

Feature Review

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Optimizing Feed Formulations for Enhanced Growth and Environmental Sustainability in Common Carp Aquaculture

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Abstract This study provides an overview of the nutritional requirements of common carp, including protein, lipids, carbohydrates, and micronutrients. It explores strategies to promote carp growth through the use of alternative protein sources, optimization of feed conversion ratios, and the inclusion of digestibility enhancers. Additionally, the study delves into the environmental impacts of feed, proposing effective strategies to reduce nitrogen and phosphorus pollution as well as lower the carbon footprint. Case studies, such as the use of plant-based feeds in China and the integration of insect meal in Europe, demonstrate successful sustainable practices in carp aquaculture. Technological advancements, including precision nutrition, machine learning, and smart feeding systems, are identified as key factors for future development. This study focuses on optimizing feed formulations in common carp aquaculture to enhance growth and environmental sustainability.

Keywords Common carp aquaculture; Feed optimization; Environmental sustainability; Alternative protein Sources; Precision nutrition

1 Introduction

Common carp (*Cyprinus carpio* L.) is one of the most widely cultivated freshwater fish species globally, owing to its adaptability to diverse environmental conditions and its significant role in food security. The aquaculture of common carp has seen substantial growth, driven by the increasing demand for fish protein and the decline in wild fish stocks (Sobczak et al., 2021). Traditional pond aquaculture remains the predominant method for raising common carp, particularly in regions such as Europe and Asia (Biermann and Geist, 2019). However, the industry faces challenges related to environmental sustainability and the need for efficient feed formulations to enhance growth performance and fish health.

Optimizing feed formulations is crucial for the sustainable development of common carp aquaculture. The choice of feed ingredients not only impacts the growth and health of the fish but also has significant environmental implications. For instance, replacing conventional feed components with sustainable alternatives such as microalgae and macroalgae can improve the nutritional quality of carp fillets while reducing the reliance on fishmeal and vegetable oils. Dietary supplements like polyphenols and ginger extract have been shown to enhance growth performance, immune response, and oxidative status in common carp, further contributing to the overall sustainability of aquaculture practices (Jahazi et al., 2020; Mohammadi et al., 2020). Life Cycle Assessment (LCA) studies highlight the environmental benefits of organic feed sources and the need to address critical issues such as feed type, pond dredging, and nutrient retention to minimize the ecological footprint of carp farming.

This study will comprehensively analyze the latest advancements in carp feed formulation, with a focus on its impact on growth performance, fish health, and environmental sustainability. It will evaluate the nutritional and sensory characteristics of carp fillets produced from different feed formulations. Additionally, the study will use the Life Cycle Assessment (LCA) method to compare the environmental impacts of traditional and organic carp farming, identifying key areas for improvement in feed formulation and aquaculture practices to enhance sustainability.

2 Nutritional Requirements of Common Carp

2.1 Protein and amino acid requirements

Protein is a critical component of the diet for common carp (*Cyprinus carpio*), as it directly influences growth performance and overall health. Studies have shown that the inclusion of high-quality protein sources, such as fishmeal, can significantly enhance growth rates and feed conversion ratios. For instance, a study demonstrated that replacing half of the fishmeal with a blend of microalgae and macroalgae resulted in higher protein levels in carp fillets, indicating the potential of sustainable protein sources in aquaculture diets. Supplementation with β -mannanase in plant protein-rich diets has been shown to improve nutrient digestibility and growth performance, highlighting the importance of enzyme supplementation in optimizing protein utilization (Dawood and Shi, 2022).

2.2 Lipid and fatty acid requirements

Lipids are essential for providing energy and essential fatty acids, which are crucial for maintaining cellular integrity and metabolic functions. Research indicates that the type of lipid source can significantly affect the nutritional quality of carp meat. For example, replacing vegetable oils with salmon oil in the diet of common carp improved the fatty acid profile of the meat, making it a more nutritious option for human consumption (Sobczak et al., 2021). Moreover, dietary supplementation with thyme essential oil has been shown to reduce triglyceride levels and improve overall lipid metabolism in common carp (Ghafariarsani et al., 2022).

