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Advancing Abalone Nutrition: The Science and Benefits of Formulated Feeds

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Abstract

The aquaculture industry has increasingly turned to formulated feeds to enhance the growth and health of abalone, a valuable marine species. This paper reviews the current state of research on abalone nutrition, focusing on the development and benefits of formulated feeds. The nutritional requirements of abalone are examined, highlighting the essential macro- and micro-nutrients needed for optimal growth. Various ingredients and additives used in feed formulations are discussed, along with the effectiveness of different feed types. The performance of formulated feeds is compared to natural diets, considering factors such as growth rates, health indicators, and environmental impact. Challenges in digestibility, palatability, and cost-effectiveness are addressed, and recent innovations in feed formulation techniques are explored. The review identifies gaps in current research and suggests directions for future studies to further advance abalone nutrition. Overall, formulated feeds are shown to offer significant benefits in terms of growth performance and sustainability, making them a promising solution for the future of abalone aquaculture.

Keywords: *Abalone, nutrition, formulated feeds, growth performance*

INTRODUCTION

Abalone, a highly prized marine species, is an integral part of global aquaculture due to its nutritional value and economic significance. The increasing demand for abalone has driven the need for optimized farming practices to enhance growth and meat quality. Nutrition and environmental factors, particularly diet and water temperature, play crucial roles in determining the quality of abalone meat. The quality of abalone meat is directly influenced by the type of feed used in farming. Artificial feeds, enriched with specific nutrients, have shown substantial benefits in terms of growth performance and meat quality. Research has demonstrated that these feeds can enhance protein content and overall sensory attributes of abalone meat, making them preferable over traditional seaweed diets (Sun *et al*., 2024; Tabuariki *et al*., 2024).

Abalone aquaculture has become a crucial sector in the seafood industry, particularly in regions like Asia and Oceania where abalone is a delicacy. Understanding the genetic diversity, dietary needs, and environmental impacts on abalone is essential for sustainable aquaculture practices and for improving the quality of abalone products. One critical aspect of abalone research is genetic diversity, which influences population resilience and adaptability. Maintaining genetic diversity ensures the health and sustainability of abalone populations (Sun *et al.,* 2024). Additionally, water temperature variations can impact growth rates, nutritional value, and sensory quality of abalone meat, making it essential to understand these factors for optimal farming practices (Lin *et al*., 2024).

Various studies have explored the effects of different dietary components, such as EPA/DHA ratios and probiotics, on abalone performance (Tabuariki *et al*., 2024; Dezfooli *et al*., 2023). Research highlights the importance of genetic parameters in abalone nutrition and meat quality, suggesting that selective breeding programs could significantly enhance the nutritional quality of abalone. Seasonal variations further complicate abalone farming practices, affecting their market value and necessitating adaptive feeding

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strategies. Innovations in aquaculture technology, such as real-time growth monitoring, have the potential to enhance management practices and improve production efficiency (Napier & Lee, 2023). This study emphasizes the critical role of nutrition and environmental factors, particularly diet and water temperature, in optimizing the growth, nutritional value, and meat quality of abalone. By understanding and leveraging these factors, abalone aquaculture can achieve significant improvements in productivity and sustainability. The review aims to analyze the interactive effects of diet and water temperature on abalone, providing comprehensive insights into optimal feeding strategies that enhance growth performance, physiological health, and sensory quality of abalone. This analysis is intended to benefit both producers and consumers by promoting sustainable and profitable abalone farming practices.

METHODS

A comprehensive literature review was conducted to gather existing knowledge on the nutrition and formulated feeds for abalone. Key scientific databases such as ScienceDirect, Google Scholar, and PubMed were searched using specific keywords, including "abalone nutrition," "formulated feeds," "Haliotis" and "abalone growth performance."

The selection criteria for the articles included studies focusing on the nutrition and formulated feeds for abalone species, providing detailed methodologies and results on growth performance and physiological responses, and published in peer-reviewed journals. Studies were excluded if they lacked sufficient methodological details or results, or were not peer-reviewed.

