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Algae and nano-enabled feed strategies for Pacific white shrimp (*Litopenaeus vannamei*): nutritional enhancement, gut microbiome modulation and sustainable aquaculture

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Abstract
The search for sustainable and functionally effective aquafeeds has increased interest in algal ingredients and nanotechnology-based feed formulations for shrimp aquaculture. Algae provide valuable nutrients and bioactive compounds, while nano-enabled technologies offer potential approaches to improve their stability, dispersion and delivery. This review examines the nutritional and functional applications of algae and nano-enabled feed strategies in Pacific white shrimp (*Litopenaeus vannamei*), with particular emphasis on growth performance, physiological responses, gut microbiome modulation and sustainability. A structured literature search covering publications from 2010 to 2025 was conducted using Google Scholar, PubMed, OpenAlex, Crossref and other scholarly sources. A total of 250 publications were screened, and 16 peer-reviewed research articles were selected for detailed review following eligibility assessment. The selected literature was synthesised qualitatively, distinguishing conventional algal supplementation, nano-sized algal biomass and nano-enabled delivery of bioactive compounds. Available findings indicate that algal ingredients and selected nano-sized algal formulations can improve growth performance, feed utilisation, antioxidant capacity and immune responses in *L. vannamei*. Conventional algal supplementation has also been associated with changes in intestinal microbial communities. However, direct evidence demonstrating that nano-enabled algal formulations improve nutrient bioavailability or specifically modulate gut microbiome functionality remains limited. Further comparative feeding trials, microbiome-based investigations and biosafety assessments are required to establish their mechanisms of action, environmental implications and commercial feasibility. Integrating algal nutrition with appropriately validated nanotechnology may offer a promising direction for developing sustainable and functionally improved shrimp feeds.

Keywords: Algae, Nano-enabled feeds, *Litopenaeus vannamei*, Nutritional enhancement, Gut microbiome, Nanotechnology, Sustainable aquaculture

1. Introduction

The sustainability and long-term productivity of shrimp aquaculture remain closely associated with the availability, nutritional quality and efficient utilization of formulated feeds. Fishmeal has traditionally served as an important protein ingredient in shrimp diets because of its favourable amino acid profile, digestibility and palatability. Nevertheless, fluctuations in fishmeal availability, increasing ingredient costs and concerns regarding the ecological sustainability of marine resources have encouraged the investigation of alternative protein and functional feed ingredients (Chen *et al.*, 2024) [1].

Experimental investigations have demonstrated that dietary incorporation of different macroalgal species can influence growth performance, nutrient digestibility, antioxidant status and immune responses in *L. vannamei*. Niu *et al.* (2019) [2], for instance, evaluated four macroalgal species and reported differences in growth performance, antioxidant responses, immune-related gene expression and intestinal microbial composition. Similarly, Abbas *et al.* (2023) [3] investigated polysaccharides extracted from *Sargassum dentifolium* and demonstrated improvements in selected growth, survival, microbial abundance and immune-related responses. More recently, Lin *et al.* (2024) [4] demonstrated that supplementation with *Haematococcus pluvialis* influenced growth performance, innate immunity and gut bacterial communities under different temperature conditions.

The intestinal microbiome contributes to nutrient metabolism, digestive processes, intestinal homeostasis and immune regulation (Holt *et al.*, 2021; Zeng *et al.*, 2024) [5, 6]. Niu *et al.* (2019) [2] observed dietary macroalgae-associated changes in the intestinal bacterial community of *L. vannamei.* Similarly, Abbas *et al.* (2023) [3] reported changes in intestinal and water microbial abundance following dietary supplementation

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with seaweed-derived polysaccharides. Lin *et al.* (2024) [4] further investigated the relationship between *H. pluvialis* supplementation, temperature conditions and gut bacterial community characteristics. Nanoencapsulation and other nano-enabled delivery systems may offer opportunities for protecting sensitive compounds, improving dispersion, controlling release characteristics and modifying the bioaccessibility of specific feed constituents (Ahmed *et al.*, 2023; Shah *et al.*, 2020) [7, 8].