2.3 Carbohydrate utilization in carp diets

Carbohydrates serve as an important energy source in fish diets, although their utilization can vary among species. In common carp, the inclusion of carbohydrate-rich ingredients such as field peas and wheat dried distillers grain with soluble (WDG) has been studied. It was found that diets containing WDG resulted in higher growth rates and better nutrient digestibility compared to other carbohydrate sources (Prabhu et al., 2019). This suggests that selecting appropriate carbohydrate sources can enhance the efficiency of energy utilization in carp diets.

2.4 Micronutrients: vitamins and minerals

Micronutrients, including vitamins and minerals, play vital roles in various physiological processes and overall health of common carp. Vitamin C supplementation, for instance, has been shown to improve growth performance, survival rates, and biochemical indices in common carp. Similarly, the inclusion of iodine and selenium from natural sources in the diet has been found to enhance the elemental nutritional value of carp fillets, making them a richer source of essential nutrients for human consumption (Barbosa et al., 2020). The use of prebiotics, probiotics, and synbiotics has been demonstrated to boost immune responses and antioxidant status, further supporting the importance of micronutrient supplementation in aquaculture (Ajdari et al., 2022).

3 Feed Formulation Strategies for Enhanced Growth

3.1 Use of alternative protein sources

The use of alternative protein sources in aquaculture feed formulations has been extensively studied to enhance growth performance and sustainability. For instance, soybean meal (SBM) and soybean protein concentrate (SPC) have been evaluated as replacements for fish meal (FM) in the diet of white snook, showing that up to 45% replacement can be achieved without negatively affecting growth or digestibility (Arriaga-Hernández et al., 2021). Similarly, the inclusion of *Clostridium autoethanogenum* protein (CAP) in the diet of juvenile Jian carp significantly improved growth performance and feed conversion ratios (FCR) (Li et al., 2021). Another promising alternative is spirulina meal (SPM), which has been shown to significantly improve final body weight, specific growth rate, and protein efficiency ratio in fish and shrimp.

3.2 Optimization of feed conversion ratios (FCR)

Optimizing the feed conversion ratio (FCR) is crucial for enhancing growth efficiency in aquaculture. Studies have demonstrated that dietary supplementation with prebiotics, probiotics, and synbiotics can significantly reduce FCR in common carp. For example, the inclusion of PrimaLac, inulin, and Biomin Imbo in the diet of common carp resulted in a significant decrease in FCR, along with improvements in weight gain and specific growth rate (Ajdari et al., 2022). The use of acidified fish feeds has been shown to reduce the energetic costs of

digestion, leading to a 14% improvement in the conversion of food into fish growth in juvenile barramundi (Goodrich et al., 2022). Furthermore, the application of a hybrid method combining bioenergetics factorial models with fuzzy logic control technology has been shown to reduce FCR by 12.24% in grass carp, thereby enhancing feed efficiency (Zhao et al., 2020).

3.3 Role of digestibility enhancers in feed formulation

Digestibility enhancers play a vital role in improving the efficiency of nutrient absorption and overall growth performance in fish. The supplementation of medium-chain fatty acids and taurine (AQUAGEST®) in the diet of common carp has been shown to significantly increase digestive enzyme activities, leading to improved growth and feed utilization (Magouz et al., 2020). Similarly, the inclusion of brown seaweed (*Padina australis*) extract in the diet of common carp has been found to enhance digestive enzyme activities and intestinal immunity, resulting in better growth performance and disease resistance (Sheikhzadeh et al., 2022). The use of herbal additives such as thyme essential oil and quercetin has been shown to significantly enhance digestive enzyme activities and biochemical parameters in common carp, further supporting their role as effective digestibility enhancers (Ghafarifarsani et al., 2022).

4 Environmental Impacts of Common Carp Feed

4.1 Reduction of nitrogen and phosphorus pollution

The reduction of nitrogen (N) and phosphorus (P) pollution is a critical aspect of sustainable aquaculture. Various studies have explored strategies to minimize these pollutants in common carp farming. For instance, the use of biofloc technology (BFT) has shown promise in reducing ammonia nitrogen, nitrite, and nitrate concentrations in aquaculture systems. Specifically, a C/N ratio of 19:1 was found to improve water quality and growth performance in common carp without negatively affecting carcass composition (Minabi et al., 2020; Chen, 2024). Modified cereals, such as thermally-treated and pressed wheat, have been shown to improve nutrient digestibility, thereby reducing nutrient concentrations in effluent water. These findings suggest that optimizing feed formulations and incorporating innovative technologies can significantly mitigate nitrogen and phosphorus pollution in common carp aquaculture.

