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WHY AQUACULTURE MUST REDUCE ITS DEPENDENCE ON FISHMEAL

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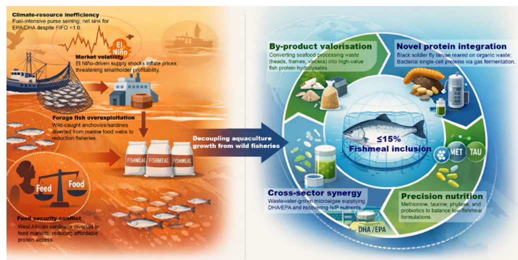
HIGHLIGHTS

- Fishmeal dependence undermines aquaculture sustainability and food system equity
- Circular aquafeeds can decouple growth from wild forage fisheries
- Insects, single-cell proteins, and by-products enable viable low-fishmeal diets
- Policy, innovation, and nutrition science drive the fishmeal-smart transition

GRAPHICAL ABSTRACT



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ABSTRACT

Aquaculture, as the world's fastest-growing food production sector is indispensable for global food security and nutrition. Yet, its environmental and economic sustainability is critically jeopardised by a deep-seated reliance on fishmeal, a finite resource derived from wild-caught forage fisheries. This comprehensive review argues that reducing this dependency is an urgent imperative, synthesising evidence from 2020 onward across environmental, economic, and social dimensions. The overexploitation of small pelagic fish for reduction to meal disrupts marine trophic webs, compromises ecosystem resilience, and conflicts with direct human consumption needs in vulnerable regions. Economically, it binds the industry to volatile commodity markets, threatening profitability and stability. The article meticulously evaluates the scientific and commercial progress in alternative proteins, including precision-formulated plant blends, insect meals, single-cell proteins, and by-product valorisation, demonstrating that viable pathways exist. Through detailed case studies and policy analysis, it concludes that a systemic transition toward circular aquafeed systems is not only feasible but essential. This transition, supported by coherent policy, targeted R&D, and market incentives, is the key to unlocking aquaculture's potential as a truly sustainable, resilient, and equitable pillar of the future global food system, aligning with the United Nations (UN) Sustainable Development Goals.

Introduction

The Aquaculture Paradox and the Fishmeal Conundrum

Aquaculture's rapid growth is a defining feature of 21st century food systems. Surpassing capture fisheries as a major source of aquatic food for human consumption, it now contributes a substantial share of global protein supply and is expected to continue expanding in the coming decade, underscoring its central role in meeting rising demand for seafood worldwide (Boyd *et al.*, 2022). With output reaching 87.5 million tonnes in 2020, 30% above the 2000s average, and projected to hit 106 million tonnes by 2030, aquaculture is outpacing both capture fisheries and most other food sectors. Its role as a pillar of global food security is now firmly established (FAO, 2022a).

Despite these successes, intensive aquaculture relies heavily on a single critical input, fishmeal. This protein- and lipid-rich powder, made from small pelagic forage fish, has long been the backbone of high-density aquaculture. Its balanced amino acid profile, high digestibility, essential phospholipids, and abundance of long-chain polyunsaturated fatty acids (LC-PUFAs), including EPA and DHA, make it crucial for carnivorous species such as Atlantic salmon, shrimp, and marine finfish. However, growing concerns about sustainability and supply have prompted exploration of alternative proteins that can partially or fully replace fishmeal without compromising fish growth or health (Serra *et al.*, 2024).

Yet, this success has created a sustainability paradox. Aquaculture, initially intended to ease pressure on wild fisheries, now consumes millions of tonnes of wild-caught forage fish each year for fishmeal and fish oil production. Life-cycle assessments show that reliance on these marine ingredients significantly contributes to resource depletion, emissions, and ecological stress. Encouragingly, studies demonstrate that alternative aquafeeds formulated without forage fish can markedly reduce these impacts, indicating that sustainable growth is achievable by supplementing or replacing traditional marine-derived ingredients (Ghamkhar & Hicks, 2020). As aquafeed production remains a major environmental hotspot, reducing dependence on marine-derived fishmeal and fish oil is one of the most effective strategies to improve sustainability (Henriksson *et al.*, 2021).

The central thesis of this review is that this dependency is no longer tenable. Reducing aquaculture's reliance on fishmeal is an urgent environmental, economic, and ethical imperative. The following sections will deconstruct the multidimensional risks of this dependency, analyse its sector-specific impacts, provide a critical appraisal of the expanding portfolio of alternative protein sources, present illustrative case studies of successful transition, and delineate the policy and innovation pathways required to secure a sustainable future for global aquaculture.

Global Challenges of Fishmeal Dependency: A Multifaceted Crisis

The reliance on fishmeal creates interconnected crises that threaten marine ecology, climate stability, economic resilience, and social equity (Figure 1).

