology are expected to significantly advance novel strain identification and probiotic efficacy enhancement (Fachri, Amoah et al. 2024). Probiogenomics the application of genomic technologies to probiotic research has emerged as a powerful approach in aquaculture for elucidating probiotic mechanisms and developing enhanced strains, integrating genomics, transcriptomics, proteomics, and metabolomics to understand molecular effects in aquatic species (Pérez-Sánchez, Ruiz-Zarzuela et al. 2014). Innovative delivery platforms including microencapsulation and nanoencapsulation will critically influence future probiotic and paraprobiotic development (Hoseinifar, Sun et al. 2018). Advances in microencapsulation methodologies can improve stability and targeted delivery, with ongoing research exploring novel materials and techniques to enhance digestive system survival (Liu, Cui et al. 2019; Yao, Xie et al. 2020). Nanotechnology applications offer innovative approaches for improving bioavailability and controlled release profiles. Developing precision delivery systems, such as intelligent feed formulations or site-specific administration technologies, can optimize distribution efficiency, minimize environmental impact, and enhance overall effectiveness (Karunathilake, Le et al. 2023). A systematic approach combining research innovation and collaborative efforts is essential for successful integration of probiotics and paraprobiotics into aquaculture practices (Fachri, Amoah et al. 2024). The transformation of aquaculture systems into resilient, productive, and sustainable operations will require multidisciplinary research, supportive policy frameworks, and industry collaboration. The transition from antibiotics to probiotics represents not merely an alternative choice but a fundamental requirement for achieving sustainable, ethical, and economically viable aquaculture. Probiotic development signifies a paradigm shift in preventive health management for aquatic organisms and ecological sustainability (Fachri, Amoah et al. 2024).

Table 4: Challenges, Safety Considerations, and Future Perspectives for Probiotics in Aquaculture.

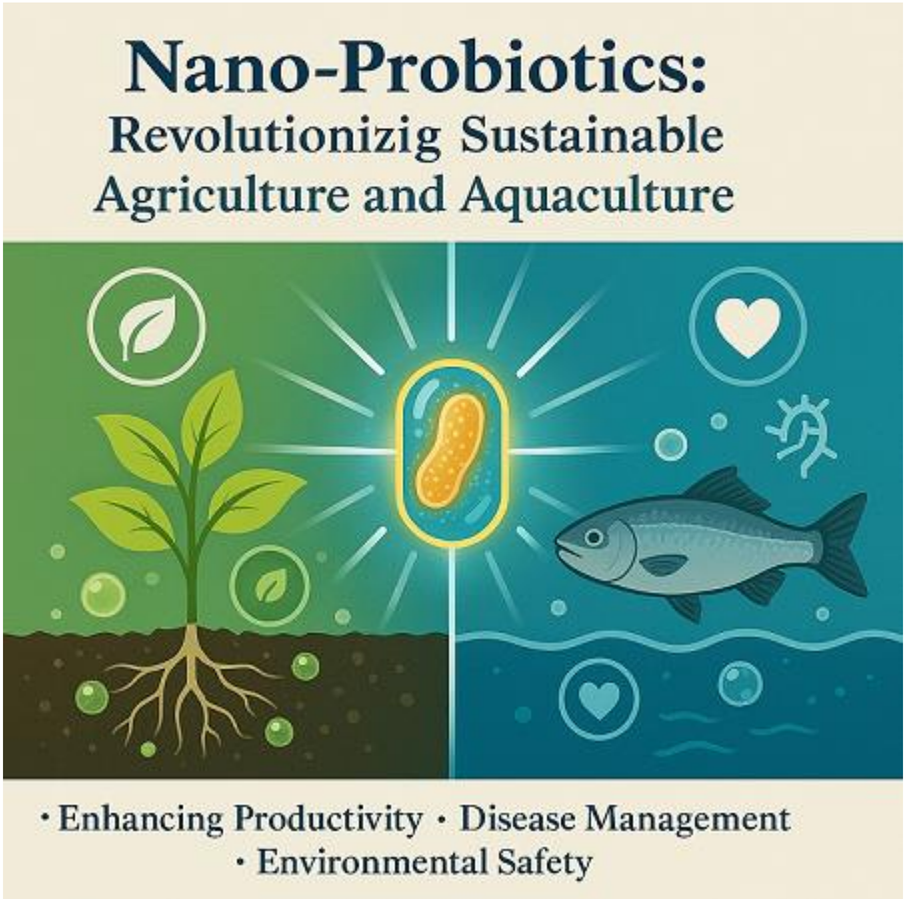
Category	Specific Issue / Aspect	Description / Proposed Solution	Key References
Implementation Challenges	Strain Specificity	Efficacy varies greatly across host species and environments; requires meticulous selection.	(Arora & Baldi, 2017)
	Formulation & Standardization	Challenges in determining optimal dosage, ensuring stability, and maximizing shelf-life.	(Ahmed et al., 2024)
	Stability & Viability	Affected by temperature, moisture, oxygen; requires stabilizers, encapsulation, optimized storage.	(Terpou et al., 2019); (Sun et al., 2023)
	Host Specificity	Strains effective in one species may not work in others; need for species-specific formulations.	(Fontana et al., 2013); (Das et al., 2022)
Regulatory & Safety Issues	Regulatory Heterogeneity	Lack of harmonized international regulations complicates application and approval.	(Lulijwa et al., 2020); (Fachri et al., 2024)
		Solution: Proactive engagement with regulators, evidence generation, and international frameworks.	(Arora & Baldi, 2017)
	Environmental Concerns	Risks of ecological disruption and resistance development upon release into ecosystems.	(Hancz, 2022)