4.2 Strategies to lower carbon footprint in aquaculture feeds

Lowering the carbon footprint of aquaculture feeds is essential for enhancing the environmental sustainability of common carp farming. A comprehensive study comparing the environmental impacts of various blue foods found that improving feed conversion ratios (FCR) and increasing fish yield can reduce greenhouse gas emissions and other environmental stressors (Gephart et al., 2021). The life cycle assessment (LCA) of conventional and organic carp aquaculture in Germany revealed that conventional production has higher climate change indicator values due to the sourcing of feed grains from non-organic origins. However, both conventional and organic systems have significantly lower carbon footprints compared to other animal products, such as beef (Biermann and Geist, 2019). These insights highlight the importance of optimizing feed types and sourcing sustainable ingredients to lower the carbon footprint in common carp aquaculture.

4.3 Impact of feed on water quality and ecosystem health

The type of feed used in common carp aquaculture can have profound effects on water quality and ecosystem health. Studies have shown that different supplementary feeds, such as cereal grains and pelleted feeds, can influence water variables and nutrient budgets. For example, the use of cereal grains was found to generate higher economic and environmental benefits compared to pelleted and extruded feeds, as it resulted in lower nutrient concentrations in effluent water (Hlaváč et al., 2015; 2016). The application of eco-substrates and carbon addition in pond polyculture systems has been demonstrated to improve water quality, fish growth, and nutrient utilization efficiency (Guo et al., 2022). These findings underscore the need for careful selection and management of feed types to maintain water quality and support ecosystem health in common carp aquaculture.

5 Case Study: Success Stories in Sustainable Carp Aquaculture

5.1 Plant-based feeds in China's carp industry

China has made significant strides in incorporating plant-based feeds into carp aquaculture, which has shown promising results in terms of both growth performance and environmental sustainability. A study assessing the nutritional value and sensory properties of common carp (*Cyprinus carpio* L.) fed with a blend of microalgae and macroalgae demonstrated that these plant-based ingredients could effectively replace a portion of fishmeal in the diet. The experimental diet led to higher protein levels and better quality intramuscular fat in the carp fillets, making them a nutritious and sensorily attractive option for consumers (Sobczak et al., 2021). This approach not only reduces reliance on fishmeal but also leverages sustainable and natural feed ingredients, contributing to the overall sustainability of the aquaculture industry.

5.2 Insect meal integration in European carp farms

European carp farms have begun integrating insect meals into their feed formulations, with notable success. Insect meals, such as those derived from black soldier fly larvae and mealworms, have been shown to be effective protein sources that can replace traditional fishmeal. A meta-analysis revealed that low to moderate levels of insect meal incorporation did not negatively impact fish growth, and in some cases, even improved it (Hua, 2021). A study on the use of insect-based fish feed for grass carp (*Ctenopharyngodon idella*) found that diets containing 20% to 40% insect meal significantly accelerated growth rates and reduced mortality (Naz et al., 2023). These findings highlight the potential of insect meals to enhance the sustainability and economic viability of carp aquaculture in Europe.

5.3 Environmental and economic benefits observed in case studies

The integration of alternative protein sources, such as plant-based and insect-based feeds, in carp aquaculture has demonstrated substantial environmental and economic benefits. For instance, the use of *Hermetia illucens* larvae and *Lemna minor* in fish feed production has shown ecological competitiveness and sustainability compared to standard feeds. This approach efficiently combines waste and environmental service concepts, producing high-quality raw materials for the fish feed industry while reducing the environmental footprint (Goyal et al., 2021). The economic analysis of insect meal integration in aquaculture revealed that, despite higher initial costs, the long-term environmental benefits and potential for consumer acceptance make it a viable alternative (Arru et al., 2019; Llagostera et al., 2019). These case studies underscore the importance of innovative feed formulations in promoting sustainable and economically feasible carp aquaculture practices.

