Revolutionising Shrimp Disease Management: Sustainable Solutions from Nanotechnology and Biotechnology

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Abstract

Shrimp aquaculture plays a critical role in meeting the rising global demand for seafood, yet it faces persistent challenges from infectious diseases and the growing threat of antimicrobial resistance. Conventional reliance on antibiotics has led to resistant pathogens, posing risks to shrimp health, ecosystems, and human consumers. This article explores sustainable disease management strategies rooted in nanotechnology and biotechnology. Nanoparticles offer innovative applications in vaccine delivery, disease diagnostics, antimicrobial treatments, and biofilm inhibition. Concurrently, biotechnological tools—including phytobiotics, probiotics, prebiotics, and synbiotics—enhance shrimp immunity and disease resistance through environmentally safe mechanisms. By integrating these advanced approaches, the aquaculture industry can shift towards more sustainable, efficient, and resilient shrimp farming systems.

Introduction

Shrimp aquaculture involves breeding, rearing, and harvesting shrimp in controlled environments to meet growing global demand for seafood (FAO 2019). As populations rise, aquaculture plays a crucial role in ensuring sustainable shrimp production while reducing overfishing pressures on marine ecosystems. However, farming shrimp in artificial environments exposes them to various pathogens and unfavourable conditions such as pH fluctuations, temperature changes, and poor water quality, leading to weakened immunity and mass mortalities. Exporting farmed shrimp has contributed to disease outbreaks in aquaculture industries, which pose risks not only to shrimp but also to wild aquatic species and human health. Antibiotics were initially effective in disease prevention, but the emergence of antibiotic-resistant bacteria has made infections harder to control, with resistant genes potentially spreading to nearby ecosystems and human pathogens. To address this challenge, researchers are exploring environmentally friendly alternatives, such as algal extracts, phytobiotics, phages, biofilm-based vaccines, probiotics, and synbiotics, as sustainable solutions for disease prevention in shrimp aquaculture.

Infectious diseases and antimicrobial resistance

Shrimp aquaculture faces significant challenges due to bacterial, viral, protozoan, and fungal infections, leading to substantial economic losses. Acute hepatopancreatic necrosis disease (AHPND), caused by *Vibrio* species, is a major threat, alongside *White Spot Syndrome Virus (WSSV)* and *Infectious Myonecrosis Virus (IMNV)*. Shrimp larvae are also vulnerable to fungal infections like *Saprolegnia parasitica* and *Achlya flagellate*, while *Enterocytozoon hepatopenaei (EHP)* slows growth and contributes to white feces syndrome.

Antibiotic resistance is an alarming issue in shrimp farming due to indiscriminate antibiotic use, often based on farmer knowledge rather than veterinary guidance. Resistant *Vibrio* strains and food-borne pathogens like *Salmonella* and *Bacillus* species have been detected in farmed shrimp, posing food safety risks. The release of antibiotics into marine ecosystems promotes resistance, and plasmids and integrons further accelerate the spread of resistance genes. With climate change increasing the likelihood of antibiotic-resistant pathogens, the aquaculture industry must adopt sustainable disease management strategies to reduce dependency on antibiotics, ensuring the health of shrimp populations, marine ecosystems, and human consumers.

Nanomaterials and their versatile applications

Nanoparticles, ranging in size from 1 to 100 nm, possess unique properties due to their small scale. Metallic salts undergo reduction with the aid of reducing agents to form nanoparticles, while polymeric nanoparticles are synthesised through the polymerisation of monomers using various techniques. In the biological field, nanotechnology plays a crucial role in advancing drug delivery systems, bio-imaging, and gene delivery. Additionally, it has significant applications in aquaculture, serving as carriers for vaccine delivery, diagnostic tools, antimicrobial agents, and anti-biofilm treatments.

1. Vaccine delivery

Vaccination in aquaculture enhances immunity against infections, with oral DNA vaccines for shrimp utilising carriers like PLGA and chitosan due to their biodegradable and non-toxic properties. Chitosan-based nanoparticles have shown promise in boosting immunity, such as pVp28 for WSSV protection in *P. monodon* and ompK gene delivery against *V. parahemolyticus* in *Acanthopagrus schlegelii*, though its efficacy in shrimp remains uncertain. Liposome-based vaccines, resembling cell membranes, offer better antigen protection and delivery, with recombinant VP28 yielding 78.9% survival in *Marsupenaeus japonicus*. Despite limited progress in spike protein-based nanoparticles and other advanced methods, these technologies could revolutionize mass vaccination in aquaculture without requiring injections.

