

Economic Feasibility and Ecological Effects of Alternative Protein Feeds: Input Evidence and Subsequent Environmental Impacts of Fish and Other Farmed Animals

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Abstract. The large-scale production of traditional fish and farmed animal feed is causing increasingly severe resource consumption and greenhouse gas emissions, and alternative protein feed is seen as a potential solution to alleviate the above environmental pressures. However, the existing technology and research are still immature in terms of environmental assessment methods and cost control systems. This paper discusses the economic feasibility and ecological effect of alternative protein feed, life cycle assessment and economic feasibility through integrated analysis. The results show that the core dilemmas faced by alternative protein feed at present include: due to the supply of raw materials and production scale, its cost competitiveness is still weaker than that of traditional feed; In terms of ecological effects, although the performance of greenhouse gas, land and water resources indicators is better than that of traditional protein, there are phenomena of environmental burden transfer such as energy consumption transfer, land occupation transfer and nutrient transfer; In addition, regulations and market access barriers also restrict its promotion. Overall, alternative proteins have shown economic potential in specific scenarios, but do not yet have the conditions to fully replace conventional feeds. Future research should focus on cost control, raw material selection, technological innovation and policy guidance to promote alternative protein feeds from experimental stage to large-scale application.

Keywords: Alternative protein feed; Economic feasibility; Ecological effects; Environmental burden transfer; Life Cycle Assessment.

1. Introduction

Traditional fish meal feed is facing the double dilemma of resource shortage and rising prices. This phenomenon profoundly reveals that the global demand for protein feed in aquaculture and animal husbandry continues to rise, and that traditional supply systems are difficult to keep up with the pace of growth. In recent years, the environmental and social problems brought by traditional animal husbandry and aquaculture have emerged one after another. Conventional livestock farming occupies more than three-quarters of the world's agricultural land while contributing about two-thirds of agricultural greenhouse gas emissions, according to official scientific assessments released commissioned by the European Union Parliament. However, the EU faces a serious "feed protein deficit"-the self-sufficiency rate of high-protein oilseed meals is only 24% [1].

What are alternative proteins, their classification, nutritional composition, current development status of alternative proteins (not only in feed, but also in other fields), and environmental impact

It is in this context that alternative proteins have become the hot topic of current research. Although alternative proteins generally outperform traditional proteins in terms of land use, some production processes instead consume more energy. In view of this, this paper systematically sorts out the related research around the alternative protein feed, aimed at whether the alternative protein feed really has economic feasibility and environmental sustainability for further assessment.

2. Classification and Mechanism of Alternative Proteins

Alternative protein feeds can be mainly classified into plant-derived proteins (e.g., soybean protein, rapeseed meal), insect proteins (e.g., black fly larval meal, mealworm), single-cell proteins (e.g.,

bacterial or yeast fermentation products), and microalgal proteins [2]. There are significant differences in nutrient composition (protein, fat, carbohydrate, trace elements) and effects on fish growth, reproduction and immune function. In this paper, the protein source and production process are discussed separately.

2.1. 2Plant-derived Proteins

Soybean protein has a crude protein content of about 44% to 48%, a low-fat content, and carbohydrates predominantly in the form of non-starch polysaccharides. Proper substitution of fish meals has no significant negative impact on the growth performance of most farmed fish, but if the substitution ratio is too high, it may induce intestinal inflammation and immunosuppression [3]. Furthermore, rapeseed meal, as another type of plant protein source, has a protein content of about 35% to 40%, but a high content of antinutrient factors, limiting its wide application in aquatic feed [3].

2.2. Insect Proteins

Insect proteins (especially black fly larval meal) have crude protein content ranging from 35% to 45%, high fat content and high lauric acid. Such proteins can maintain or even improve the growth performance and immune index of fish at appropriate substitution ratios. Studies have shown that the proportion of fish meals substituted by larval meals of black tabfly can reach 25% to 75%, but the specific value depends on the cultivated species and environmental conditions [4].

2.3. Single Cell Proteins

Single cell proteins are produced by bacteria, yeast or microalgae through fermentation, and the protein content can be as high as more than 50%, and the amino acid composition is relatively balanced. However, some products have problems with high nucleic acid content and low digestibility. This kind of protein can use wastewater, organic waste or clean energy as a matrix, so it has high resource utilization efficiency [5].

2.4. Microalgae Proteins

Microalgae proteins are rich in essential amino acids and omega-3 fatty acids, but they are limited by the difficult-to-digest cell wall structure and must be treated with wall breaking [6,7]. At present, the production cost of microalgae protein is still on the high side, and it is mainly used as functional feed additive. Studies have shown that the environmental performance of microalgal proteins is largely dependent on the design of production systems and their by-product valorization strategies [6,7].

