



Nanoparticles in shrimp aquaculture: applications in nutrition, disease management, diagnostics and biosafety

Porselvan S.¹ • Saravanan S.¹ • Kaviarasu D.¹ • Selvaraj S.² • Sudhan C.³ • Senthil Kumar E.⁴ • Navin Kumar D.¹ • Dhinesh P.¹

¹ Department of Aquatic Animal Health Management, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India

² Department of Aquaculture, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India

³ Department of Fisheries Resource Management, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India

⁴ Department of Physics and Nanotechnology, Faculty of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur – 603 203, Tamil Nadu, India

Correspondence

Porselvan S. and Saravanan S.; Department of Aquatic Animal Health Management, Dr. M.G.R. Fisheries College and Research Institute, Tamil Nadu Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204, Tamil Nadu, India

✉ porselvan503@gmail.com (PS) and saravanan@tnfu.ac.in (SS)

Manuscript history

Received 22 August 2026 | Accepted 27 September 2026 | Published online 5 October 2026

Citation

Porselvan S, Saravanan S, Kaviarasu D, Selvaraj S, Sudhan C, Kumar SE, Kumar ND, Dhinesh P (2027) Nanoparticles in shrimp aquaculture: applications in nutrition, disease management, diagnostics and biosafety. Journal of Fisheries 15(1): 151301. DOI: 10.17017/j.fish.1482

Abstract

Nanotechnology has emerged as a promising approach to improve nutrition, health management, disease control and pathogen detection in shrimp aquaculture. This review evaluates nano-enabled applications in penaeid shrimp, with particular emphasis on nutrition and feed utilisation, immunomodulation and antioxidant responses, disease management, biosafety and rapid diagnostics. A critical narrative search of Google Scholar, PubMed, Scopus and Wiley Online Library was conducted up to 31 July 2026, with emphasis on direct in vivo evidence from penaeid shrimp. Nano-minerals, polymeric carriers, nanoencapsulated phytochemical compounds and mechanically reduced nano-enabled biological materials have shown potential to enhance growth, feed utilisation and physiological responses. Metallic and bimetallic nanoparticles have demonstrated antibacterial and antiviral activity, while nanocarriers have facilitated the oral delivery of bioactive compounds, antiviral proteins and nucleic acids. Gold nanoparticle-based platforms have also enabled rapid detection of important shrimp pathogens, particularly white spot syndrome virus. However, the biological performance of nano-enabled formulations varies depending on formulation characteristics, active dose, route of administration and exposure regime, while excessive exposure to certain metallic nanoparticles may result in oxidative disturbance and tissue injury. Most of the available evidence has been generated under controlled experimental conditions, with limited information on long-term residues, environmental fate and farm-scale performance. Nano-enabled technologies represent promising application-specific tools for shrimp aquaculture, but their commercial adoption will depend on reproducible efficacy, reliable delivery, acceptable animal and environmental safety and validation under realistic farming conditions.

Keywords: biosafety; disease management; immunomodulation; nanoencapsulation; nanotechnology; shrimp aquaculture

1 | INTRODUCTION

Shrimp aquaculture represents an important part of global aquatic food production, with *Penaeus vannamei* and *Penaeus monodon* being the major penaeid species cultured worldwide. The intensification of shrimp farming has contributed substantially to increased production. However, it has also intensified challenges related to environmental stress, organic loading and infectious diseases. Among these, viral infections such as white spot syndrome virus (WSSV) infection and *Vibrio* associated diseases, including acute hepatopancreatic necrosis disease (AHPND), continue to be major constraints affecting shrimp health and production (Camacho-Jiménez *et al.* 2020; Seethalakshmi *et al.* 2021).

Current shrimp health-management practices include biosecurity measures, the use of specific-pathogen-free stocks, proper water-quality management, functional nutrition and appropriate therapeutic interventions. At the same time, excessive or inappropriate use of antimicrobials may contribute to the development of antimicrobial resistance, alteration of microbial communities and the accumulation of residues in cultured animals and the surrounding environment (Camacho-Jiménez *et al.* 2020; Seethalakshmi *et al.* 2021). As a result, increasing attention has been given to alternative approaches that can improve host health and disease resistance while reducing dependence on conventional antimicrobials. Such approaches are particularly important in penaeid shrimp, where defence mechanisms are primarily based on innate cellular and humoral responses, including haemocyte-mediated reactions, phagocytosis, the prophenoloxidase system, antimicrobial effectors and antioxidant pathways (Campa-Córdova *et al.* 2002; Dechamma *et al.* 2015).

Nanotechnology has emerged as one of these promising approaches because nanoscale materials and engineered particulate carriers can improve or modify the stability, dispersion and delivery of biologically active compounds. A commonly used size-based definition describes nanomaterials as materials having at least one dimension approximately within the 1–100 nm range; however, the shrimp aquaculture literature also includes broader nano-enabled systems such as nanoemulsions, nanocapsules, nanocomposites and mechanically reduced submicron materials. The biological behaviour of these materials is influenced by several factors, including particle composition, size, surface properties, aggregation, dissolution and payload characteristics (Shah and Mraz 2020; Fajardo *et al.* 2022). Nano-enabled applications investigated in shrimp aquaculture include nano-mineral supplementation, encapsulated vitamins and phytochemical compounds, nanosized biological feed ingredients, antimicrobial and antiviral nanoparticles, delivery systems for

proteins and double-stranded RNA and nanoparticle-assisted diagnostic approaches (Camacho-Jiménez *et al.* 2020; Seethalakshmi *et al.* 2021; Jonjaroen *et al.* 2024).

The biological performance of nano-enabled formulations is influenced by formulation characteristics, the dose of the active compound and the conditions of exposure. At the same time, variations in particle characterisation, experimental design and dose reporting among studies can make direct comparisons difficult (Fajardo *et al.* 2022). Accordingly, this review critically evaluates nano-enabled applications in shrimp aquaculture, with particular focus on nutrition and feed utilisation, immunomodulation and antioxidant regulation, disease management, nanotoxicity and biosafety and rapid diagnostics. Particular emphasis is placed on direct evidence obtained from penaeid shrimp and on evaluating the efficacy, safety and translational relevance of nano-enabled technologies for their practical application in shrimp production.

2 | REVIEW METHODOLOGY

This critical review was based on peer-reviewed literature identified through Google Scholar, PubMed, Scopus and Wiley Online Library, with the final literature search conducted on 31 July 2026. Publications relevant to the scope of the review and published between 2002 and 2026 were considered. Search terms were used individually and in different combinations using the Boolean operators “AND” and “OR” and included “shrimp”, “*Penaeus vannamei*”, “*Litopenaeus vannamei*”, “*Penaeus monodon*”, “nanotechnology”, “nanoparticles”, “nanomaterials”, “nano-formulation”, “nanoencapsulation”, “nanoemulsion”, “nanocomposite”, “nanocarrier”, “nano-minerals”, “functional feed”, “growth performance”, “feed utilisation”, “immunomodulation”, “immune response”, “antioxidant response”, “disease resistance”, “*Vibrio*”, “AHPND”, “WSSV”, “RNA interference”, “dsRNA delivery”, “nanotoxicity”, “biosafety” and “pathogen diagnostics”.

Peer-reviewed original research articles and short communications were considered the principal evidence base, while review articles were used mainly for background information and identification of relevant primary studies. Particular emphasis was placed on direct in vivo studies conducted in penaeid shrimp, especially feeding, toxicity and pathogen-challenge studies reporting biologically relevant outcomes. In vitro, formulation and characterisation studies and evidence from other aquaculture species were used mainly for mechanistic, methodological or comparative support.

The available evidence was critically interpreted with consideration of dose, nanomaterial characteristics, experimental replication, control treatments, administra-

tion route and biological outcomes. Greater interpretive weight was given to direct shrimp evidence with clearly reported experimental conditions. Owing to differences among nanoparticle types, formulations, exposure conditions and experimental endpoints, the evidence was synthesised narratively rather than quantitatively.

Nano-enabled systems investigated in shrimp aqua-

culture include polymeric and lipid-based carriers, nano-minerals, metallic and bimetallic nanoparticles, mechanically reduced biological materials, and specialised protein or nucleic-acid delivery systems. Their principal applications in shrimp nutrition, health management and diagnostics are summarised in Figure 1 and Table 1.