		Mitigation: Targeted delivery systems, environmental monitoring, responsible application.	(Fachri et al., 2024)
Safety & Alternatives	Paraprobiotics (Inactivated Cells)	Safer alternative; retains benefits (immunomodulation, gut health) without risks of live bacteria (e.g., gene transfer).	(Taverniti & Guglielmetti, 2011); (Monteiro et al., 2023)
		Thermal inactivation is the most prevalent and safe method.	(Choudhury & Kamilya, 2019); (Tran et al., 2022)
Future Perspectives	Combination Therapies	Research synergies with prebiotics, phytogenic extracts, and nanoparticles.	(Vijayaram et al., 2024)
	Nanobiofertilizers (NBFs)	Integration of nanomaterials (NMs) and plant probiotics (PPs) for sustainable agriculture.	(Kumari & Singh, 2020); (Agri et al., 2022)
	Long-Term Validation	Field trials essential to translate lab success to commercial scale in diverse environments.	(Grumet et al., 2020)
	Emerging Technologies	Use of genomics, metabolomics, nanobiotechnology, and **probiogenomics** for strain discovery and efficacy enhancement.	(Fachri et al., 2024); (Pérez-Sánchez et al., 2014)
	Advanced Delivery Systems	Microencapsulation and nanoencapsulation to improve stability, targeted delivery, and survival.	(Hoseinifar et al., 2018); (Liu et al., 2019)

Conclusion

The convergence of probiotic technology and nanotechnology represents a paradigm shift in our approach to sustainable aquaculture and agriculture. This review has elucidated the profound potential of nano-probiotics and nano-biofertilizers in addressing some of the most pressing challenges in these sectors: combating disease outbreaks, enhancing growth and productivity, improving stress resilience, and mitigating environmental pollution. The evidence presented demonstrates that probiotics, both live and inactivated (paraprobiotics), offer a multifaceted, eco-friendly alternative to antibiotics and agrochemicals. Their mechanisms of action through competitive exclusion, immunomodulation, production of antimicrobial compounds, and gut microbiota modulation provide a holistic strategy for promoting health and sustainability. The integration of nanotechnology amplifies these benefits significantly. Nano-encapsulation techniques enhance the stability, bioavailability, and targeted delivery of probiotic strains, ensuring their viability and efficacy until they reach their intended site of action. Furthermore, the synergistic combination of nanomaterials (NMs) and plant probiotics (PPs) in "nanobiofertilizers" (NBFs) promises a revolution in agriculture by enabling the controlled release of nutrients, improving nutrient use efficiency, and enhancing plant tolerance to abiotic and biotic stresses. However, the path forward is not without its challenges. Issues of strain specificity, optimal dosage, formulation stability, and host-specific responses must be meticulously addressed through further research. The regulatory landscape for these novel products requires harmonization on a global scale to ensure safety, efficacy, and responsible use. Moreover, comprehensive long-term studies are crucial to fully understand the environmental impact and ensure that the application of nano-probiotics contributes positively to ecosystem health. Future perspectives are undoubtedly promising. Advancements in emerging fields like probiogenomics will be instrumental in deciphering the molecular dialogues between hosts, probiotics, and nanoparticles, leading to the design of next-generation, highly specific probiotic

formulations. Innovations in delivery systems, such as smart nano-carriers and precision agriculture applications, will further optimize the effectiveness and reduce the ecological footprint of these technologies.
In conclusion, the transition from conventional, chemical-dependent practices to the use of nano-probiotics is not merely a choice but a necessity for building resilient, productive, and sustainable food production systems. By harnessing the synergistic potential of microbiology and nanotechnology through multidisciplinary research, supportive policies, and industry collaboration, we can pave the way for a more food-secure and environmentally safe future.



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