Sharawy *et al.* (2022) [9] demonstrated that dietary supplementation with *Arthrospira platensis* nanoparticles improved growth indices, feed utilization and growth-related gene expression in *L. vannamei*. Abdel-Warith *et al.* (2020) [10] investigated the combined dietary application of *Spirulina platensis* and chitosan nanoparticles in *Penaeus monodon*. More recently, Ashour *et al.* (2025) [11] evaluated nanoparticles prepared from the red seaweed *Pterocladia capillacea* in L. vannamei.

The environmental and economic implications of algae-integrated nano-enabled feeds warrant critical consideration before their wider adoption in commercial shrimp farming (Shah *et al.*, 2020) [8]. Hernández-Sain *et al.* (2025) [12] examined the nutraceutical and functional applications of seaweed in shrimp aquaculture, including the potential contribution of nanotechnology. Building upon this research, the present review seeks to integrate algal nutritional functionality, nano-enabled delivery approaches and gut microbiome responses in *L. vannamei*.

2. Materials and Methods

This review adopted a structured literature search to examine the nutritional, physiological, gut microbiome and sustainability aspects of algae-integrated nanofeeds in *Litopenaeus vannamei*. Relevant publications published between January 2010 and December 2025 were identified through Google Scholar, PubMed, OpenAlex, Crossref and other freely accessible scholarly sources. Publish or Perish software was used to retrieve and organise bibliographic records. Search terms included combinations of "algae", "microalgae", "seaweed", "nanoparticles", "nanoencapsulation", "aquafeed", "gut microbiome" and "*Litopenaeus vannamei*".

A total of 250 publications were screened based on their titles, abstracts and relevance to the review objectives. Following eligibility assessment and final screening, 16 peer-reviewed research articles were selected for detailed review. Studies addressing algal nutritional properties, nano-enabled feed technologies, shrimp growth, physiological responses, intestinal microbiota and biosafety were considered. Relevant findings were extracted and synthesised qualitatively, distinguishing conventional algal supplementation from nano-sized algal biomass and algal-derived compounds delivered through nanocarriers. The literature selection process was organised in accordance with the PRISMA 2020 framework.

3. Algae as nutritional and functional feed ingredients in shrimp aquaculture

Algae, comprising microalgae and macroalgae, represent promising alternative and functional feed ingredients in aquaculture because of their diverse nutritional composition and bioactive properties. Depending on the species and cultivation conditions, algal biomass contains proteins, essential amino acids, lipids, polyunsaturated fatty acids, vitamins, minerals, pigments and complex polysaccharides. Microalgae such as *Arthrospira platensis*, *Chlorella vulgaris*, *Nannochloropsis* spp. and *Haematococcus pluvialis* are recognised for their nutritional and pigment composition, whereas macroalgae such as *Gracilaria*, *Ulva*, *Sargassum* and *Porphyra* are important sources of structurally diverse polysaccharides and other bioactive compounds (Shah *et al.*, 2020; Chen *et al.*, 2024; Hernández-Sain *et al.*, 2025) [8, 1, 12].

In *Litopenaeus vannamei*, dietary algal supplementation has been investigated for its effects on growth, feed utilisation, antioxidant capacity and immune responses. Niu *et al.* (2019) [2] demonstrated species-dependent effects of four macroalgae on shrimp growth, immune responses and intestinal microbial communities. Similarly, Abbas *et al.* (2023) [3] reported changes in growth performance, microbial abundance and immune-related gene expression following dietary supplementation with *Sargassum dentifolium*-derived polysaccharides. Lin *et al.* (2024) [4] further demonstrated that *Haematococcus pluvialis* supplementation influenced growth performance, innate immunity and gut bacterial communities under different temperature conditions. These findings indicate that algal ingredients may contribute to shrimp performance through nutritional and physiological pathways.