2. Diagnostic tools

Gold nanoparticles play a crucial role in diagnosing shrimp diseases caused by viruses, bacteria, and protozoa. Loop-mediated isothermal amplification (LAMP) enables efficient DNA amplification even in the presence of undesirable fragments, though it lacks a hybridization step for DNA structural analysis. Gold nanoparticles, bound to alkyl thiol-terminated oligonucleotides, remain stable in saline conditions and can hybridize with complementary DNA strands. Their surface plasmon resonance changes with particle clustering, causing a visible colour shift, aiding naked-eye detection without PCR or gel electrophoresis.

3. Antimicrobial agents

Nanoparticles are widely used as antimicrobial agents in medicine, food, and agriculture, particularly in shrimp aquaculture. They can be added to shrimp feed or rearing water, enhancing survival and growth. Silver nanoparticles (AgNPs), immobilized in water filters, have shown strong antimicrobial effects, while gold nanoparticles (AuNPs) have demonstrated immunostimulatory properties without toxicity. AgNPs are the most studied and frequently used, proving effective against various pathogens while exhibiting minimal toxicity in shrimp. Green-synthesised AgNPs from plant extracts have enhanced shrimp survival and immune responses against infections. Polymer-based nanoparticles, such as chitosan, offer a biodegradable alternative, improving immunity and enabling sustained drug release, presenting new possibilities for disease management in aquaculture.

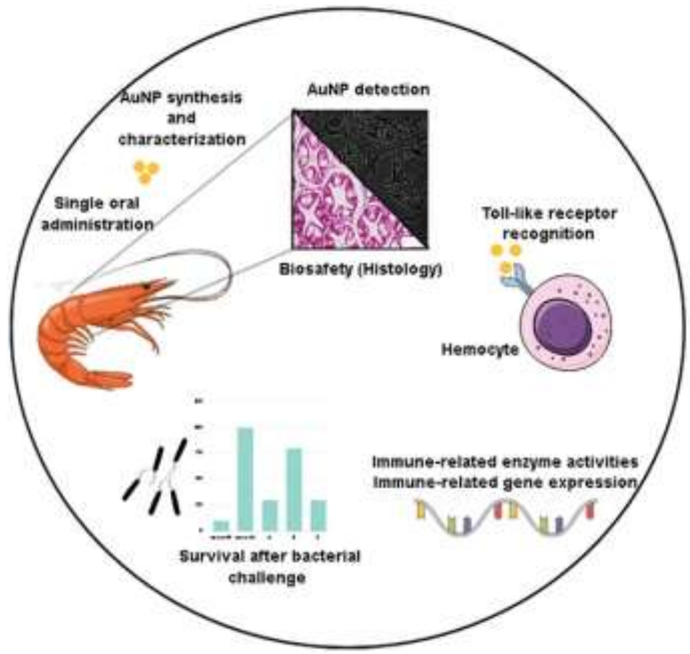

Fig 1. Gold nanoparticles (AuNP) exert immunostimulatory and protective effects in shrimp (*Litopenaeus vannamei*) against *Vibrio parahaemolyticus* (Tello-Olea *et al*., 2019)

4. Anti-biofilm agents

Quorum sensing in bacteria regulates virulence and biofilm formation, posing challenges in aquaculture. Pathogens like *Vibrio* species rely on this mechanism, making biofilm infections persistent and resistant to antibiotics. Silver and copper nanoparticles have shown promise in inhibiting biofilm formation by reducing extracellular polysaccharide production and motility without affecting bacterial growth. However, studies have primarily been conducted in vitro, and concerns remain regarding nanoparticle toxicity, long-term antimicrobial resistance, and human safety in shrimp consumption. Green synthesis of nanomaterials offers a safer alternative, but further research is needed for successful application in aquaculture.

Phytobiotics for shrimp disease management

Phytobiotics are plant-derived extracts containing bioactive compounds such as phenolics, tannins, flavonoids, and essential oils, known for their antimicrobial and immunomodulatory properties. Unlike synthetic antibiotics, they are less likely to cause resistance in pathogens due to the diverse molecules they contain, making them a cost-effective and environmentally friendly alternative. The oral administration of phytobiotics is widely adopted for its ease and effectiveness.

1. Phytobiotics as an immunomodulating agent

Plant-derived substances show promise as natural immunostimulants in shrimp farming, offering an alternative to synthetic antibiotics for disease management. Various compounds, such as *Eleutherine bulbosa* powder, *Theobroma cacao* pod husks, and α-Phellandrene, have been found to enhance immune gene expression and restrict infections caused by *Vibrio* species. These findings highlight the potential of leveraging plant-based solutions to improve shrimp immunity, thereby promoting sustainable aquaculture practices.