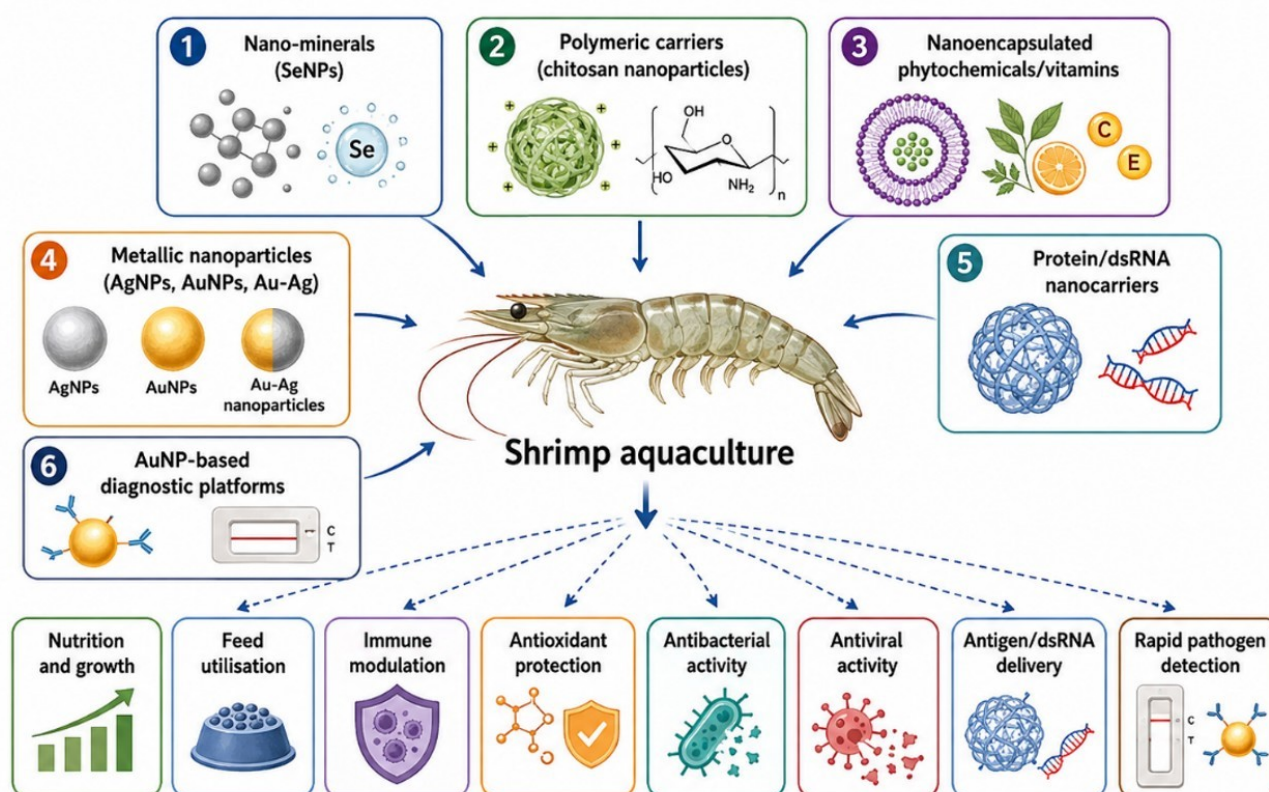


FIGURE 1 Major nano-enabled platforms and their applications in shrimp aquaculture. The graphical illustration was prepared with the assistance of generative AI and subsequently reviewed and modified by the authors.

3 | NANO-ENABLED NUTRITION, GROWTH AND FEED UTILISATION IN SHRIMP

Nano-enabled dietary strategies in shrimp have primarily been investigated as a means of improving the delivery and utilisation of minerals, vitamins, phytogenic compounds and biological feed ingredients. Most of the direct *in vivo* nutritional evidence has been generated in *P. vannamei*, with several studies reporting improvements in growth, feed conversion, digestive activity and nutrient utilisation.

3.1 Nano-minerals

Selenium nanoparticles (SeNPs) are among the most extensively studied nano-minerals in shrimp nutrition. Ghafarizadeh *et al.* (2022) supplemented diets with 0–1.2 mg Se-N kg⁻¹ diet; because the basal diet contained selenium, the measured total dietary selenium concentrations

ranged from approximately 0.38 to 1.55 mg kg⁻¹. Moderate Se-N supplementation improved growth and feed-conversion performance, indicating a dose-dependent nutritional response. In contrast, Yu *et al.* (2022) compared sodium selenite, L-selenomethionine, selenium yeast and SeNPs at an equivalent concentration of 0.4 mg elemental Se kg⁻¹ diet and found that SeNPs did not consistently outperform the conventional selenium sources. Mustafa *et al.* (2025) evaluated 25–45 mg kg⁻¹ of a chitosan-stabilised selenium nanoparticle formulation (CSSeNPs); these values represent the amount of the complete nanoparticle formulation rather than elemental selenium. Overall, nano-selenium has nutritional potential in shrimp diets, but comparisons among studies require clear distinction between elemental selenium dose and the mass of the nanoparticle formulation.

TABLE 1 Classification, representative systems and principal applications of nano-enabled platforms investigated in shrimp aquaculture.

Nano-enabled platform	Representative systems	Principal application in shrimp	References
Polymeric carriers	Chitosan and chitosan–tripolyphosphate particles	Delivery of vitamins, phyto-genic compounds, proteins and dsRNA	Bhoopathy <i>et al.</i> (2021); Asaikkutti <i>et al.</i> (2023); Taju <i>et al.</i> (2018); Abdi <i>et al.</i> (2026)
Lipid-based systems	Nanoemulsions and related lipid carriers	Delivery of poorly water-soluble bioactive compounds	Fath El-Bab <i>et al.</i> (2024)
Nano-minerals	Selenium nanoparticles and stabilised selenium formulations	Nutritional supplementation and antioxidant support	Ghaffarizadeh <i>et al.</i> (2022); Yu <i>et al.</i> (2022); Mustafa <i>et al.</i> (2025)
Metallic and bimetallic nanoparticles	AgNPs, AuNPs and Au–Ag systems	Antibacterial, antiviral and host-modulatory applications	Tello-Olea <i>et al.</i> (2019); Romo-Quiñonez <i>et al.</i> (2020); Kamble <i>et al.</i> (2024)
Mechanically reduced nano-enabled biological materials	Ball-milled <i>Arthrospira</i> and seaweed biomass	Functional nutrition and improved feed utilisation	Sharawy <i>et al.</i> (2022); Ashour <i>et al.</i> (2025)
Protein and nucleic-acid delivery systems	Chitosan–TPP–VP28 and nanoparticle-assisted dsRNA carriers	Oral delivery of antiviral proteins and RNA molecules	Taju <i>et al.</i> (2018); Jonjaroen <i>et al.</i> (2024)
Nanodiagnostic platforms	AuNP lateral-flow assays, AuNP-assisted LAMP and AuNP-modified electrodes	Rapid pathogen detection	Sithigorngul <i>et al.</i> (2006, 2011); Seetang-Nun <i>et al.</i> (2013); Nordin <i>et al.</i> (2017)

3.2 Nanoencapsulated vitamins and phyto-genic compounds

Polymeric and lipid-based carriers have been investigated as delivery systems to improve the stability and availability of functional dietary compounds. Vitamin C-loaded chitosan nanoparticles enhanced growth and feed efficiency while also improving vitamin stability during storage (Asaikkutti *et al.* 2023).

At the formulation level, curcumin-loaded chitosan nanoparticles were successfully incorporated into shrimp feed pellets (Bhoopathy *et al.* 2020), whereas direct *in vivo* dietary supplementation with the formulation improved growth and survival in *P. vannamei* (Bhoopathy *et al.* 2021). Similarly, a curcumin-loaded olive-oil nanoemulsion improved final weight, feed conversion and digestive-enzyme activity (Fath El-Bab *et al.* 2024).