3. Economic Feasibility Assessment

According to data published by the International Organization of Marine Raw Materials, the price of fishmeal protein reached USD 2,214 per tonne, and the global market size in 2025 is approximately USD 10 billion [8]. This price is significantly higher than that of plant proteins such as soybean meals. Surprisingly, however, even though fishmeal is expensive, farmers still tend to use it-for no other reason: fishmeal has a balanced amino acid ratio and essential fatty acids. In other words, for alternative proteins to truly capture market share, they must not only be competitive in price but also provide nutritional value as good as traditional fish meal.

In terms of insect powder, take black fly larval powder as an example. In Kenya, researchers replaced fish meal with 25%, 50% and 75% insect meal in an earth pond. The results showed that the feed cost of the 75% replacement group decreased to \$0.79 per kg, the lowest of all the tested groups, and its net profit was even higher than that of the whole fishmeal group [9,10]. However, this result was achieved in low-and middle-income countries under the conditions of earth pond farming-the presence of natural bait in the pond can supplement the nutritional gap to some extent. As for whether

this experience can be replicated to high-density factory farming, there is still a lack of clear conclusion. Overall, the production cost of insect protein is greatly affected by the stability of kitchen waste raw material supply and the scale of larval culture [11].

In terms of single-cell proteins, Fasihi et al. use clean energy hydrogen production combined with carbon capture technology to produce single-cell proteins on a large scale. According to its forecast, the cost of single-cell protein can be reduced to 2.1 to 2.3 euros per kilogram of protein by 2050, which is basically the same or even lower than the long-term average price of fish meal. In particular, the study pointed out that Global South, such as Africa and Latin America, is best placed for such production lines because of its abundant light resources [2]. However, there is still a big gap between ideal and reality. At present, the main bottleneck of single-cell protein production is concentrated in purification and drying, and excessive energy consumption leads to high cost [12,13]. Fernández-López et al. [3] also pointed out that most of the existing studies focus on environmental accounts, while the data on economic feasibility are seriously insufficient. The review by Chamodi et al. [5] further confirmed that single-cell proteins face multiple challenges in the commercialization process, such as fermentation efficiency, downstream processing costs, and food safety certification.

In terms of microalgae protein, Beal et al. analyzed the data from the pilot facility in Hawaii and found that if high-value by-products such as pigments and omega-3 in microalgae were extracted and sold together, the environmental load of the main product protein could be reduced by more than 40% [6]. Unfortunately, microalgae culture itself is not cheap-photobioreactors and open ponds are not only expensive, but also occupy a huge area, and the initial investment is prohibitive [11]. The technical and economic evaluation of Quiroz-Arita et al. even pointed out that the extraction of high-value components (such as carotenoids) from microalgae biomass is of key significance to improve the overall economic feasibility [11].

Overall, alternative proteins have indeed shown economic potential under certain conditions. For example, using kitchen waste to farm insects, or in low-cost earth pond farming scenarios, the yield may even exceed that of fishmeal [6]. But the biggest obstacle remains the bottleneck of scale. Official report of the European Union Insufficient production capacity in food-grade industries is an "old difficulty" in the global promotion of microbial fermentation technology [1]. From several tons per year in laboratories to hundreds of thousands of tons per year in industrialization, every link such as equipment, supply chain and quality control means huge capital investment. Ismail & Mokhtar' s study of *Azolla pinnata* as a source of tropical feed protein also showed that although this plant protein has high nutritional potential, the economy of large-scale cultivation and processing remains doubtful [11]. It can be said that the economic feasibility of alternative proteins is still highly dependent on specific application scenarios; If it wants to truly move towards large-scale promotion, it must continue to tackle difficulties in reducing costs, expanding production capacity and supplementing empirical economic data.

4. Ecological Effect Assessment

The report by TOA provides a striking set of figures: livestock farming occupies more than three-quarters of the world's agricultural land while contributing approximately two-thirds of agricultural greenhouse gas emissions [1]. The supply of fishmeal is highly concentrated in a few countries such as Peru and Chile. When El Niño phenomenon comes, the whole supply chain will suffer heavily. This means that the traditional protein production mode not only consumes high resources and emits large carbon emissions but also has serious hidden dangers in vulnerability to climate change.

It is precisely because the traditional model is unsustainable that alternative protein has been held up as an "environmental savior". Life cycle assessment (LCA) studies have indeed given a lot of bright data.