The functional potential of algae is largely associated with compounds such as carotenoids, polyphenols, sulphated polysaccharides and essential fatty acids, which may influence antioxidant activity, immune regulation and intestinal microbial communities. However, their effectiveness depends on species-specific composition, inclusion levels, digestibility and nutrient bioavailability. Differences in cell-wall structure, ash content and processing requirements may also limit the nutritional utilisation of certain algal ingredients (Chen *et al.*, 2024; Hernández-Sain *et al.*, 2025) [1, 12].

Despite their potential, the practical application of algal ingredients requires consideration of production costs, nutritional consistency, processing efficiency and commercial scalability. Furthermore, the susceptibility of certain bioactive compounds to degradation and their limited bioaccessibility provide a rationale for investigating nano-enabled delivery approaches. Such technologies may improve the stability and delivery of selected algal constituents, although their nutritional effectiveness, microbiome-related benefits and environmental safety require independent experimental validation.

4. Nano-enabled feed technologies for algal nutrient delivery

Nanotechnology offers potential approaches to improve the stability, dispersion, protection and delivery of nutrients and bioactive compounds in aquafeeds. In shrimp nutrition, nano-enabled feed systems may be particularly relevant for compounds that are poorly water-soluble, sensitive to oxidation or degradation, or rapidly lost from feed under aquatic conditions. However, the use of nanoparticles in feed should be distinguished from simply reducing algal biomass to a smaller particle size.

Table 1. Major algal resources and their nutritional and functional relevance in shrimp aquaculture

Algal group/species	Important nutritional or bioactive constituents	Potential relevance to shrimp	Sources
Arthrospira platensis (microalga/cyanobacterium)	Protein, phycocyanin and other bioactive compounds	Nutritional supplementation, growth and antioxidant responses	Sharawy *et al.* (2022) [9]
Haematococcus pluvialis (microalga)	Astaxanthin, lipids and other antioxidants	Growth performance, antioxidant and immune responses	Lin *et al.* (2024) [4]
Nannochloropsis spp. (microalgae)	EPA and other lipids	Essential fatty acid supplementation	Shah and Mraz (2020) [8]

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Algal group/species	Important nutritional or bioactive constituents	Potential relevance to shrimp	Sources
Chlorella vulgaris (microalga)	Protein, pigments, vitamins and lipids	Alternative nutritional ingredient	Chen *et al.* (2024) [1]
Gracilaria spp. (red macroalgae)	Agarans, minerals and other polysaccharides	Nutritional supplementation and functional feed applications	Niu *et al.* (2019) [2]; Hernández-Sain *et al.* (2025) [12]
Porphyra spp. (red macroalgae)	Protein, pigments and polysaccharides	Growth, antioxidant and intestinal microbial responses	Niu *et al.* (2019) [2]
Undaria pinnatifida (brown macroalga)	Fucoidan, laminarin and minerals	Growth, immunity and intestinal microbial responses	Niu *et al.* (2019) [2]
Sargassum dentifolium (brown macroalga)	Sulphated polysaccharides and other bioactive compounds	Microbial abundance and immune-related responses	Abbas *et al.* (2023) [3]
Ulva spp. (green macroalgae)	Ulvans, minerals and pigments	Potential functional and prebiotic applications	Shah and Mraz (2020) [8]; Hernández-Sain *et al.* (2025) [12]

4.1. Major nano-enabled approaches

Three approaches are relevant to algal feed development:

1. Nano-sized algal biomass: Physical processing, such as high-energy milling, reduces algal particle size and may alter surface area and accessibility of cellular constituents. However, particle-size reduction alone does not establish improved nutrient bioavailability; digestibility and nutrient absorption must be measured.
2. Nanoencapsulation of algal bioactive compounds: Algal-derived compounds, such as carotenoids, pigments and polysaccharides, may be incorporated into carrier systems. Chitosan, alginate and lipid-based materials are potential carriers. Encapsulation can protect sensitive compounds from degradation and may facilitate their controlled release in the digestive tract (Ahmed *et al.*, 2023) [7]. Direct evidence for algal-compound nanoencapsulation in *L. vannamei*, however, remains limited.
3. Algal-derived nanoparticles and nanocomposites: Algal biomass or extracts may be processed into particulate formulations or used in the synthesis of nanoparticles. These products should be distinguished from conventional algal supplements and from nanoparticles merely coated with algal extracts. Their composition, particle-size distribution, stability and biological effects require independent characterisation.

4.2. Evidence from shrimp-feeding studies

Studies involving *L. vannamei* provide initial evidence for the use of nano-sized algal materials. Sharawy *et al.* (2022) [9] evaluated dietary *Arthrospira platensis* nanoparticles and reported improvements in growth performance, feed utilisation, survival and growth-related gene expression. Similarly, Ashour *et al.* (2025) [11] investigated mechanically processed *Pterocladia capillacea* seaweed particles in shrimp diets. The study reported improvements in growth, digestive enzyme activity, feed efficiency, antioxidant activity and innate immune responses.

Importantly, the latter study used planetary ball milling, and the reported particle-size distribution extended from 151 to 835 nm. Therefore, it is more precise to describe the material as nano-sized or submicron seaweed particles, rather than assuming that all particles were within the conventional 1–100 nm range. Neither study directly demonstrated improved gut microbiome composition or nutrient absorption. These outcomes should not be inferred from growth or feed-conversion improvements alone.

Evidence from non-algal nanoencapsulated feed additives also illustrates the potential of carrier-based delivery. For example, Bhoopathy *et al.* (2021) [13] investigated curcumin-loaded chitosan nanoparticles in *L. vannamei* and reported improved immune responses under *Vibrio harveyi* challenge. Although this study did not use an algal compound, it provides a relevant example of a nano-carrier approach that could be investigated for algal bioactive ingredients.

4.3. Research considerations

Despite promising findings, the application of nano-enabled algal feeds requires careful evaluation. Particle size, polydispersity, surface charge, morphology, chemical composition and stability should be characterised before feeding trials. Experimental comparisons should include an unsupplemented control, conventional algal biomass and its nano-sized counterpart at equivalent inclusion levels. This is necessary to determine whether observed effects arise from the algal ingredient itself or from particle-size modification.

Further, studies should evaluate feed-water stability, leaching, digestibility, nutrient retention, growth, feed conversion, immune responses and intestinal microbial communities. The safety of the carrier material and the potential accumulation or environmental release of nanoparticles also require investigation. Thus, nano-enabled algal feed development should be assessed not only in terms of growth improvement but also through nutritional effectiveness, biological safety and production feasibility.

5. Nutritional enhancement and physiological responses to algal and nano-enabled feeds

The nutritional effects of algae-integrated feeds in *Litopenaeus vannamei* can be assessed through three related outcomes: nutrient utilisation and growth, tissue-level nutritional enhancement, and physiological responses associated with antioxidant defence and immunity. These outcomes are influenced by algal species, inclusion level, processing method, basal diet composition and culture conditions. Importantly, findings from conventional algal supplementation should not automatically be attributed to nano-sized algal formulations.

5.1. Growth performance and feed utilisation

Algal ingredients can contribute protein, essential fatty acids, pigments, vitamins and minerals to shrimp diets. Their effects on growth and feed utilisation depend on the nutritional composition and digestibility of the biomass, as well as the extent to which it replaces conventional feed ingredients.