Comparable responses have also been reported with other phyto-genic formulations. Pumpkin-seed-oil-loaded chitosan nanoparticles improved growth and feed utilisation (Eissa *et al.* 2025b), whereas *Cyperus rotundus* extract-loaded chitosan nanoparticles enhanced growth, survival, moulting and digestive activity in an inclusion-dependent manner (Hassona *et al.* 2026). However, these studies did not include corresponding unencapsulated phyto-genic compounds supplied at equivalent active doses. Similarly, the vitamin C, curcumin and curcumin-nanoemulsion studies primarily compared nanoformulations with basal diets and/or unloaded carriers rather than dose-matched free compounds (Bhoopathy *et al.* 2021; Asaikkutti *et al.* 2023; Fath El-Bab *et al.* 2024). Therefore, while these studies demonstrate biological

activity of the nanoformulations, they do not by themselves establish that nanoencapsulation provides superior efficacy over the corresponding free compounds. Direct dose-matched comparisons are required to demonstrate a specific nanoencapsulation advantage.

3.3 Nano-enabled mechanically reduced algal and seaweed ingredients

Mechanical reduction of particle size represents a distinct nano-enabled approach and may improve the accessibility of nutrients and intracellular constituents within biological feed materials. Ball-milled *Arthrospira platensis* improved the growth and feed utilisation of *P. vannamei* compared with conventional biomass, although the mean particle size was approximately 184 nm and therefore predominantly within the submicron range (Sharawy *et al.* 2022). Similarly, ball-milled *Pterocladia capillacea* improved growth, feed conversion, protein utilisation and digestive-enzyme activity compared with conventional seaweed powder (Ashour *et al.* 2025). Because the processed material exhibited a broad nanoscale-to-submicron particle-size distribution, these improvements may be associated with greater matrix disruption and nutrient accessibility rather than with a uniquely nanoscale effect.

Overall, nano-enabled dietary approaches have the potential to improve shrimp growth and feed utilisation through improved mineral supplementation, protection and delivery of functional compounds and greater accessibility of nutrients from biological feed ingredients. However, their practical value should be established through

direct comparison with conventional formulations supplied at equivalent active doses.

4 | IMMUNOMODULATORY AND ANTIOXIDANT EFFECTS OF NANO-ENABLED FORMULATIONS

Penaeid shrimp depend largely on innate defence mechanisms, including haemocyte-mediated responses, phagocytosis, respiratory burst activity, the prophenoloxidase system, antimicrobial effectors and antioxidant enzymes. Consequently, nano-enabled formulations have been investigated for their ability to modulate these defence responses and improve the physiological resilience of shrimp (Campa-Córdova *et al.* 2002; Chiu *et al.* 2007).

4.1 Polymeric delivery of immunostimulatory compounds

Direct *in vivo* studies in *P. vannamei* have shown that chitosan-based nanoparticles can influence immune and antioxidant responses. Vitamin C-loaded chitosan nanoparticles increased total haemocyte count, respiratory burst and phenoloxidase activity in *P. vannamei* and also altered the expression of lectin, lysozyme and manganese superoxide dismutase (Asaikkutti *et al.* 2023). Similarly, curcumin-loaded chitosan nanoparticles enhanced haemocyte-associated responses, phenoloxidase and superoxide dismutase activity, while also modulating immune and antioxidant-related genes (Bhoopathy *et al.* 2021).

Similar effects have been observed with other phyto-genic payloads. Bee-venom-loaded chitosan nanoparticles enhanced haemocyte responses, phenoloxidase, lysozyme and phagocytic activity, together with increased superoxide dismutase and catalase activity. Pumpkin-seed-oil loaded formulations also influenced both cellular and humoral immune indices (Eissa *et al.* 2025a, 2025b). Likewise, *Cyperus rotundus* extract-loaded chitosan nanoparticles affected phenoloxidase, lysozyme and antioxidant responses in an inclusion-dependent manner (Hassona *et al.* 2026).

More informative comparative evidence was provided by Abdi *et al.* (2026), who included free quercetin, unloaded chitosan nanoparticles and quercetin-loaded nanoparticles. However, the treatments were not matched for active quercetin dose: 0.5 g kg⁻¹ of the loaded formulation delivered approximately 83.75 mg quercetin kg⁻¹ feed, compared with 500 mg kg⁻¹ in the free-quercetin treatment. The loaded formulation nevertheless produced favourable immune and antioxidant responses under silver nanoparticle-induced oxidative stress, although this comparison should not be interpreted as a strictly dose-equivalent demonstration of nanoencapsulation superiority.

4.2 Nano-minerals and antioxidant regulation

Selenium nanoparticles have also been studied for their

effects on immune and antioxidant regulation. Dietary supplementation with SeNPs increased hepatopancreatic superoxide dismutase, catalase and glutathione peroxidase activities and enhanced phenoloxidase activity and immune-related gene expression in *P. vannamei* (Ghafarizadeh *et al.* 2022). Stabilised selenium nanoparticle formulations produced comparable effects on genes associated with innate immunity and antioxidant defence (Mustafa *et al.* 2025). Together, these findings indicate that selenium-based nanoformulations can influence both redox balance and immune pathways, although differences in formulation and dose expression make direct comparisons among studies difficult.

4.3 Interpretation of immune and antioxidant responses

Immune and antioxidant biomarkers should not be interpreted independently, as changes in enzyme activity or gene expression may reflect beneficial immune stimulation, compensatory responses to stress or changes in physiological demand. This is illustrated by nanoencapsulated carvacrol and thymol, where an intermediate dietary inclusion level produced favourable physiological and hepatopancreatic responses despite reduced transcription of some antioxidant enzymes in stressed shrimp (Ríos-Ortiz *et al.* 2026).

Accordingly, nano-enabled immunomodulatory effects should be assessed using an integrated set of indicators, including haemocyte function, humoral immunity, antioxidant activity and oxidative damage. Greater expression of an individual biomarker should therefore not automatically be interpreted as evidence of improved health.

5 | NANO-ENABLED DISEASE MANAGEMENT IN SHRIMP AQUACULTURE

Nano-enabled disease management in shrimp includes nanoparticles with direct antimicrobial or antiviral activity and particulate carriers used to deliver bioactive compounds, proteins or nucleic acids. Current evidence is concentrated mainly on *Vibrio*-associated diseases and white spot syndrome virus (WSSV), with comparatively limited work on other pathogens.

5.1 Bacterial diseases and AHPND

Chitosan-based carriers have shown promising activity against *Vibrio*-associated infections in *P. vannamei*. Dietary curcumin-loaded chitosan nanoparticles improved survival following *Vibrio harveyi* challenge, while vitamin C, bee-venom and pumpkin-seed-oil-loaded formulations also enhanced resistance to *Vibrio* infection (Bhoopathy *et al.* 2021; Asaikkutti *et al.* 2023; Eissa *et al.* 2025a, 2025b). These responses, however, reflect the activity of the complete carrier payload formulation rather than the nanocarrier alone.

Metallic nanoparticles have been investigated primarily for direct antibacterial effects. Supporting *in vitro* evidence showed that silver nanoparticles inhibited shrimp-associated *Vibrio* isolates (Bahabadi *et al.* 2017), whereas direct *in vivo* evidence showed that gold nanoparticles reduced pathological damage and improved protection against *V. parahaemolyticus* (Tello-Olea *et al.* 2019). Biosynthesised AgNPs also reduced mortality and hepatopancreatic lesions during necrotising hepatopancreatitis, although surviving shrimp remained PCR-positive, indicating disease mitigation rather than confirmed pathogen clearance (Acedo-Valdez *et al.* 2017).

Against AHPND-associated *V. parahaemolyticus*, plant-mediated AgNPs and dietary Ag/AgCl nanoparticles improved survival under experimental challenge (León-Valdez *et al.* 2024; Maldonado-Muñiz *et al.* 2025). Sulfated-galactan-coated Au–Ag nanoparticles additionally showed antibacterial, antibiofilm and antivirulence activity against *V. parahaemolyticus* and *V. harveyi* and reduced hepatopancreatic damage (Kamble *et al.* 2024). Such coated systems should be interpreted as composite antimicrobial formulations because both the metallic core and biological coating may contribute to activity.