In terms of greenhouse gas emissions, a review by Fernández-López et al. found that if wastewater or organic waste is used to cultivate microorganisms to produce single-cell proteins, its environmental impact can be reduced by 60% to 96% compared with traditional proteins-the higher the matrix

quality, the more obvious the emission reduction effect [3]. The black fly protein performed even better: under the optimized scenario, the climate impact could be reduced by 79%, while the carbon storage effect jumped by 577%, because the insects fixed carbon in biomass [1]. Data on land use and water resources are equally encouraging. Compared with soybeans, Fasihi et al. discovered that, the land occupation of single-cell protein is only 1/2 to 1/35 of the former, and the water consumption is less than 1/200 [2]. Insect protein is also superior to soybean in the three core indicators of climate change, land use and water resources [1]. Ismail & Mokhtar's study of Mitsulis furthermore revealed that this aquatic plant protein source can grow without chemical fertilizers and simultaneously has nitrogen fixation, showing potential in reducing non-point source pollution in agriculture. Li et al.'s comprehensive evaluation of low-protein diet technology in poultry farming also showed that reducing feed protein levels significantly reduces nitrogen emissions, but it needs to be weighed against production performance and economic benefits [11].

This data further indicate that it would be too hasty to jump to the conclusion that "alternative proteins are absolutely environmentally friendly". Because more and more research is beginning to draw attention to an easily overlooked but crucial issue: environmental burden transfer. In other words, the replacement protein simply transfers some environmental stress from one end to the other.

Specifically, there are at least three types of transfers that cannot be ignored.

First, energy consumption transfer. The report by STOA puts it bluntly: the production process of certain alternative proteins is inherently quite energy-intensive, and in individual cases even more electricity-intensive than conventional proteins [1]. This means that if the electricity used in production is still mainly from coal-fired power plants, its carbon reduction advantage will be greatly reduced. In other words, the environmentally friendly color of alternative proteins depends largely on the "cleanliness" of the energy structure. The evaluation by Quiroz-Arita et al. also confirmed that the energy consumption of microalgae culture systems can reach more than 30% of the total environmental impact under high light conditions [10].

Second, land transfer. When Beal et al. conducted LCA analysis of microalgae proteins, they found that land occupation was the only obvious environmental shortcoming of microalgae proteins [6]. A large number of photobioreactors and open pools, although increasing output, also occupy a large area of land. In other words, the pressure on land has not really disappeared, but has simply moved from pastures to factories. T

Third, nutrient transfer. Starting from the whole animal production chain, Gil et al. pointed out an easily overlooked risk: replacing animal proteins entirely with alternative proteins may bring new nutritional problems [7]. Traditional fish meals are naturally rich in vitamin B12, long-chain omega-3 fatty acids, and heme iron, which are either extremely low or absent in many plant-or microbial-based alternative proteins. Once the feed lacks these nutrients, it will first affect the health of farmed animals themselves. In the long run, it may also be transmitted along the food chain to humans, resulting in nutritional risks-this is not only an environmental problem, but also related to public health. Yan et al.'s nutritional analysis of mealworm, black fly and barley worm also verified this concern: although insect protein is rich in lauric acid, its long-chain omega-3 content is generally lower than that of fish meal, which still needs to be compensated by formula optimization [4].

In summary, alternative proteins do outperform traditional proteins in indicators such as greenhouse gases, land and water resources, which gives them the basic conditions to be an environmentally friendly alternative. But the "burden shift" doesn't exist. Energy consumption, land, nutrition — these are the costs that are quietly diverted out and likewise need to be included in the systematic evaluation. Only by breaking the casserole and asking to the end will not be fascinated by the "environmental protection aura" on the surface.

5. Regulations and Obstacles to Market Access

In addition to economic and environmental factors, alternative protein feeds also face regulatory and market access obstacles that cannot be ignored. STOA pointed out that the approval process for

new feed proteins in the European Union and other regions is lengthy, especially when it comes to insect and microbial fermented products, and sufficient data on food safety and anti-nutritional factors must be provided. In addition, some of the alternative protein raw materials come from waste or by-products, which may touch the red line of waste management regulations [1]. Chamodi et al. also emphasized in the Single Cell Protein Review that food safety certification (such as the new EU food regulation) is an important threshold in the commercialization process [5]. From a market perspective, farmers' acceptance of new feeds is generally low, mainly due to unstable supply, quality fluctuations, and lack of long-term usage data [14]. The research of Long et al. also confirmed that insufficient market acceptance and imperfect supply chain are one of the main obstacles to the promotion of alternative proteins [14, 15]. These regulations and market constraints have further delayed the process of alternative proteins from laboratory to field, and from pilot to large-scale promotion.