Ecological Overshoot: Overfishing and Trophic Cascades

Forage fish are keystone species in marine ecosystems, forming dense aggregations that transfer energy from planktonic primary producers to higher trophic levels, including piscivorous fishes, seabirds, and marine mammals (Essington *et al.*, 2015). While aquaculture has significantly boosted global food security, supplying 17% of the world's animal protein and over 50% in parts of Asia and Africa, its growth has come at an ecological cost (FAO, 2022a). Millions of tonnes of wild-caught forage fish are diverted annually into fishmeal and fish oil production, creating a paradox: Species intended to relieve fishing pressure on wild stocks now contribute to overexploitation.

Although some major stocks such as the peruvian anchoveta are managed through quota-based systems, these frameworks often rely on single-species assessment models that fail to account for the critical prey role of forage fish in broader food webs (Pikitch *et al.*, 2014). Recent meta-analyses and ecosystem-based evaluations indicate that current harvest levels for many forage fish stocks remain too high to sustain predator populations, generating far-reaching ecosystem consequences.

The Climate and Resource Inefficiency Quotient

Pelagic fishing operations are fuel-intensive, making fishmeal production a significant carbon and resource burden. For example, diesel consumption by the Cantabrian purse-seine fleet drives most greenhouse gas emissions in fishmeal supply chains (Martínez-Ibáñez *et al.*, 2024). Even with improvements in feed efficiency, sustainability constraints persist. While the Fish-In Fish-Out (FIFO) ratio for salmon has fallen below 1.0 (FIFO Data | IFFO - The Marine Ingredients Organisation, n.d.), nutrient-based analyses reveal that farmed salmon remain a net sink for long-chain omega-3 fatty acids. EPA and DHA from wild fish are retained with comparatively low efficiency (Newton *et al.*, 2025).

Relying on traditional feed efficiency measures such as feed conversion ratio (FCR), which do not account for feed composition, edible yield, or nutrient quality, may misrepresent the actual efficiency of aquaculture production. These limitations underscore the need to adopt nutrient-retention metrics that more accurately reflect the proportion of feed converted into edible product (Fry *et al.*, 2018). This transformation of wild-caught fish, much of which is directly edible, into feed for luxury aquaculture products represents a questionable allocation of finite marine resources within the global food system.

Economic Volatility as a Systemic Risk

Fishmeal markets can be constrained by climatic variability such as El Niño–Southern Oscillation events, which have contributed to declining fishmeal production and increased prices, exposing aquaculture producers to long-term cost pressures and limited feed availability. These trends highlight the inevitability of fishmeal replacement in aquafeeds and the need to develop alternative protein sources, particularly plant-based ingredients (Jannathulla *et al.*, 2019). Trade restrictions and currency fluctuations further amplify these risks.

In many small-scale aquaculture operations, increases in the prices of feed ingredients, particularly fishmeal, significantly raise operating costs and can overwhelm already thin profit margins, sometimes forcing farmers to cut back or cease feeding their fish. Volatility in feed costs thus represents a persistent economic challenge for vulnerable producers, highlighting the importance of strategies to reduce reliance on expensive ingredients and improve feed efficiency (Price & Egna, 2014).

The Equity Dilemma: Fish for Feed Versus Fish for Food

A critical ethical challenge arises from competition between human consumption and aquafeeds. Small pelagic species such as sardinella in West Africa are vital sources of affordable, nutrient-dense protein for low-income populations (Robinson *et al.*, 2022). Increasing demand for these fish in aquaculture feed markets can inflate local prices, reducing access for vulnerable communities and worsening food insecurity.

This paradox highlights a tension in aquaculture's contribution to global nutrition, while farmed fish supply high-quality protein, reliance on forage species can inadvertently undermine local diets (Pleić *et al.*, 2022). Addressing feed cost volatility for small-scale farmers requires practical strategies such as greenwater technology, alternate-day feeding, and locally sourced alternative ingredients. These measures reduce reliance on expensive, globally traded fishmeal, lower production costs, and enhance the capacity of small-scale aquaculture to improve local food security and poverty alleviation (Price & Egna, 2014)