5.2 Antiviral applications against WSSV

Silver nanoparticles are the most extensively investigated metallic nanomaterials for WSSV control. Experimental studies have evaluated direct virus nanoparticle interactions and administration through injection or diet (Ochoa-Meza *et al.* 2019; Romo-Quirñonez *et al.* 2020; Romo Quirñonez *et al.* 2022).

Pre-incubation of WSSV with AgNPs reduced viral infectivity, while dietary administration lowered WSSV-associated mortality, supporting both direct antiviral activity and the feasibility of feed-based delivery (Romo-Quirñonez *et al.* 2020). Protection was also strongly influenced by administration frequency, with intermittent exposure producing more favourable outcomes than frequent feeding (Romo Quirñonez *et al.* 2022). Injection studies provide supporting mechanistic evidence but are less applicable to commercial shrimp production (Ochoa-Meza *et al.* 2019).

5.3 Nanocarrier mediated delivery of antiviral proteins and dsRNA

Nanoparticles have also been used to protect and deliver antiviral biomolecules. Chitosan tripolyphosphate nanoparticles carrying recombinant WSSV VP28 provided greater oral protection than non-encapsulated VP28 preparations, demonstrating an encapsulation-related delivery advantage (Taju *et al.* 2018).

Nanoparticle-assisted double-stranded RNA (dsRNA) delivery is another promising antiviral strategy. Chitosan-based, modified polymeric and lipid carriers have been investigated to protect dsRNA from degradation and im-

prove uptake in shrimp (Jonjaroen *et al.* 2024). However, effective oral delivery remains constrained by stability during feed manufacture and storage, leaching into culture water and degradation within the digestive tract.

5.4 Emerging disease targets

Evidence for other pathogens remains limited. Dietary curcumin nanoparticles reduced mortality following *Fusarium solani* challenge in *P. vannamei*, indicating potential application against fungal infection (Eissa *et al.* 2024). In contrast, direct evidence for nanoparticle-based treatment of *Enterocytozoon hepatopenaei* remains insufficient, making EHP a potential future therapeutic target.

Overall, nano-enabled disease management research has progressed furthest against *Vibrio*-associated infections and WSSV. Polymeric carriers facilitate delivery of functional compounds and antiviral biomolecules, whereas metallic and bimetallic nanoparticles provide more direct pathogen-targeting activity. Disease-control efficacy should nevertheless be judged primarily from live-shrimp challenge studies, and improved survival should not be equated automatically with pathogen clearance. Representative *in vivo* evidence for nano-enabled disease management in *P. vannamei* is summarised in Table 2.

6 | NANOTOXICITY, BIOSAFETY AND THERAPEUTIC WINDOWS

The benefits of nano-enabled formulations must be considered alongside potential adverse effects. Nanoparticle toxicity depends on composition, particle characteristics, concentration, administration route and exposure duration. Therefore, safety cannot be inferred solely from chemical composition or absence of acute mortality (Camacho-Jiménez *et al.* 2020; Fajardo *et al.* 2022).

6.1 Acute and sublethal toxicity

Silver nanoparticles provide the strongest direct evidence of nanoparticle-associated toxicity in shrimp. Waterborne AgNP exposure produced concentration and time-dependent effects on survival and altered metabolic and haematological variables in *P. vannamei* (Juárez-Moreno *et al.* 2017; Lam *et al.* 2020). Histopathological lesions have also been reported in the gills, muscle, antennal gland and lymphoid organ, demonstrating that sublethal effects may occur even when mortality remains limited (Chávez-Sánchez *et al.* 2021).

Other nanomaterials show similar concerns. Fe₃O₄ nanoparticle exposure increased whole-body iron accumulation and produced hepatopancreatic alterations despite relatively low mortality (Suharyadi *et al.* 2025). Changes in antioxidant enzymes may reflect either adaptive responses or oxidative stress; therefore, oxidative damage markers, histopathology and functional out-

comes should be interpreted together (Chávez-Sánchez *et al.* 2021; Suharyadi *et al.* 2025).

Nanoparticle toxicity may also be modified by co-occurring contaminants. Combined exposure to titanium

dioxide nanoparticles and inorganic arsenic altered biochemical and oxidative responses in shrimp, highlighting the potential importance of contaminant interactions under culture conditions (Cordeiro *et al.* 2016).

TABLE 2 Representative *in vivo* evidence for nano-enabled disease management in *Penaeus vannamei*.

Study	Nanoformulation	Target	Principal outcome
Bhoopathy <i>et al.</i> (2021)	Curcumin-loaded chitosan nanoparticles; dietary	<i>V. harveyi</i>	73.3% survival versus 46.7% in challenged controls
Asaikkutti <i>et al.</i> (2023)	Vitamin C-loaded chitosan nanoparticles; dietary	<i>V. harveyi</i>	88.9% survival in challenged VC-CSNP-fed shrimp versus 70.2% in challenged controls
Tello-Olea <i>et al.</i> (2019)	AuNPs	<i>V. parahaemolyticus</i>	80% survival at 2 µg AuNP g ⁻¹ feed versus 10% in infected controls; reduced hepatopancreatic damage
Acedo-Valdez <i>et al.</i> (2017)	Biosynthesised AgNPs	Necrotising hepatopancreatitis bacterium	0% mortality with 35 µg AgNP treatment versus 41% in infected untreated shrimp; survivors remained PCR-positive
León-Valdez <i>et al.</i> (2024)	Plant-mediated AgNPs	AHPND-associated <i>V. parahaemolyticus</i>	Improved post-challenge survival
Maldonado-Muñiz <i>et al.</i> (2025)	Dietary Ag/AgCl nanoparticles	AHPND	~78% survival at 100 mg Ag kg ⁻¹ diet versus ~27% in infected controls
Romo-Quiñonez <i>et al.</i> (2020)	Dietary AgNPs	WSSV	3% cumulative mortality at 1,000 µg Ag g ⁻¹ feed at 192 h; infected untreated shrimp reached 43% mortality at 84 hpi.
Romo Quiñonez <i>et al.</i> (2022)	Dietary AgNPs at different frequencies	WSSV	53% survival with weekly AgNP feeding versus 30% with feeding every four days, 10% with daily feeding and 7% in the infected control.
Taju <i>et al.</i> (2018)	Chitosan–TPP-encapsulated VP28; oral	WSSV	~80% protection versus ~65–70% with non-encapsulated VP28

6.2 Therapeutic windows

Nano-enabled interventions frequently show a nonlinear exposure-response relationship, in which insufficient exposure produces limited benefit, an intermediate range provides the desired response and excessive or prolonged exposure increases adverse effects.

This pattern has been observed with both selenium and silver-based formulations. Moderate SeNP supplementation improved growth and antioxidant responses, whereas higher supplementation reduced the beneficial effect (Ghaffarizadeh *et al.* 2022). Similarly, Ag/AgCl nanoparticles provided disease-control benefits at selected dietary concentrations but caused greater hepatopancreatic damage at higher exposure (Maldonado-Muñiz *et al.* 2025). Administration frequency is also important, as intermittent dietary AgNP exposure provided a more favourable balance between WSSV protection and host condition than frequent administration (Romo Quiñonez *et al.* 2022).

Nonlinear responses also occur with non-metallic formulations; carvacrol–thymol chitosan nanocapsules produced the most favourable physiological response at an intermediate dietary inclusion under thermal stress (Ríos-Ortiz *et al.* 2026). Thus, therapeutic windows are

formulation-specific and depend collectively on dose, frequency, duration and administration route. The conceptual relationship between nanoparticle exposure, biological efficacy and toxicity is illustrated in Figure 2. Representative evidence for exposure-dependent benefits and toxicity of nano-enabled formulations in shrimp is summarised in Table 3.

6.3 Bioaccumulation and food-safety considerations

Food safety assessment must extend beyond acute toxicity to tissue retention and elimination. Exposure to Fe₃O₄ nanoparticles increased whole-body iron concentrations in shrimp, while oral AuNP administration resulted in tissue-associated gold signals in the hepatopancreas (Tello-Olea *et al.* 2019; Suharyadi *et al.* 2025). Such measurements indicate tissue association or elemental retention but do not necessarily establish that the detected material persists as intact nanoparticles, because dissolved ions or transformed products may also contribute to the measured signal.