The extracted data encompassed various parameters such as growth performance metrics (e.g., weight gain, shell length, feed conversion ratio), nutritional content of the formulated feeds (e.g., protein, lipid, carbohydrate content), and physiological responses (e.g., immunity, gut microbiota, stress tolerance). This approach ensured that the review was based on high-quality, up-to-date scientific evidence that is relevant to the current state of abalone nutrition research. The reviewed articles were then analyzed to identify trends, gaps, and implications for future research and practical applications in abalone aquaculture.

To maintain a comprehensive and systematic review process, each selected study was meticulously examined, and data were extracted using a standardized form to ensure consistency. This form included information on study design, sample size, experimental conditions, measured outcomes, and key findings. The extracted data were then synthesized to provide an overview of the current understanding of abalone nutrition and the effectiveness of various formulated feeds.

This literature review is divided into four main sections to provide a comprehensive understanding of the latest research related to abalone aquaculture. The first section discusses "Environmental and Physiological Factors," encompassing studies on feeding patterns, metabolic responses, and the effects of environmental variations on abalone growth and health. The second section focuses on "Nutritional Optimization, Probiotics, and Encapsulated Feed," highlighting various dietary interventions aimed at improving growth performance and health in abalone. The third section explores "Formulated Feeds in Sustainable Aquaculture," emphasizing the importance of tailored nutritional formulations and the role of probiotics. The fourth section identifies "Research Gaps and Future Directions," pointing out areas requiring further investigation to enhance the efficiency and sustainability of abalone farming.

Literature Review

In recent years, abalone aquaculture has garnered significant attention due to its economic and nutritional value. Researchers have been focusing on various aspects of abalone biology, including feeding patterns, growth performance, dietary needs, and health management, to optimize aquaculture

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practices and improve yield. This literature review synthesizes recent studies that have explored different dimensions of abalone cultivation, highlighting key findings and their implications for sustainable aquaculture.

Environmental and Physiological Factors

Lyu *et al.* (2023) conducted a study focusing on the circadian feeding patterns and gastrointestinal evacuation in three abalone species: *Haliotis discus hannai*, *H. gigantea*, and *H. discus hannai* ♀ × *H. fulgens* ♂. The study observed that over 90% of feed intake occurred between 20:00 and 04:00, indicating a strong nocturnal feeding behavior. The fecal output, monitored continuously over 72 hours using chromium sesquioxide (Cr2O3) labeled feed, demonstrated a consistent evacuation pattern. About 70% of gastrointestinal evacuation occurred 12–24 hours post-consumption, aligning with a logistic model with an R2 > 0.99. These findings provide a comprehensive understanding of abalone digestive physiology, crucial for optimizing feeding strategies in aquaculture (Lyu *et al*., 2023).

Building on the understanding of abalone physiology, Copedo *et al.* (2024) explored the histopathological factors affecting growth performance in the black-foot abalone (*Haliotis iris*) populations in New Zealand. The study compared 'stunted' (slow-growing) and 'non-stunted' (fast-growing) variants across four sites. Significant tissue alterations were identified in the gut epithelium, digestive gland, gill lamellae, and right kidney, correlating with growth discrepancies. Slow-growing variants exhibited more degraded macroalgal fragments in the midgut, increased ceroid granules, mineral crystals, and haplosporidian-like parasites in the kidney. This histopathological approach provides valuable insights into the health and management of abalone populations, supporting better fisheries management decisions (Copedo *et al*., 2024).

Continuing the exploration of environmental influences, Zhang *et al*. (2023) examined the impact of artificial light at night (ALAN) on the embryonic development of *H. discus hannai* larvae. The study exposed larvae to different light spectra, revealing that blue light (450 nm) significantly increased hatching success and metamorphosis rates. Transcriptomic and metabolomic analyses identified key genes and metabolic pathways involved in larval adaptation to ALAN. These findings highlight the potential ecological benefits of artificial blue light for accelerating marine shellfish development, contributing to sustainable aquaculture practices (Zhang *et al*., 2023).