Lin *et al.* (2024) [4] evaluated *Haematococcus pluvialis* supplementation in a low-fishmeal diet under normal and low-temperature conditions. At 30 °C, supplementation with 0.03% *H. pluvialis* improved weight gain compared with the unsupplemented low-fishmeal diet. The study also reported improvements in antioxidant capacity and immune-related responses. This indicates that algal supplementation may help maintain selected performance and physiological responses in nutritionally constrained diets, although it should not be interpreted

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as evidence that algae can universally compensate for reduced fishmeal.

Table 2. Nano-enabled approaches and evidence relevant to shrimp feed development

Approach	Example / study	Reported outcome or potential	Evidence limitation
Nano-sized microalgal biomass	*Arthrospira platensis* nanoparticles (Sharawy *et al.*, 2022) [9]	Improved growth, survival, feed utilisation and growth-related gene expression in *L. vannamei*	Does not independently establish enhanced nutrient bioavailability or microbiome modulation
Nano-sized seaweed particles	*Pterocladia capillacea* (Ashour *et al.*, 2025) [11]	Improved growth, digestive enzymes, feed efficiency, antioxidant activity and innate immunity	Particle sizes ranged from 151 to 835 nm; gut microbiome effects were not assessed
Bioactive compound encapsulation	Curcumin-loaded chitosan nanoparticles (Bhoopathy *et al.*, 2021) [13]	Improved immune responses in *L. vannamei*, including under bacterial challenge	Demonstrates a carrier platform, not nano-delivery of an algal compound
Nanoencapsulation of feed ingredients	Aquafeed delivery systems reviewed by Ahmed *et al.* (2023) [7]	Potential protection, improved dispersion and controlled release of sensitive ingredients	Broad aquaculture evidence; efficacy depends on the ingredient, carrier and target species

A 2025 feeding study by Liu *et al.* (2025) [14] further demonstrated the potential of macroalgal ingredients. Diets containing 3% *Saccharina japonica*, *Sargassum fusiforme* or *Neoporphyra haitanensis*, and diets supplemented with purified carotenoids, improved weight gain and specific growth rate relative to the control. The magnitude of response differed among treatments, highlighting the importance of ingredient-specific evaluation.

5.2. Pigmentation and tissue-level nutritional enhancement

Carotenoids are important functional components of algal feed ingredients. Because *L. vannamei* cannot synthesise carotenoids de novo, dietary supply contributes to tissue pigmentation and carotenoid deposition. Liu *et al.* (2025) [14] found that dietary macroalgae and purified carotenoids altered carotenoid accumulation in shrimp tissues. *Neoporphyra haitanensis* produced the greatest increase in total carotenoid accumulation among the tested algal diets, while the exoskeleton was the principal deposition site. Astaxanthin esters showed tissue-specific distribution, including detection in muscle.

These findings are relevant to commercial quality because pigmentation can influence product appearance and market acceptance. However, pigmentation should be considered separately from nutritional quality: increased carotenoid deposition does not necessarily demonstrate improved muscle protein, fatty-acid composition or human nutritional value. Such claims require direct tissue-composition measurements.

5.3. Antioxidant defence and immune responses

Algal bioactive compounds, particularly carotenoids, phycobiliproteins and certain polysaccharides, may influence antioxidant and immune-related processes. In *L. vannamei*, Lin *et al.* (2024) [4] reported higher antioxidant capacity and changes in immune-related gene expression following *H. pluvialis* supplementation. They also observed differences in gut bacterial composition, including changes in the abundance of selected bacterial groups. These results suggest that the physiological effects of algae may extend beyond nutrient contribution, although the relative roles of carotenoids, other algal constituents and microbiome changes require further investigation.

Evidence from nano-sized algal formulations is also emerging. Sharawy *et al.* (2022) [9] reported improved growth and feed utilisation with dietary *Arthrospira platensis* nanoparticles, while Ashour *et al.* (2025) [11] reported changes in digestive enzyme activity, antioxidant responses and innate immunity following supplementation with nano-sized *Pterocladia capillacea* particles. These studies support further investigation of nano-sized algal ingredients, but they do not establish that nanoparticle processing itself caused improved nutrient absorption. Equivalent-dose comparisons with conventional algal biomass are needed to demonstrate this mechanism.