Evidence on edible muscle residues and depuration remains limited, as most studies terminate shortly after exposure or pathogen challenge (Romo Quiñonez *et al.* 2022; Maldonado-Muñiz *et al.* 2025). Consequently,

available data are insufficient to establish nanoformulation-specific withdrawal periods or consumer safety limits. Future studies should therefore evaluate tissue distribution, edible-muscle residues, transformation and depuration before routine use in food producing shrimp.

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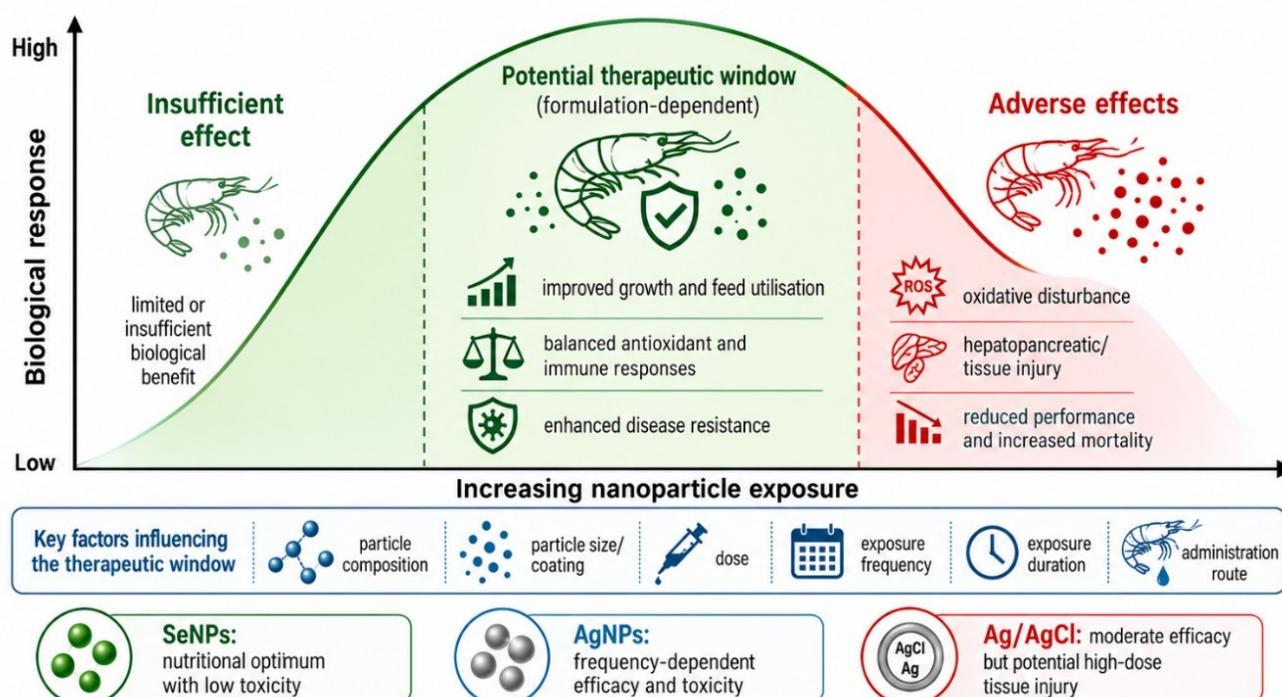


FIGURE 2 Conceptual schematic illustrating the relationship between nanoparticle exposure, biological efficacy and toxicity in shrimp aquaculture. Low exposure may provide insufficient biological activity, whereas an intermediate exposure range may produce favourable nutritional, physiological or disease-management responses. Excessive or prolonged exposure may increase oxidative disturbance and tissue injury. This schematic illustrates a general formulation-dependent concept and should not be interpreted as a universal empirically derived dose–response curve. The potential therapeutic window varies with nanoparticle characteristics, dose, exposure duration, frequency and administration route.

6.4 Environmental biosafety

Unconsumed or excreted nano-enabled materials may enter culture water, biofloc and sediment, where aggregation, sedimentation, dissolution and interactions with organic matter can alter their behaviour (Camacho-Jiménez *et al.* 2020; Fajardo *et al.* 2022).

This is particularly relevant for metallic nanoparticles because antimicrobial activity may also affect non-target microbial communities involved in culture system function. Biological or “green” synthesis should likewise not be assumed to ensure environmental safety. Because information on nanoparticle persistence and distribution among shrimp, water, biofloc, sediment and microbial communities remain limited, environmental fate and non-target effects should be evaluated alongside efficacy.

7 | NANO-ENABLED RAPID DIAGNOSTICS AND BIOSENSORS FOR SHRIMP DISEASES

Rapid pathogen detection is essential in shrimp health management because infections may spread before obvi-

ous clinical signs develop. Conventional PCR-based methods are highly sensitive but require nucleic-acid extraction, specialised equipment and trained personnel. Nanomaterials, particularly gold nanoparticles (AuNPs), have therefore been incorporated into immunochromatographic, colorimetric and electrochemical platforms to improve speed and portability.

7.1 AuNP-based detection of viral pathogens

White spot syndrome virus (WSSV) is the principal target of nano-enabled shrimp diagnostics. Colloidal gold immunochromatographic strips enabled rapid visual detection of WSSV directly from infected shrimp tissues, demonstrating the potential for field screening without specialised equipment (Sithigorngul *et al.* 2006).

Subsequent lateral flow systems used either antibody or peptide-based recognition and were evaluated using suspected field samples (Kulabhusan *et al.* 2017a, 2017b). A dual immunochromatographic strip also enabled simultaneous detection of WSSV and yellow head virus (YHV), although such rapid tests generally remain

less sensitive than PCR-based methods (Sithigorngul *et al.* 2011). AuNP-assisted immunodot blotting further improved WSSV signal detection, but its multiple processing steps limit true pondside application (Thiruppathiraja *et al.* 2011).

7.2 AuNP-assisted molecular detection

AuNPs have also been coupled with nucleic-acid amplifi-

cation. Seetang-Nun *et al.* (2013) combined loop-mediated isothermal amplification (LAMP) with DNA functionalised AuNPs and detected approximately 2×10^2 copies of WSSV plasmid DNA using a visible colour response. Although this approach avoids conventional thermal cycling and provides sensitive endpoint detection, nucleic acid extraction and amplification are still required.

TABLE 3 Representative evidence for exposure-dependent benefits and toxicity of nano-enabled formulations in shrimp.

Nanomaterial/ formulation	Exposure evaluated	Key exposure–response finding	Reference
Selenium nanoparticles	0–1.2 mg Se-N supplement kg^{-1} diet (total dietary Se ≈ 0.38 – 1.55 mg kg^{-1}) for 56 d	Moderate supplementation produced the greatest growth and antioxidant responses; estimated optimum $\approx 0.38 \text{ mg kg}^{-1}$, while higher levels reduced benefits	Ghaffarizadeh <i>et al.</i> (2022)
Dietary AgNPs	Different feeding frequencies	Weekly exposure provided a more favourable protection–host response balance than frequent, particularly daily, exposure	Romo Quiñonez <i>et al.</i> (2022)
Ag/AgCl nanoparticles	0–1000 mg Ag kg^{-1} diet	Intermediate exposure improved disease-related outcomes; the highest exposure caused marked hepatopancreatic damage	Maldonado-Muñiz <i>et al.</i> (2025)
Silver nanoparticles	Graded experimental exposure	Lower concentrations were better tolerated; histopathological lesions occurred despite relatively high survival	Chávez-Sánchez <i>et al.</i> (2021)
Waterborne AgNPs	Concentration- and time-dependent exposure	Toxicity increased with concentration and exposure duration	Lam <i>et al.</i> (2020)
Fe_3O_4 nanoparticles	50–125 mg L^{-1} for up to 96 h	Limited mortality but increased body iron and hepatopancreatic injury	Suharyadi <i>et al.</i> (2025)
Carvacrol–thymol chitosan nanocapsules	Graded dietary supplementation	Intermediate inclusion produced the most favourable physiological response	Ríos-Ortiz <i>et al.</i> (2026)

7.3 Nanobiosensors for bacterial pathogens

Nanoenabled bacterial diagnostics remain less developed than WSSV detection. An AuNP-modified electrochemical DNA biosensor enabled sensitive detection of *Vibrio parahaemolyticus* and demonstrated the potential of portable nanoparticle-based electrodes (Nordin *et al.* 2017). However, the platform was evaluated mainly using bacterial DNA and shellfish samples and targeted *V. parahaemolyticus* at the species level rather than the *pirA/pirB* virulence genes associated with AHPND. It should therefore be regarded as proof-of-concept rather than a validated AHPND diagnostic.