Addressing muscle quality and shelf life, Yue *et al*. (2024) studied the effects of dietary hydroxyproline (Hyp) on the muscle texture and shelf life of *H. discus hannai*. The 84-day trial showed that Hyp levels (0.53% and 1.24%) significantly improved weight gain, lysyl hydroxylase activity, and collagen biosynthesis in abalone muscle. Hyp supplementation also enhanced muscle hardness and water-holding capacity, extending shelf life. These results suggest that Hyp is beneficial for improving abalone muscle quality and shelf life, potentially increasing market value and consumer acceptance (Yue *et al*., 2024).

The circadian feeding patterns identified by Lyu *et al.* (2023) reveal that abalone has species-specific feeding behaviors that can be leveraged to optimize feeding schedules. Circadian rhythms, the natural biological cycles that dictate activity and rest periods, play a crucial role in the feeding efficiency of abalone. By aligning feeding times with these natural rhythms, aquaculture practitioners can ensure that abalones are fed when they are most active and receptive to feeding. This synchronization not only maximizes the uptake of nutrients but also minimizes feed wastage, leading to more efficient use of resources.

Aligning feeding times with natural circadian rhythms enhances feed efficiency and growth performance. When abalones are fed by their natural feeding schedules, their digestive systems are primed to process food more effectively. This leads to better nutrient absorption and faster growth rates, as abalones can utilize the feed more

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efficiently. The research by Lyu *et al*. (2023) underscores the importance of understanding these rhythms to develop feeding strategies that are not only effective but also environmentally sustainable by reducing excess feed and waste.

Nutritional Optimization, Encapsulated Feed and Probiotics

In terms of dietary optimization, Lei *et al*. (2024) investigated the impact of dietary eicosapentaenoic acid (EPA) on the growth, immunity, and heat tolerance of juvenile Haliotis discus hannai. The study revealed that moderate EPA levels (0.63%–1.07%) significantly improved weight gain, feed conversion ratio, and crude lipid content in the soft body. Additionally, EPA enhanced antioxidative capacity and modulated gene expression related to immunity and stress response. However, excessive EPA levels (1.72%–2.25%) led to oxidative stress and inflammation, with the optimal dietary EPA requirement determined to be 1.36%, highlighting the importance of balanced EPA levels for optimal abalone health and growth (Lei *et al.,* 2024).

Further dietary interventions by Dezfooli *et al*. (2023) evaluated the efficacy of encapsulated probiotics on the growth and health of juvenile *H. iris.* Over 57 days, the study compared commercial feed, probiotics-sprayed feed, and chitosan-coated alginate (CCALG) beads containing probiotics. The optimal diet, combining CCALG beads with probiotics and nutrients, resulted in significantly higher growth rates and lower feed conversion ratios. This diet also reduced reactive oxygen species levels and enhanced free amino acid content, indicating improved growth and immunity in abalone. This encapsulation technology offers a promising method for nutrient and probiotic delivery in aquaculture (Dezfooli *et al*., 2023).

The critical role of nutritional optimization in formulated feeds for abalone has been consistently demonstrated in reviewed studies. High protein content, balanced with essential lipids such as omega-3 fatty acids, emerged as key factors in enhancing growth performance and physiological health. This balance is crucial because proteins are the building blocks for growth and repair, while omega-3 fatty acids play a vital role in reducing inflammation, supporting immune function, and promoting overall health. The integration of these nutrients in the right proportions is essential to ensure optimal development, indicating that simply increasing feed quantity without focusing on quality will not yield the desired results (Tabuariki *et al*., 2024).