Table 3. Nutritional and physiological outcomes reported in algal feeding studies involving *L. vannamei*

Algal ingredient or formulation	Major outcome assessed	Main reported findings	Study
Haematococcus pluvialis	Growth, antioxidant status, immunity and gut bacteria	Improved weight gain in the normal-temperature low-fishmeal treatment; increased astaxanthin and pigmentation; changes in antioxidant and immune responses	Lin *et al.* (2024) [4]
Saccharina japonica, Sargassum fusiforme and *Neoporphyra haitanensis*	Growth and tissue carotenoid deposition	Improved growth indices and altered tissue-specific carotenoid accumulation	Liu *et al.* (2025) [14]
Arthrospira platensis nanoparticles	Growth and feed utilisation	Improved growth performance and feed utilisation	Sharawy *et al.* (2022) [9]
Nano-sized *Pterocladia capillacea*	Digestive enzymes, antioxidant status and immunity	Improved digestive enzyme activity and selected antioxidant and innate immune responses	Ashour *et al.* (2025) [11]

5.4. Implications for nano-enabled algal feed development

The available studies indicate that algal supplementation can influence growth, feed utilisation, pigmentation, antioxidant capacity and immune responses in *L. vannamei*. Nevertheless, three distinctions are essential when interpreting these findings:

- Nutritional improvement: Demonstrated through measurements such as apparent digestibility, nutrient retention, body composition and feed utilisation.
- Physiological improvement: Demonstrated through digestive enzyme activity, antioxidant biomarkers, immune parameters and relevant gene expression.

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- Nano-specific improvement: Demonstrated only when a nano-enabled formulation is directly compared with an equivalent conventional algal formulation under otherwise comparable feeding conditions.

Future feeding trials should therefore compare conventional algal biomass, nano-sized algal biomass and, where applicable, algal bioactive compounds delivered through nanocarriers. Measuring digestibility, nutrient retention, tissue composition, oxidative stress markers and immune responses would help establish whether nano-processing provides benefits beyond those of the algal ingredient itself.

6. Gut microbiome modulation and host–microbiome interactions

The gut microbiome plays an important role in shrimp digestion, nutrient metabolism, immune regulation and resistance to opportunistic pathogens. In *Litopenaeus vannamei*, intestinal microbial communities are influenced by diet composition, culture environment, developmental stage and health status. Consequently, dietary algae may influence shrimp health not only through their nutritional contribution but also through interactions between algal bioactive compounds and intestinal microorganisms (Holt *et al.*, 2021; Zeng *et al.*, 2024) [5, 6].

6.1. Effects of algal ingredients on gut microbial communities

Algal polysaccharides, including sulphated polysaccharides and other complex carbohydrates, may act as substrates for selected intestinal microorganisms. Their fermentation can potentially produce metabolites that influence intestinal conditions and host physiology. However, the extent of microbial utilisation depends on the chemical structure of the polysaccharide and the metabolic capabilities of the resident microbial community.

Niu *et al.* (2019) [2] investigated four macroalgal species in diets for *L. vannamei* and evaluated growth, immune responses and intestinal microbiota. Their findings demonstrated that dietary macroalgae can influence intestinal microbial composition, although the responses varied with the algal ingredient.

Similarly, dietary supplementation with *Sargassum cristaefolium* powder was associated with changes in intestinal bacterial abundance, including a gradual reduction in intestinal *Vibrio* counts as dietary inclusion increased (2021 study) [15]. Abbas *et al.* (2023) [3] reported that polysaccharides extracted from *Sargassum dentifolium* reduced total heterotrophic bacterial and *Vibrio* counts in shrimp intestine and culture water. These findings indicate that algal ingredients can influence microbial abundance, but culture-based bacterial counts do not provide the taxonomic resolution of high-throughput sequencing.