Evidence for nano-enabled detection of AHPND and *Enterocytozoon hepatopenaei* remains limited. Among the nano-enabled diagnostic studies identified in this review, WSSV has received the most extensive development and evaluation. Lateral-flow assays provide rapid and portable screening, whereas nanoparticle-assisted molecular platforms offer greater sensitivity but retain sample-preparation and amplification requirements. Future

development should emphasise pathogen-specific targets and validation using naturally infected shrimp. Representative nano-enabled diagnostic platforms investigated for shrimp pathogens are summarised in Table 4.

8 | CRITICAL APPRAISAL AND COMMERCIAL TRANSLATION OF NANO-ENABLED TECHNOLOGIES

Although nano-enabled interventions have produced encouraging results in shrimp, their practical relevance depends on experimental robustness and the ability to deliver formulations safely, consistently and economically under production conditions.

8.1 Experimental robustness and interpretation

Experimental design strongly influences the reliability of nano-enabled shrimp studies. In feeding and challenge trials, adequate independent tank replication is particularly important because shrimp within the same tank share diet, water quality and environmental conditions

(Cordeiro *et al.* 2016; Ríos-Ortiz *et al.* 2026).

Appropriate comparators are equally important. Nanoformulations should ideally be evaluated against untreated controls, unloaded carriers and equivalent doses of the conventional or free active compound. Direct comparison of nano-selenium with conventional selenium sources, for example, showed that nanoformulation does not necessarily provide superior performance (Yu *et al.* 2022).

Interpretation is further complicated by inconsistent dose expression and physicochemical characterisation. Mineral and metallic formulations may be reported as elemental dose or total formulation mass, whereas encapsulated compounds may not clearly specify the deliv-

ered payload (Ghaffarizadeh *et al.* 2022; Mustafa *et al.* 2025). Because particle size, aggregation, dissolution and payload loading influence biological behaviour, characterisation should reflect the formulation actually administered to shrimp, including after incorporation into feed or exposure to saline water (Fajardo *et al.* 2022).

Biological endpoints also require careful interpretation. Changes in immune-gene expression or antioxidant enzymes indicate physiological modulation but do not alone demonstrate improved health, while increased survival after challenge does not necessarily indicate pathogen clearance. Stronger evidence combines molecular and biochemical responses with functional outcomes such as growth, pathogen burden, histopathology and survival.

TABLE 4 Nano-enabled diagnostic platforms for shrimp pathogens.

Target	Nano-enabled platform	Performance/application	Reference
WSSV	Monoclonal-antibody colloidal-Au lateral-flow strip	Visible result in ~15 min; infected gill detectable to ~1:50 dilution; lower sensitivity than PCR	Sithigorngul <i>et al.</i> (2006)
WSSV	AuNP-enhanced immunodot blot	~1 ng mL ⁻¹ purified WSSV; improved signal detection but multistep	Thiruppathiraja <i>et al.</i> (2011)
WSSV + YHV	Dual colloidal-Au lateral-flow strip	~15 min; rapid multiplex screening; lower sensitivity than PCR/RT-PCR	Sithigorngul <i>et al.</i> (2011)
WSSV	LAMP with DNA-functionalised AuNPs	~2 × 10 ² plasmid copies; sensitive visual molecular detection	Seetang-Nun <i>et al.</i> (2013)
WSSV	Antibody-based AuNP lateral-flow assay	~20 min; detection limit ~10 ³ viral copies; evaluated with 75 suspected field samples	Kulabhusan <i>et al.</i> (2017a)
WSSV	Peptide–AuNP lateral-flow assay	~20 min; evaluated with 118 suspected field samples	Kulabhusan <i>et al.</i> (2017b)
<i>V. parahaemolyticus</i>	AuNP-modified electrochemical DNA biosensor	Detection limit 2.16 pM; portable proof-of-concept, not <i>pirA/pirB</i> -specific	Nordin <i>et al.</i> (2017)

Across the reviewed studies, methodological reporting was variable. Several direct in vivo studies used replicated experimental designs and clearly defined controls; for example, Asaikkutti *et al.* (2023) used triplicate groups and characterised particle size, zeta potential and encapsulation efficiency. However, comparator design was not consistently complete. Some nanoencapsulation studies included unloaded-carrier controls but lacked equivalent-dose free-active treatments, limiting attribution of any advantage specifically to nanoencapsulation. Abdi *et al.* (2026), for example, included free quercetin and unloaded chitosan nanoparticles, but the free and encapsulated treatments were not matched for actual quercetin dose. Physicochemical characterisation was also generally performed on the prepared formulation, whereas information on particle behaviour after incorporation into feed or exposure to saline culture conditions was comparatively limited. These differences in replication, comparator structure, dose reporting and formulation characterisation were considered when interpreting the strength of individual findings.

8.2 Feed delivery, scalability and commercial validation

Dietary delivery is the most practical administration route for large-scale shrimp production and has been used for nano-minerals, phytochemicals, recombinant proteins, dsRNA carriers and metallic nanoparticles (Taju *et al.* 2018; Ghaffarizadeh *et al.* 2022; Jonjaroen *et al.* 2024; Maldonado-Muñiz *et al.* 2025).

However, feed-based application requires adequate stability during manufacture and storage, retention after immersion and consistent delivery of the active component. Experimental studies have incorporated nanoformulations into shrimp diets either by surface spraying or coating of finished pellets, or by direct mixing with feed ingredients followed by laboratory pelleting (Bhoopathy *et al.* 2020, 2021; Ghaffarizadeh *et al.* 2022; Fath El-Bab *et al.* 2024). Commercial evaluation should therefore assess particle characteristics and active-compound retention in the finished feed rather than only in freshly prepared formulations.

A major translational limitation is the scarcity of farm-scale validation. Most studies have been conducted

under controlled tank conditions, whereas commercial ponds introduce greater variation in environmental conditions, microbial communities, feeding and pathogen pressure (Fajardo *et al.* 2022). Promising formulations therefore require replicated pilot and pond-scale trials before commercial adoption.

Economic feasibility is equally important. Biological benefits must offset the additional costs of nanoparticle synthesis, encapsulation, feed incorporation and quality control. Although dietary curcumin nanoemulsion has shown experimental economic benefits, these estimates do not fully represent commercial production costs (Fath El-Bab *et al.* 2024), while dsRNA-based systems may face additional manufacturing and scalability constraints (Jonjaroen *et al.* 2024).

Overall, commercial adoption will depend on demonstrating a reproducible advantage over conventional alternatives, reliable feed delivery, acceptable safety and favourable economics under realistic farming conditions. At present, most nano-enabled formulations remain experimental rather than established components of routine shrimp production.

9 | CONCLUSIONS

Current evidence demonstrates that nano-enabled approaches can improve selected nutritional, physiological and disease-related outcomes in shrimp and can support targeted delivery and rapid pathogen detection. However, their performance is formulation and exposure-dependent and the available evidence does not establish that nanoformulations are inherently superior to conventional approaches.

Major research gaps remain before nano-enabled technologies can be translated into routine shrimp aquaculture. Many studies lack dose-matched conventional or free-active comparators, making it difficult to determine whether observed benefits arise specifically from nanoformulation. Inconsistent reporting of active dose and physicochemical characteristics further limits comparison among studies. Long-term information on edible-tissue residues, depuration, environmental fate and non-target effects is also scarce, while most efficacy studies remain restricted to controlled laboratory conditions with limited farm-scale validation. In diagnostics, further development and validation are particularly needed for AHPND and EHP-specific nano-enabled platforms.