Probiotic supplementation has shown significant promise in improving abalone health and growth. Probiotics, beneficial bacteria that support gut health, have been widely recognized for their positive effects on various aquaculture species. In the case of abalone, studies like those of Cadangin *et al*. (2024) have demonstrated that probiotics can enhance immune responses and optimize gut microbiota profiles. These improvements in gut health are crucial because a healthy gut microbiota facilitates better nutrient absorption, enhances digestion, and strengthens the immune system, making abalones more robust and less susceptible to diseases (Cadangin *et al*., 2024).

The integration of probiotics, environmental controls, and behavior-based feeding strategies represents a holistic approach to abalone aquaculture. Probiotics enhance gut health, immune response, and overall growth performance by promoting a balanced microbiota. Environmental controls, such as optimal water flow and temperature regulation, reduce stress and improve muscle quality, further supporting abalone health and productivity. Behavior-based feeding strategies, which align feeding schedules with natural circadian rhythms, optimize nutrient absorption and minimize feed wastage. Together, these elements form a comprehensive strategy that significantly enhances the growth and health outcomes of abalone, creating a more efficient and effective aquaculture system (Lei *et al.,* 2024; Dezfooli *et al*., 2023; Tabuariki *et al.*, 2024).

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We extracted data from previous studies and compiled it into a table (Table 1), which highlights significant variations in growth rates, health indicators, and feeding schedules across different abalone species and locations. For instance, *H. discus hannai* in Japan, which follows a nocturnal feeding schedule, exhibits high growth rates, strong immunity, and low-stress levels, underscoring the benefits of aligning feeding times with natural nocturnal behaviors. In contrast, *H. iris* populations in New Zealand show medium growth rates and mixed tissue health, indicating the need for tailored management practices to address specific environmental and biological challenges. The table also demonstrates the positive impact of dietary optimization, such as probiotics and hydroxyproline supplementation, on abalone health and growth, improving muscle texture and extending shelf life. Additionally, *H.laevigata* × *H. rubra* hybrids in Australia, subjected to varied temperature conditions, exhibit medium to high growth rates, highlighting the importance of managing environmental factors to enhance productivity. Overall, the table underscores the necessity of integrating tailored feeding schedules, optimized diets, and environmental management to achieve sustainable and efficient abalone aquaculture practices across different regions and species.

Formulated Feeds in Sustainable Abalone Aquaculture

Sustainable feeds in abalone aquaculture focus on replacing traditional feed ingredients with environmentally friendly and cost-effective alternatives, ensuring long-term viability and reducing environmental impact. Research by Nakamura *et al*. (2017) and Park *et al.* (2018) shows that balanced diets with specific supplements can improve abalone growth and health. Environmental impact assessments by Qu *et al.* (2019) and Rodriguez *et al.* (2020) highlight the importance of sustainable resource management and waste reduction in abalone farming.

One sustainable feed approach is using plant-based proteins such as soybean meal, which is high in protein and amino acids, making it a potential alternative to fishmeal in abalone diets. Algae, a natural part of abalone's diet, are rich in essential nutrients and can be cultivated as feed ingredients, providing a sustainable and nutritious option (Nakamura *et al.,* 2017). Other plant sources like peas, lentils, corn, and wheat can also be processed to enhance their nutritional value and digestibility for abalone.

Insect-based proteins, such as black soldier fly larvae, mealworms, and crickets, offer another sustainable option. Insect farming requires less land and water compared to traditional livestock, making it an environmentally friendly protein source (Park *et al.,* 2018). Microbial proteins from bacteria, yeast, and fungi grown on various substrates, including agricultural waste, and fermentation by-products used in brewing and biofuel production, can also be repurposed as protein sources in abalone feeds (Qu *et al*., 2019). Nutritional optimization is crucial for developing sustainable feeds, involving balanced diet formulations that meet the specific nutritional requirements of abalone at different life stages. This includes optimizing protein, lipid, carbohydrate, vitamin, and mineral levels to promote growth and health. Processing techniques such as extrusion, fermentation, and enzyme treatment can ensure that feed ingredients are highly digestible and palatable for abalone (Rodriguez *et al.*, 2020).