6.2. Algal bioactive compounds and microbial balance

Seaweed-derived polysaccharides may influence microbial communities through selective utilisation by bacteria and changes in intestinal conditions. Abbas *et al.* (2023) [3] found that dietary *Sargassum dentifolium* polysaccharides reduced total heterotrophic bacterial and *Vibrio* counts, with the 3 g kg^{-1} treatment producing the greatest reduction in *Vibrio* abundance. The study also reported changes in growth-, immune- and stress-related gene expression. These results support the potential of seaweed polysaccharides as functional feed additives, but do not establish that the polysaccharides selectively stimulated beneficial bacteria.

More recent evidence comes from biologically fermented *Ulva fasciata*. A 2025 study used *Enterococcus durans* E23 to prepare a fermented seaweed extract and evaluated it as a feed supplement for *L. vannamei*. The treatment increased lactic acid bacterial counts in the shrimp gut, improved growth and feed conversion, and enhanced immune-related gene expression (2025 study). This provides evidence for a combined seaweed–probiotic approach. However, because the supplement contained both fermented seaweed extract and the probiotic bacterium, the individual contributions of the seaweed compounds and probiotic cannot be separated without appropriate treatment controls.

6.3. Possible links between the gut microbiome and host performance

Changes in microbial composition may be associated with several host responses:

- Nutrient utilisation: Intestinal microorganisms may contribute to the breakdown and transformation of dietary components, potentially influencing nutrient availability.
- Colonisation resistance: Competition for nutrients and attachment sites, together with the production of inhibitory metabolites, may limit the establishment of opportunistic pathogens.
- Immune regulation: Microbial signals and metabolites may interact with host immune pathways, influencing the expression of antimicrobial peptides and other immune-related genes.
- Intestinal homeostasis: Microbial interactions with the intestinal environment may contribute to maintaining epithelial integrity and physiological stability.

These mechanisms are biologically plausible, but they should not be treated as proven effects of every algal feed ingredient. Demonstrating them requires measurements beyond total bacterial counts, such as 16S rRNA gene sequencing, microbial functional profiling, metabolite analysis and intestinal histology.

Table 4. Evidence for algal-associated changes in the gut microbiome of *L. vannamei*

Algal ingredient or treatment	Microbial assessment	Main findings	Interpretation
Four macroalgal species	Intestinal microbiota	Dietary treatments altered microbial community composition	Demonstrates that algal species can influence intestinal microbial profiles
Sargassum cristaefolium powder	Intestinal bacterial counts	Increasing inclusion was associated with reduced intestinal *Vibrio* counts	Evidence of changes in bacterial abundance, not necessarily beneficial community restructuring
Sargassum dentifolium polysaccharides	Total heterotrophic bacteria and *Vibrio* counts	Reduced bacterial counts in intestine and culture water	Supports an effect on microbial abundance; does not demonstrate selective prebiotic activity
Ulva fasciata fermented extract with *Enterococcus durans* E23	Gut lactic acid bacterial counts	Increased lactic acid bacterial counts alongside improved growth and immune responses	Combined seaweed–probiotic effect; individual contributions require further investigation

6.4. Relevance to algae-integrated nanofeeds

The relationship between algal feed ingredients, nanoparticles and the gut microbiome remains insufficiently investigated in *L. vannamei*. Nano-sized algal particles or encapsulated algal polysaccharides may potentially alter the release, stability and accessibility of bioactive compounds in the digestive tract. These changes could influence microbial utilisation and host responses. However, this remains a research hypothesis rather than an established mechanism.

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Future studies should compare conventional algal biomass, nano-sized algal biomass and algal-derived compounds encapsulated in nanocarriers. Microbiome analysis should be integrated with intestinal histology, microbial metabolite profiling, digestive enzyme activity and immune biomarkers. Such an approach would help establish whether nano-enabled delivery produces reproducible microbiome-related benefits beyond conventional algal supplementation.