Future research should therefore prioritise standardised formulation characterisation and dose reporting, appropriate comparator groups and independent replication, long-term animal and environmental safety assessment, pathogen-specific diagnostic validation and replicated commercial-pond trials that include economic feasibility. Until these requirements are addressed, nano-enabled formulations should be considered application-

specific experimental tools rather than established components of routine shrimp production.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

AUTHORS' CONTRIBUTION

Porselvan S and Saravanan S: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. Kaviarasu D, Selvaraj S, Sudhan C and Senthil Kumar E: Supervision, Validation, Writing – review & editing. Navin Kumar D and Dhinesh P: Writing – review & editing. All authors read and approved the final manuscript.

AI-USE STATEMENT

Generative artificial intelligence tools, including ChatGPT, were used during manuscript development for language editing, organisation, drafting assistance and the creation of graphical illustrations. All AI-assisted content, including figures, was reviewed, modified where necessary and verified by the authors. All scientific statements, interpretations, citations and references were independently checked and approved by the authors, who take full responsibility for the final manuscript.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article because no new datasets were generated or analysed during the preparation of this review.

REFERENCES

- Abdi V, Ghasemi Z, Sourinejad I, Johari SA (2026) [Protective effect of quercetin encapsulated in chitosan nanoparticles against silver nanoparticle-induced toxicity in Pacific white shrimp \(*Penaeus vannamei*\)](#). Scientific Reports.
- Acedo-Valdez MR, Grijalva-Chon JM, Larios-Rodríguez E, Maldonado-Arce AD, Mendoza-Cano F, ... Castro-Longoria R (2017) [Antibacterial effect of biosynthesized silver nanoparticles in Pacific white shrimp *Litopenaeus vannamei* \(Boone\) infected with necrotizing hepatopancreatitis bacterium \(NHP-B\)](#). Latin American Journal of Aquatic Research 45(2): 421–430.
- Asaikkutti A, Vimala K, Jha N, Saravana Bhavan P, Arul V (2023) [Effect of dietary supplementation of vitamin C-loaded chitosan nanoparticles on growth, immune-physiological parameters, and resistance of white shrimp *Litopenaeus vannamei* to *Vibrio harveyi* challenge](#). Animal Feed Science and Technology 305: 115764.
- Ashour M, Mabrouk MM, Mansour AIA, Naiel MAE, Mansour AT, ... Abdelhamid AF (2025) [Seaweed \(*Pterocladia capillacea*\) nanoparticles improves](#)

- growth performances, digestive enzymes, antioxidant activities, innate immunity, and related-immunity gene expressions of *Litopenaeus vannamei*. *Frontiers in Marine Science* 12: 1600260.
- Bahabadi MN, Delavar FH, Mirbakhsh M, Niknam K, Johari SA (2017) Assessment of antibacterial activity of two different sizes of colloidal silver nanoparticle (cAgNPs) against *Vibrio harveyi* isolated from shrimp *Litopenaeus vannamei*. *Aquaculture International* 25: 463–472.
- Bhoopathy S, Inbakandan D, Rajendran T, Chandrasekaran K, Kasilingam R, Gopal D (2020) Curcumin-loaded chitosan nanoparticles fortify shrimp feed pellets with enhanced antioxidant activity. *Materials Science and Engineering C* 117: 111737.
- Bhoopathy S, Inbakandan D, Rajendran T, Chandrasekaran K, Prabha BS, ... Dharani G (2021) Dietary supplementation of curcumin-loaded chitosan nanoparticles stimulates immune response in the white leg shrimp *Litopenaeus vannamei* challenged with *Vibrio harveyi*. *Fish and Shellfish Immunology* 117: 188–191.
- Camacho-Jiménez L, Álvarez-Sánchez AR, Mejía-Ruiz CH (2020) Silver nanoparticles as antimicrobials in marine shrimp farming: a review. *Aquaculture Reports* 18: 100512.
- Campa-Córdova AI, Hernández-Saavedra NY, Ascencio F (2002) Superoxide dismutase as modulator of immune function in American white shrimp (*Litopenaeus vannamei*). *Comparative Biochemistry and Physiology Part C* 133(4): 557–565.
- Chávez-Sánchez MC, Abad-Rosales S, Lozano-Olvera R, Montoya-Rodríguez L, Franco-Nava MA, ... Bogdanchikova N (2021) Silver nanoparticles induce histopathological alterations in juvenile *Penaeus vannamei*. *Environmental Science and Pollution Research* 28(7): 8224–8234.
- Chiu CH, Guu YK, Liu CH, Pan TM, Cheng W (2007) Immune responses and gene expression in white shrimp, *Litopenaeus vannamei*, induced by *Lactobacillus plantarum*. *Fish and Shellfish Immunology* 23: 364–377.
- Cordeiro L, Müller L, Gelesky MA, Wasielesky W, Fattorini D, ... Ventura-Lima J (2016) Evaluation of coexposure to inorganic arsenic and titanium dioxide nanoparticles in the marine shrimp *Litopenaeus vannamei*. *Environmental Science and Pollution Research* 23(2): 1214–1223.
- Dechamma MM, Rajeish M, Maiti B, Mani MK, Karunasagar I (2015) Expression of Toll-like receptors (TLR) in lymphoid organ of black tiger shrimp (*Penaeus monodon*) in response to *Vibrio harveyi* infection. *Aquaculture Reports* 1: 1–4.
- Eissa ESH, El-Haroun E, Abdel-Warith AA, Younis EM, Davies SJ, ... Ahmed HO (2024) Effects of dietary curcumin nanoparticles (C-NPS) on growth performance, digestive enzyme activities, antioxidant status and immunity responses for enhancing the intestinal mucosa of white-leg shrimp (*Litopenaeus vannamei*) challenged by *Fusarium solani*. *Annals of Animal Science* 25(2): 747–757.
- Eissa ESH, Salama WM, Elbahnaswy S, El-Son MAM, Eldin ZE, ... Rizk EST (2025b) Pumpkin seed oil-loaded chitosan nanoparticles enhance growth, digestive enzymes, and immune response in whiteleg shrimp *Litopenaeus vannamei*: impacts on histopathology and survival against *Vibrio parahaemolyticus*. *Aquaculture Reports* 40: 102599.
- Eissa MEH, Hendam BM, ElBanna NI, Aly SM (2025a) Bee venom-loaded chitosan nanoparticles enhances growth, immunity and resistance to *Vibrio parahaemolyticus* in Pacific white shrimp. *Scientific Reports* 15(1): 26179.
- Fajardo C, Martinez-Rodriguez G, Blasco J, Mancera JM, Thomas B, De Donato M (2022) Nanotechnology in aquaculture: applications, perspectives and regulatory challenges. *Aquaculture and Fisheries* 7(2): 185–200.
- Fath El-Bab AF, El-Ratel IT, Abdel-Warith AA, Younis EM, Davies SJ, El-Raghi AA (2024) Investigating the impact of nanoemulsion of curcumin-loaded olive oil on growth performance, feed utilization, immunological responses, and redox status of *Litopenaeus vannamei* shrimp with emphasis on economic efficiency of supplementation. *Journal of Animal Physiology and Animal Nutrition* 108(6): 1877–1889.
- Ghaffarizadeh A, Sotoudeh E, Mozanzadeh MT, Sanati AM, Ghasemi A (2022) Supplementing dietary selenium nanoparticles increased growth, antioxidant capacity and immune-related genes transcription in Pacific whiteleg shrimp (*Penaeus vannamei*) juveniles. *Aquaculture Reports* 25(4): 101215.
- Hassona NN, Khan N, Alenize M, Tayel A, Elhussein S, ... Dai X (2026) Dietary nutgrass (*Cyperus rotundus*) extract-loaded chitosan nanoparticles: enhance growth performance, boost immune responses, improve antioxidant capacity, and physiological performance in white leg shrimp (*Litopenaeus vannamei*). *Journal of the World Aquaculture Society* 57: e70122.
- Jonjaroen V, Charoonnart P, Jitrakorn S, Payongsri P, Surarit R, ... Niamsiri N (2024) Nanoparticles-based double-stranded RNA delivery as an antiviral agent in shrimp aquaculture. *Reviews in Aquaculture* 16: 1647–1673.
- Juárez-Moreno K, Mejía-Ruiz CH, Díaz F, Reyna-Verdugo H, Re AD, ... Bogdanchikova N (2017) Effect of silver nanoparticles on the metabolic rate, hematological response, and survival of juvenile white shrimp *Litopenaeus vannamei*. *Chemosphere* 169: 716–724.