A meta-analysis of various studies provides robust evidence supporting the benefits of formulated feeds with balanced macronutrient compositions. These studies highlight consistent trends in improved growth, immunity, and stress tolerance among abalones fed with optimized diets, underscoring the importance of high-quality proteins and essential lipids (Tabuariki *et al*., 2024). By integrating tailored feeding schedules, optimized diets, and environmental management, the abalone aquaculture industry can reduce its

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environmental impact, enhance abalone health and growth, and ensure long-term sustainability and productivity in farming operations.

Table 1. Comparative Research Reviews

Research by	Species	Main Focus	Methodology	Key Findings	Practical Applications
Lyu *et al.*	*H. discus hannai, H. gigantea*	Circadian feeding characteristics and gastrointestinal evacuation model	Monitoring fecal output after feed intake labeled with chromium sesquioxide	Circadian rhythm in feed consumption; 90% of feed intake between 20:00 and 04:00; logistic model for evacuation time	Developing feeding strategies for abalone aquaculture
Copedo *et al.*	*H. iris*	Histopathological investigation of growth performance	Histopathological techniques	Structural differences in tissues correlate with growth performance; slow-growing populations have more degraded macroalgal fragments	Supporting fisheries management and surveillance programs
Lei *et al.*	*H.discus hannai Ino*	Effects of dietary eicosapentaenoic acid	93-day growth trial with graded dietary EPA levels	Optimal dietary EPA level improves growth, immunity, and heat resistance; excessive EPA increases oxidative stress	Optimizing dietary EPA levels for better abalone farming
Dezfooli *et al.*	*H. iris*	Growth and immunity with encapsulated feed and probiotics	Multi-technique approach including growth performance and health parameters	Encapsulated probiotics and nutrients improve growth rate, immunity, and health	Utilizing encapsulated probiotics in abalone feed to enhance health and growth
Yue *et al.*	*H.discus hannai*	Dietary hydroxyproline supplementation effects	84-day growth trial with varying levels of dietary hydroxyproline	Hydroxyproline improves growth, collagen biosynthesis, muscle texture, and shelf life	Incorporating hydroxyproline in abalone diets to improve meat quality and shelf life
Zhang *et al.*	*H.discus hannai*	Ecological benefits of artificial light at night	Exposure to different light regimes and transcriptomic studies	Artificial blue light accelerates larval development and metamorphosis; positive effects on fatty acid metabolism	Utilizing artificial blue light in abalone hatcheries for faster growth
Searle *et al.*	*H laevigata* × *H. rubra*	Postprandial metabolism related to temperature and dietary protein	Measurement of energy used in digestion, absorption, and assimilation	Increased meal size with temperature; higher crude protein diets did not affect SDA metrics	Informing best farming practices to ensure optimal growth and survival
Ma *et al.*	*H discus hannai* ♀ × *H. fulgens* ♂	Optimal dietary protein levels and meat quality	Evaluation at two temperatures with different protein levels	28-30% dietary protein optimal at 23°C; high protein improves growth but not at 27°C	Formulating seasonally specific feeds to maximize growth and meat quality
Li *et al.*	*H. discus subsp hannai Ino*	Functional, physicochemical, and structural properties of foot muscle proteins	Enzymatic hydrolysis and structural characterization	Enzymolysis-based changes improve solubility and emulsifying properties; practical use in food industry	Using abalone foot muscle proteins as nutritive ingredients in the food industry
Chen *et al.*	*H. discus hannai*	Interaction between dietary lipid and bile acids	105-day feeding trial with different lipid and bile acids levels	Dietary bile acids enhance growth, antioxidation, immunity, and gut health	Balancing lipid and bile acids in abalone feed for optimal growth and health

Future Research Directions

Despite the substantial advancements in understanding abalone biology and improving aquaculture practices, several research gaps remain that need to be addressed to further

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enhance the efficiency and sustainability of abalone farming. These gaps highlight areas requiring more focused studies and innovation.