6 Technological Advances in Feed Formulation and Aquaculture Practices

6.1 Precision nutrition: tailoring diets for growth and sustainability

Precision nutrition in aquaculture involves customizing diets to meet the specific nutritional requirements of individual fish, thereby optimizing growth and minimizing waste. This approach integrates various factors such as genetic background, living habits, and metabolic characteristics to formulate precise nutritional interventions. By tailoring feed compositions to the specific needs of common carp, precision nutrition not only enhances growth performance but also reduces feed wastage and environmental impact (Zhang et al., 2020; Zhu and Li, 2024). For instance, the use of a hybrid method combining bioenergetics factorial models with fuzzy logic control technology has shown significant improvements in feed efficiency and growth parameters in grass carp, demonstrating the potential of precision feeding systems in aquaculture.

6.2 Use of machine learning and ai in feed formulation

The integration of machine learning (ML) and artificial intelligence (AI) in feed formulation represents a significant technological advancement in aquaculture. These technologies enable the development of predictive models that can accurately determine the nutritional needs and growth trajectories of fish. For example, a web-based combined nutritional model has been developed to predict the growth, feed requirement, and waste output of gibel carp, utilizing data from multiple sources to optimize feed formulations (Figure 1). Such models can process vast amounts of data to provide real-time recommendations, thereby enhancing feed efficiency and

reducing environmental impact. The application of ML and AI in feed formulation not only improves the precision of nutritional interventions but also supports sustainable aquaculture practices by minimizing waste and optimizing resource use (Liu et al., 2018).