- Kamble MT, Soowannayan C, Chaicherd S, Medhe SV, Rudtanatip T, ... Wongprasert K (2024) [Bimetallic nanoparticles with sulfated galactan eliminate *Vibrio parahaemolyticus* in shrimp *Penaeus vannamei*](#). Fish and Shellfish Immunology 151: 109753.
- Kulabhusan PK, Rajwade JM, Sahul Hameed AS, Paknikar KM (2017b) [Lateral flow assay for rapid detection of white spot syndrome virus \(WSSV\) using a phage-displayed peptide as bio-recognition probe](#). Applied Microbiology and Biotechnology 101(11): 4459–4469.
- Kulabhusan PK, Rajwade JM, Sugumar V, Taju G, Sahul Hameed AS, Paknikar KM (2017a) [Field-usable lateral flow immunoassay for the rapid detection of white spot syndrome virus \(WSSV\)](#). PLoS ONE 12(1): e0169012.
- Lam PH, Le MT, Dang DMT, Doan TCD, Tu NPC, Dang CM (2020) Safe concentration of silver nanoparticles in solution for white leg shrimp (*Litopenaeus vannamei*) farming. Biological and Chemical Research 7: 35–45.
- León-Valdez G, Valenzuela-Quirón W, Álvarez-Ruiz P, Soto-Robles CA, Nava-Perez E, ... Montoya-Mejía M (2024) [The extract of *Larrea tridentata* promotes the synthesis of silver nanoparticles and stimulates immune responses in *Penaeus vannamei* against *Vibrio* spp. causing acute hepatopancreatic necrosis disease](#). Microorganisms 12(11): 2219.
- Maldonado-Muñiz M, Nieto-López MG, Tapia-Salazar M, Gómez-Gil B, Guerrero A, ... Soto-Rodríguez SA (2025) [Dietary silver nanoparticle effects on *Penaeus vannamei* growth, histopathology, faecal microbiome, and acute hepatopancreatic necrosis disease survival](#). Diseases of Aquatic Organisms 162: 35–49.
- Mustafa FHA, Hassan SAH, Ashary OA, Abbas EM, Ragaza JA, ... Zaghloul EH (2025) The use of synthesized stabilized nanoparticles of selenium as a feed additive in shrimp *Litopenaeus vannamei* diets: performance, antibacterial activity, gut microbiota and immune-related genes expression. Aquaculture Reports 44: 103046.
- Nordin N, Yusof NA, Abdullah J, Radu S, Hushiaran R (2017) [A simple, portable, electrochemical biosensor to screen shellfish for *Vibrio parahaemolyticus*](#). AMB Express 7: 41.
- Ochoa-Meza AR, Álvarez-Sánchez AR, Romo-Quirón CR, Barraza A, Magallón-Barajas FJ, ... Mejía-Ruiz CH (2019) [Silver nanoparticles enhance survival of white spot syndrome virus-infected *Penaeus vannamei* shrimp by activation of its immunological system](#). Fish and Shellfish Immunology 84: 1083–1089.
- Ríos-Ortiz A, Barragán-Longoria MF, Magallón-Gayón E, Chavez-Santoscoy RA, Manriquez-Patiño A, ... Viana MT (2026) [Integrative transcriptomic and physiological assessment of nanoencapsulated carvacrol and thymol oil as an antioxidant in thermal-stressed white shrimp \(*Litopenaeus vannamei*\)](#). Veterinary Research Communications 50(2): 126.
- Romo Quiñonez CR, Alvarez-Ruiz P, Mejía-Ruiz CH, Bogdanchikova N, Pestryakov A, ... Nava Pérez E (2022) [Chronic toxicity of shrimp feed added with silver nanoparticles \(Argovit-4R\) in *Litopenaeus vannamei* and immune response to white spot syndrome virus infection](#). PeerJ 10: e14231.
- Romo-Quirón CR, Álvarez-Sánchez AR, Álvarez-Ruiz P, Chávez-Sánchez MC, Bogdanchikova N, ... Mejía-Ruiz CH (2020) [Evaluation of a new Argovit as an antiviral agent included in feed to protect the shrimp *Litopenaeus vannamei* against white spot syndrome virus infection](#). PeerJ 8: e8446.
- Seetang-Nun Y, Jaroenram W, Sriurairatana S, Suebsing R, Kiatpathomchai W (2013) [Visual detection of white spot syndrome virus using DNA-functionalized gold nanoparticles as probes combined with loop-mediated isothermal amplification](#). Molecular and Cellular Probes 27(2): 71–79.
- Seethalakshmi PS, Rajeev R, Kiran GS, Selvin J (2021) [Shrimp disease management for sustainable aquaculture: innovations from nanotechnology and biotechnology](#). Aquaculture International 29(4): 1591–1620.
- Shah BR, Mraz J (2020) [Advances in nanotechnology for sustainable aquaculture and fisheries](#). Reviews in Aquaculture 12: 925–942.
- Sharawy ZZ, Ashour M, Labena A, Alsaqufi AS, Mansour AT, Abbas EM (2022) [Effects of dietary *Arthrospira platensis* nanoparticles on growth performance, feed utilization, and growth-related gene expression of Pacific white shrimp *Litopenaeus vannamei*](#). Aquaculture 551: 737905.
- Sithigorngul P, Rukpratanporn S, Chaivisuthangkura P, Sridulyakul P, Longyant S (2011) [Simultaneous and rapid detection of white spot syndrome virus and yellow head virus infection in shrimp with a dual immunochromatographic strip test](#). Journal of Virological Methods 173(1): 85–91.
- Sithigorngul W, Rukpratanporn S, Pecharaburanin N, Longyant S, Chaivisuthangkura P, Sithigorngul P (2006) [A simple and rapid immunochromatographic test strip for detection of white spot syndrome virus \(WSSV\) of shrimp](#). Diseases of Aquatic Organisms 72: 101–106.
- Suharyadi, Yanuhar U, Widodo MS, Faqih AR, Suryanto H, Caesar NR (2025) [Study of the toxicity of Fe₃O₄ nanoparticles on Pacific whiteleg shrimp \(*Litopenaeus vannamei*\) and the antibacterial efficacy against *Vibrio harveyi*](#). Journal of Hazardous Materials Advances 18: 100674.
- Taju G, Kumar DV, Majeed SA, Vimal S, Tamizhvanan S, ... Sahul Hameed AS (2018) [Delivery of viral recombi-](#)

nant VP28 protein using chitosan tripolyphosphate nanoparticles to protect the whiteleg shrimp *Litopenaeus vannamei* from white spot syndrome virus infection. International Journal of Biological Macromolecules 107: 1131–1141.

Tello-Olea M, Rosales-Mendoza S, Campa-Córdova AI, Palestino G, Luna-González A, ... Angulo C (2019) Gold nanoparticles (AuNP) exert immunostimulatory and protective effects in shrimp *Litopenaeus vannamei* against *Vibrio parahaemolyticus*. Fish and Shellfish Immunology 84: 756–767.

Thiruppathiraja C, Kumar S, Murugan V, Adaikkappan P, Sankaran K, Alagar M (2011) An enhanced immunodot blot assay for the detection of white spot syndrome virus in shrimp using antibody-conjugated gold nanoparticle probe. Aquaculture 318: 262–267.

Yu Q, Xia C, Han F, Xu C, Rombenso A, ... Li E (2022) Effect of different dietary selenium sources on growth performance, antioxidant capacity, gut microbiota, and molecular responses in Pacific white shrimp *Litopenaeus vannamei*. Aquaculture Nutrition 2022: 5738008.



Porselvan S.  <https://orcid.org/0009-0004-6541-8042>

Saravanan S.  <https://orcid.org/0000-0001-5987-937X>

Kaviarasu D.  <https://orcid.org/0000-0001-6101-2740>

Selvaraj S.  <https://orcid.org/0009-0001-6849-0494>

Sudhan C.  <https://orcid.org/0000-0002-4680-1677>

Senthil Kumar E.  <https://orcid.org/0000-0002-0067-9928>

Navin Kumar D.  <https://orcid.org/0009-0008-3153-2217>

Dhinesh P.  <https://orcid.org/0000-0003-4075-0968>