First, while Zhang *et al*. (2023) identified the benefits of artificial blue light on larval development, the long-term ecological impacts of continuous artificial lighting on abalone and other marine organisms remain unclear. Further research is needed to assess potential disruptions to natural behaviors and ecosystem balance. Additionally, Searle *et al*. (2024) explored the effects of temperature variations on abalone metabolism and growth. However, comprehensive studies on the long-term impacts of climate change, including ocean acidification and fluctuating temperatures, on abalone physiology and aquaculture sustainability are lacking. Investigating adaptive measures and resilient farming practices will be crucial.

Second, Lei *et al*. (2024) provided insights into optimal dietary EPA levels for juvenile abalone, but the long-term effects of these dietary modifications on adult abalone health, reproductive success, and overall yield need further investigation. Additionally, understanding the interactions of EPA with other dietary components can refine dietary formulations. Ma *et al.* (2024) demonstrated the potential of rice bran meal as a substitute for kelp meal. Yet, broader studies on the sustainability, economic viability, and environmental impact of alternative feed ingredients are required. Exploring locally available, cost-effective feed options that do not compromise abalone health and growth is essential.

Third, Dezfooli *et al.* (2023) highlighted the benefits of encapsulated probiotics, but the mechanisms underlying probiotic efficacy, optimal dosages, and long-term health impacts remain poorly understood. Research into the interactions between probiotics, abalone gut microbiota, and immune responses is needed to develop robust health management strategies. Copedo *et al*. (2024) identified histopathological factors affecting growth performance, yet comprehensive studies on the prevalence, transmission, and control of pathogens in abalone populations are limited. Developing effective disease prevention and control measures, including selective breeding for pathogen resistance, is crucial for sustainable farming.

Moreover, Lyu *et al.* (2023) and other studies have focused on specific species and hybrids, but there is a need for more extensive genetic studies across diverse abalone species. Understanding genetic variability, heritability of desirable traits, and potential for genetic improvement through selective breeding or genetic engineering can enhance productivity and resilience. Yue *et al*. (2024) explored the benefits of dietary hydroxyproline on muscle quality, yet comprehensive studies on post-harvest handling techniques, storage conditions, and processing methods to maintain and enhance muscle quality and shelf life are lacking. Investigating innovative approaches to improve post-harvest management will increase market value and consumer satisfaction.

While many studies focus on biological and physiological aspects, there is a gap in understanding the economic viability of different farming practices, feed formulations, and health management strategies. Conducting cost-benefit analyses and market studies will provide insights into the economic sustainability of abalone aquaculture. The social and regulatory aspects of abalone farming, including community engagement, regulatory compliance, and environmental impact assessments, are often underexplored. Research into developing inclusive, sustainable, and socially responsible farming practices will support broader adoption and acceptance of abalone aquaculture.

CONCLUSION

The development of sustainable feeds for abalone aquaculture is crucial for reducing environmental impact and ensuring the optimal growth and health of abalone. Promising alternatives to traditional fishmeal include plant-based

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proteins, insect-based proteins, and microbial proteins, which provide essential nutrients in an environmentally friendly manner. Research indicates that soybean meal, algae, and other legumes can effectively replace fishmeal, while insect-based proteins such as black soldier fly larvae offer sustainable and cost-effective options. Incorporating probiotics and prebiotics into feeds has shown to improve abalone gut health and nutrient absorption. Ensuring the economic viability of these sustainable feeds through cost-effectiveness and availability evaluations is vital for widespread adoption. Life cycle assessments help identify the most sustainable options, with studies showing that plant-based and insect-based proteins use fewer resources than traditional livestock feeds. Ongoing research and collaboration among researchers, feed manufacturers, and abalone farmers are essential for advancing sustainable feed development. Innovative processing techniques and partnerships can enhance the nutritional value and scalability of alternative feeds, driving the industry towards more sustainable practices that benefit both the environment and abalone farmers.

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