2. Phytobiotics as antimicrobial agents

Phytobiotics play a crucial role in shrimp aquaculture by enhancing disease resistance and improving survival rates. Plant extracts like *Cynodon dactylon* and *Olea europaea* have demonstrated antiviral properties against WSSV, while Sonneratia alba effectively prevents *Vibrio harveyi* infections. Additionally, natural feed additives such as ascorbic acid, Phytocee™, chitosan, and herbal mixtures—including ginger, lemon juice, and garlic—are widely used in South India to strengthen shrimp immunity and combat *Enterocytozoon hepatopenaei* infections. These findings underscore the potential of plant-based solutions in sustainable shrimp health management.

Probiotics, prebiotics, and synbiotics to combat infectious agents

Probiotic bacteria play a crucial role in shrimp health by enhancing immune responses and preventing infections. Certain probiotics, such as *M146*, have been shown to reduce shrimp mortality by downregulating the *IMD* and *Toll* signaling pathways, while others, like *W1B*, function as antimicrobial agents without immunostimulatory effects. Studies have highlighted *Bacillus cereus* as a promising probiotic, demonstrating improved lysozyme activity and haemocyte count in shrimp reared in earthen ponds. Additionally, probiotics can act as prophylactic agents similar to vaccines by triggering immune responses.

Probiotics also prevent pathogens from colonizing shrimp intestines by competing for space and nutrients. For example, feeding shrimp with *B. cereus* led to extensive colonization, significantly reducing populations of *Vibrio alginolyticus* and *V. parahaemolyticus*. Other probiotic formulations, including freeze-dried *Bacillus* consortia and strains like *B. subtilis* and *Shewanella algae*, have been effective in reducing *Vibrio* loads. Probiotics can also be sourced from the shrimp intestine itself, with strains like *Pseudoalteromonas sp.* showing potential in controlling Acute Hepatopancreatic Necrosis Disease (AHPND).

Beyond direct pathogen control, probiotics help modulate shrimp gut microbiota, providing protection against microbial infections. Certain probiotic-enriched diets have been linked to enhanced antimicrobial responses, stimulating beneficial bacterial populations that aid in pathogen resistance. Prebiotic supplements further contribute by favoring beneficial microbial growth, improving immune parameters such as haemocyte respiratory burst and enhancing shrimp survival rates against bacterial exposure.

Synbiotics—a combination of probiotics and prebiotics—have gained attention for their effectiveness in controlling infectious diseases in shrimp farming. Specific synbiotic diets have been shown to boost immune resistance, reducing *Vibrio* populations and increasing colonization of beneficial bacteria like *Lactobacillus plantarum*. Synbiotics have demonstrated superior immune-stimulating effects compared to probiotics or prebiotics alone, making them promising candidates for disease prevention in shrimp hatcheries.

However, prolonged use of probiotics may lead to immunosuppression, highlighting the need for balanced application alongside other environmental management strategies, such as pond bottom soil improvement. Probiotics derived from marine ecosystems tend to be more effective in aquatic species, though challenges remain in culturing these organisms in vitro. While most research has focused on bacterial and viral infections, future studies could explore probiotic-based solutions for fungal infections, broadening their application in shrimp aquaculture.

Conclusion

Shrimp aquaculture, while vital for global seafood supply, is increasingly challenged by infectious diseases and antibiotic resistance. Traditional antibiotic-based treatments are no longer sustainable, prompting the need for innovative, eco-friendly alternatives. Nanotechnology offers promising solutions through advanced vaccine delivery, diagnostic tools, and antimicrobial and anti-biofilm agents. Similarly, biotechnology-based approaches—such as phytobiotics, probiotics, prebiotics, and synbiotics—have demonstrated significant potential in enhancing shrimp immunity, reducing pathogen loads, and promoting sustainable farming practices. Integrating these advanced tools with effective pond management can lead to resilient aquaculture systems that safeguard shrimp health, protect ecosystems, and ensure food safety. Continued interdisciplinary research and field-level application will be key to realising the full potential of these technologies in transforming shrimp disease management.

References

FAO (2019) FAO yearbook. In: Fishery and Aquaculture Statistics 2017

Tello-Olea, M., Rosales-Mendoza, S., Campa-Córdova, A. I., Palestino, G., Luna-González, A., Reyes-Becerril, M., ... & Angulo, C. (2019). Gold nanoparticles (AuNP) exert immunostimulatory and protective effects in shrimp (Litopenaeus vannamei) against Vibrio parahaemolyticus. *Fish & shellfish immunology*, *84*, 756-767.

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