7. Sustainability, biosafety and commercial applicability

Algae-integrated nanofeeds may contribute to sustainable shrimp aquaculture by improving the utilisation of alternative feed ingredients, reducing dependence on conventional marine-derived resources and potentially enhancing feed efficiency. However, improved growth or feed conversion alone does not establish environmental sustainability. The overall benefits depend on algal cultivation requirements, processing energy, nanoparticle production costs, feed stability and environmental fate (Shah *et al.*, 2020; Chen *et al.*, 2024) [8, 1].

Nutritional and environmental sustainability: Microalgae and macroalgae offer alternative sources of proteins, lipids, pigments and functional compounds. Their commercial value depends on consistent composition, digestibility, availability and production cost. Large-scale algal cultivation may also require substantial energy, freshwater or nutrients, depending on the production system. Life-cycle assessment (LCA) is therefore necessary to compare algal-based feeds with conventional feed ingredients.

Nanoparticle biosafety: The biological safety of nano-enabled feeds requires particular attention. Nanoparticle size, surface characteristics, concentration, carrier composition and exposure duration can influence toxicity. Potential effects on shrimp tissues, gut microbial communities, surrounding aquatic organisms and sediment quality should be investigated. The environmental persistence and release of nanoparticles from uneaten feed and faecal material also require assessment (Shah *et al.*, 2020) [8].

Commercial feasibility: Before commercial application, nano-enabled algal feeds should demonstrate reproducible improvements in growth, feed utilisation or health under farm-scale conditions. Production cost, storage stability, feed-water leaching, regulatory requirements and farmer acceptance must also be considered.

Table 5. Key considerations for sustainable commercial application

Assessment area	Important parameters
Nutritional performance	Digestibility, feed conversion ratio, growth and nutrient retention
Environmental sustainability	Resource requirements, energy consumption, waste generation and LCA
Biosafety	Nanoparticle toxicity, tissue accumulation and environmental release
Feed quality	Particle stability, storage life, palatability and nutrient leaching
Commercial feasibility	Ingredient cost, production scalability and economic returns

8. Research gaps and future perspectives

Despite promising findings, research on algae-integrated nanofeeds for *L. vannamei* remains at an early stage. Most available studies investigate conventional algal supplementation or nano-sized algal biomass separately. Direct comparisons between conventional and nano-enabled algal formulations are limited. Evidence linking nano-enabled algal delivery with nutrient bioavailability, gut microbiome functionality and long-term biosafety is particularly scarce.

Future research should prioritise:

1. Formulation development: Standardise algal species, particle size, carrier materials, inclusion levels and physicochemical characteristics.
2. Nutritional validation: Evaluate digestibility, nutrient retention, tissue composition and feed efficiency using equivalent-dose comparisons.
3. Microbiome mechanisms: Combine microbial sequencing with metabolite profiling, intestinal histology and immune-response measurements.
4. Biosafety assessment: Investigate dose-dependent toxicity, tissue accumulation and environmental release.
5. Farm-scale validation: Examine production performance, cost-effectiveness and environmental impacts under commercial farming conditions.

An integrated research framework connecting algal nutritional properties, nano-enabled delivery, host physiological responses, gut microbiome changes and environmental safety is essential for developing scientifically validated and commercially viable feeds.

9. Conclusion

Algae-integrated nanofeeds represent a promising research direction for improving the nutritional and functional quality of diets for *Litopenaeus vannamei*. Existing studies demonstrate beneficial effects of algal ingredients and selected nano-sized algal formulations on growth, feed utilisation, antioxidant activity and immune responses. However, direct evidence connecting nano-enabled algal delivery with improved nutrient bioavailability and gut microbiome functionality remains limited. Future research should prioritise comparative feeding trials, microbiome-based mechanistic investigations, biosafety evaluation and life-cycle assessment before recommending large-scale commercial application.

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