6. Conclusion

This paper systematically analyzes the economic feasibility and ecological effect of substituting protein feed under realistic production conditions. Through the comparison of different raw materials, technology paths and breeding scenarios, it is found that the economic competitiveness of alternative proteins highly depends on the scale level and the reduction of process energy consumption, while it is generally superior to traditional proteins in ecological indicators such as greenhouse gas emission, land and water resources utilization. However, the shifting phenomena of environmental burden-such as energy consumption, changes in land occupation patterns, and farming risks caused by nutrient deficiencies-are equally significant, indicating that a single-dimensional life cycle assessment is difficult to fully reflect real environmental benefits. The above analysis reveals a key insight: the promotion of alternative proteins is not only a problem of technological substitution, but also a problem of system optimization. In the future, research should jump out of the simple judgment of "whether it is environmentally friendly" and turn to multi-dimensional and whole-chain comprehensive assessment. This provides an empirical basis for developing more precise policy intervention and investment strategies.

It is worth pointing out that the current field is generally limited by the stability of raw material supply, the maturity of production process and the imperfection of regulatory access mechanism, and the evaluation methods of the literature covered in this paper are mainly short-term experiments, lacking the tracking data of long-term and large-scale demonstration scenarios.

Therefore, future research should focus on promoting process innovation to reduce production costs, broaden the sources of non-food-grade raw materials, design a full-chain assessment framework covering environmental-economic multi-indicators, and speed up the coordinated landing of policies and market mechanisms, so as to promote the popularization of alternative proteins from pilot to industrial.

References

- [1] European Parliament's Scientific Foresight Unit (STOA). Alternative proteins for animal feed: economic and environmental assessment[R]. European Union, 2024.
- [2] Fasihi M, Jouzi F, Tervasmäki P, et al. Global potential of sustainable single-cell protein based on variable renewable electricity[J]. *Nature Communications*, 2025, 16(1): 1496.
- [3] Fernández-López L, González-García P, Fernández-Ríos A, et al. Life cycle assessment of single cell protein production—a review of current technologies and emerging challenges[J]. *Cleaner and Circular Bioeconomy*, 2024, 8: 100079.
- [4] Yan Y Q, Xue M, Wu L X, Liang X F. Nutrient composition of resource insects and its application in aquaculture: a case study of mealworm, black gadfly and barley worm[J]. *Acta Animal Nutrition*, 2025.
- [5] Chamodi K K D, Nguyen T V, Domingos J, et al. Cellular solutions: evaluating single-cell proteins as sustainable feed alternatives in aquaculture[J]. *Biology*, 2025, 14(7): 764.

- [6] Beal C M, et al. Co-product valorization in microalgae protein production: economic and environmental trade-offs[J]. *Algal Research*, 2023, 71: 103045.
- [7] Gil M, Rudy M, Duma-Kocan P, et al. Sustainability of alternatives to animal protein sources: a comprehensive review[J]. *Sustainability*, 2024, 16(17): 7701.
- [8] IFFO (International Fishmeal and Fish Oil Organization). Market report 2025: fishmeal price and global market size[R]. London: IFFO, 2025.
- [9] Qureshi I. Alternative protein sources in aquaculture feed: a systematic literature review[J]. *LSP Perspectives*, 2025: 1-15.
- [10] Quiroz-Arita C E, Shinde S, Kim S, et al. Bioproducts from high-protein algal biomass: an economic and environmental sustainability review and risk analysis[J]. *Sustainable Energy & Fuels*, 2022, 6(10): 2496-2513.
- [11] Ismail R M, Mokhtar S I. Harnessing *Azolla pinnata* for tropical feed security: nutritional potential, economic viability, and environmental impact[J]. *BIO Web of Conferences*, 2025, 186: 01024.
- [12] Li D, et al. Integrated assessment of productive, environmental, and social performances of adopting low-protein diets technology for laying hens[J]. *Animals*, 2025, 15(2): 146.
- [13] Long F, Xiao J, Chen W J, Ding L Y. Research progress of new protein sources substituting fish meal in aquatic feed[J]. *Feed Industry*, 2025(2).
- [14] Dao T H, Moss A F. Canola meal: a sustainable protein source for poultry diets[J]. *Animals*, 2025, 15(24): 3609.
- [15] Millan L C, Müller C R. From side streams to functional protein materials: scenario analysis of Swiss whey [EB/OL]. *ChemRxiv*, 2025.