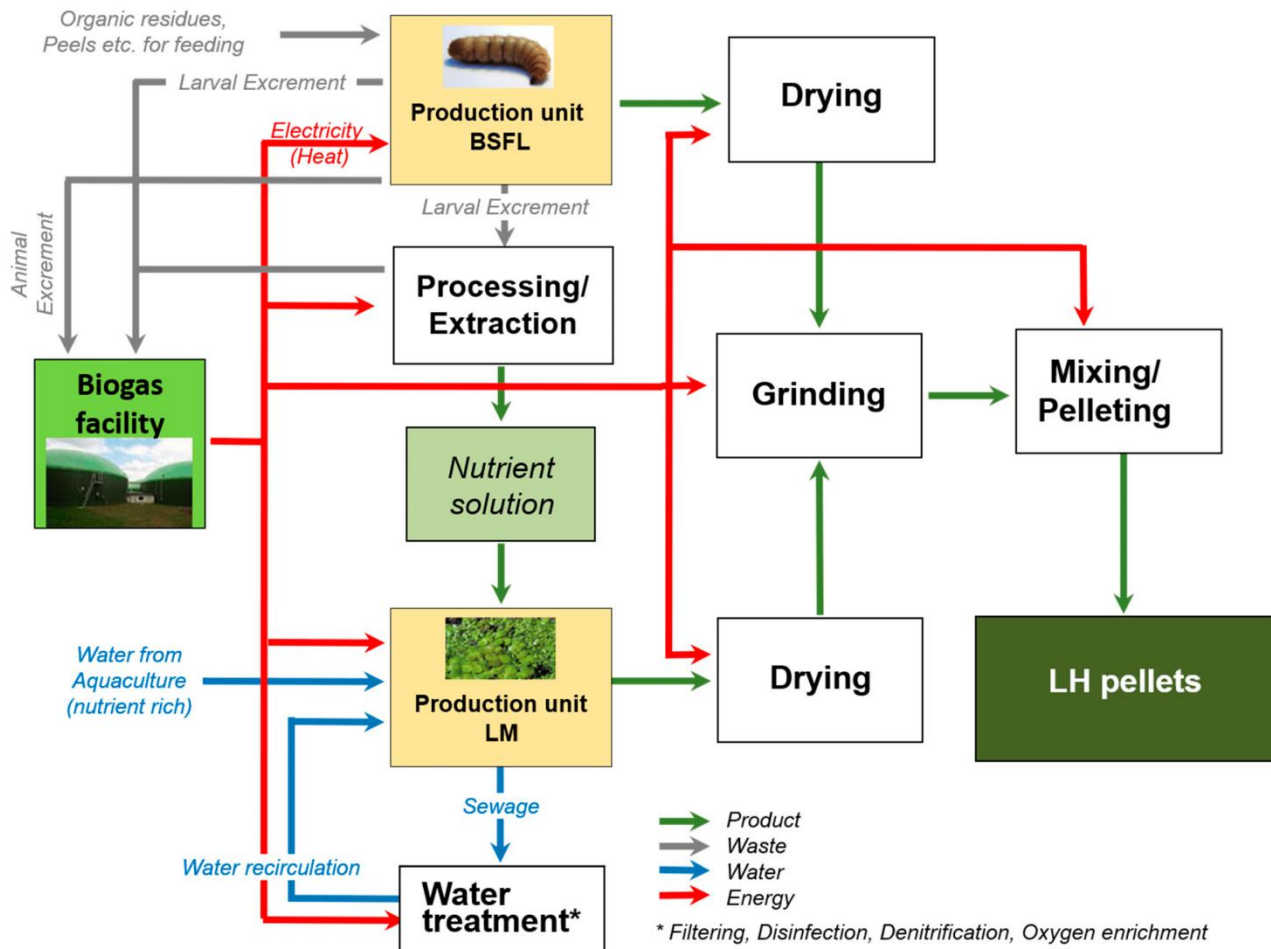


Figure 1 Sustainable production system for fish feed (Adopted from Goyal et al., 2021)

6.3 Automation and smart feeding systems for carp aquaculture

Automation and smart feeding systems are revolutionizing carp aquaculture by enabling precise control over feeding practices. These systems utilize sensors and automation technologies to monitor real-time parameters such as dissolved oxygen and water temperature, adjusting feeding schedules and quantities accordingly (Zhao et al., 2020; Şonea et al., 2023). For instance, the implementation of a precision feeding control system using fuzzy logic technology has demonstrated superior performance in predicting feed requirements and improving feed conversion rates in grass carp. Smart feeding systems can reduce labor costs and enhance the overall efficiency of aquaculture operations. By integrating automation with precision nutrition and AI, these systems contribute to the sustainable growth of the aquaculture industry, ensuring optimal fish health and minimizing environmental impact.

7 Challenges and Future Directions in Carp Feed Optimization

7.1 Overcoming the limitations of alternative protein sources

One of the primary challenges in optimizing feed formulations for common carp is the effective use of alternative protein sources. Traditional fishmeal, while effective, is not sustainable due to overfishing and high costs. Research has shown that alternative proteins such as insect meals, macroalgae, and single-cell proteins can be viable substitutes, but they come with their own set of limitations. For instance, some alternative proteins have been found to negatively impact gut health and immune responses in fish (Aragão et al., 2022). The digestibility

and nutrient absorption rates of these proteins can vary significantly, affecting growth performance and overall health (Hoerterer et al., 2022). Further research is needed to refine these alternative protein sources to ensure they provide the necessary nutrients without adverse effects on fish health.

7.2 Expanding the use of sustainable ingredients in feed

The use of sustainable ingredients in carp feed is crucial for the long-term viability of aquaculture. Ingredients such as brewer's spent grains (BSG) and various algae have shown promise in replacing traditional feed components like soybean meal and fishmeal. Studies have demonstrated that BSG can replace up to 50% of soybean meal without negatively impacting growth or nutrient utilization in fish (Jayant et al., 2018). Similarly, the inclusion of microalgae and macroalgae in feed formulations has been shown to improve the nutritional quality of fish fillets, making them more attractive for human consumption (Sobczak et al., 2021). However, the challenge lies in scaling up the production of these sustainable ingredients and ensuring their consistent quality and availability.

7.3 Regulatory and economic challenges in implementing sustainable feeds

Implementing sustainable feed formulations in common carp aquaculture is not without regulatory and economic challenges. The approval process for new feed ingredients can be lengthy and complex, involving rigorous testing to ensure safety and efficacy. Additionally, the cost of producing alternative protein sources can be higher than traditional ingredients, making them less economically viable for many farmers (Albrektsen et al., 2022). There is also the issue of market acceptance, as consumers and regulatory bodies may be hesitant to adopt new feed ingredients without substantial evidence of their benefits. Addressing these challenges will require coordinated efforts between researchers, industry stakeholders, and policymakers to develop cost-effective, sustainable feed solutions that meet regulatory standards and gain market acceptance.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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