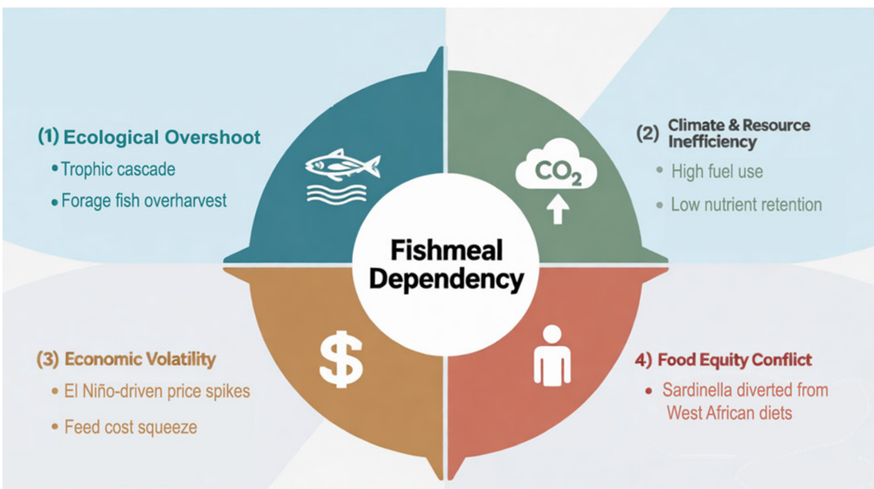

Figure 1: Global fishmeal use and its sustainability impacts

Impacts on the Aquaculture Industry: Differential Vulnerabilities and Adaptive Pressures

Fishmeal dependency strongly shapes the structure of the aquaculture industry, influencing species selection, operational strategies, and regional vulnerabilities.

Financial Resilience and the Cost-Price Squeeze

Reliance on fishmeal exposes aquaculture producers to significant economic risk. Sustained increases in feed prices, as observed in Bangladesh, can threaten profitability, particularly for small- and mid-scale farmers (Deb, 2025). These producers may be compelled to adjust feeding strategies, explore alternative ingredients, or in extreme cases, exit the sector.

This financial instability also encourages vertical integration and consolidation, as larger operations are better positioned to absorb price shocks, potentially marginalising smaller producers (Gudbrandsdottir *et al.*, 2021). Substituting fishmeal with plant-based ingredients in shrimp feeds can reduce reliance on marine resources, but it introduces trade-offs, including higher demands on land, freshwater, and nutrients such as phosphorus and nitrogen.

Thus, replacing fishmeal entirely with terrestrial alternatives does not automatically ensure sustainability. A nuanced approach, incorporating diverse ingredients, novel proteins, and mixed strategies, is essential to balance ecological impacts across both marine and terrestrial ecosystems (Malcorps *et al.*, 2019).

Species-Specific Nutritional Lock-Ins and Formulation Science

The need for fishmeal varies among aquaculture species, creating a spectrum of nutritional dependency. Studies on largemouth bass show that replacing fishmeal with alternative proteins can impair growth and health if key marine-derived nutrients, especially essential amino acids such as methionine and taurine are not supplemented (Li *et al.*, 2021). This indicates that successful fishmeal reduction requires more than simple protein substitution, formulations must address specific nutrient gaps to maintain physiological performance, gut health, and consistent growth.

Omnivorous and adaptable species, including tilapia, carp, and pangasius catfish, can maintain growth performance and health on diets with low or partially replaced fishmeal when alternative protein sources are used, and essential amino acids are properly supplemented. These findings highlight the potential of such species to support the development of more sustainable aquafeeds (Serra *et al.*, 2024).

Regional Divergence in Pathways and Challenges

In the Global North (Norway, the European Union, Canada), high-income producers have explored alternative feed ingredients in response to constraints on marine resources. Insect meals, microbial proteins, and algal oils are increasingly incorporated to reduce dependence on fishmeal and fish oil (Henry *et al.*, 2015; Sprague *et al.*, 2017). Single-cell proteins (SCPs) produced via scalable biomanufacturing platforms demonstrate further potential to replace conventional marine inputs (Chamodi *et al.*, 2025). Although adoption varies by region, these innovations illustrate a broader trend toward ingredient diversification.

In Asia-Pacific (China, Vietnam, India, Indonesia), as the world's aquaculture hub, this region exhibits a wide variety of feed strategies. China has expanded SCP, insect farming, and the utilisation of agro-industrial by-products to reduce exposure to global fishmeal price volatility (Bu *et al.*, 2024). Vietnam's pangasius sector leads in high-plant-protein diets, while India and Indonesia incorporate regional oilseed meals and emerging insect proteins. High-value shrimp production, however, faces amino acid and digestibility constraints, slowing marine-ingredient replacement relative to freshwater species.

In Latin America (Chile, Brazil, Peru), regional feed ingredient availability shapes the expansion of aquaculture. Chilean salmon farming has integrated microbial meals and algal oils, although dependence on marine oils remains due to EPA or DHA requirements. Brazilian tilapia production benefits from abundant soy-based ingredients, allowing lower fishmeal inclusion rates. Nonetheless, variability in Peruvian fishmeal supply introduces systemic uncertainty (FAO, 2022b).

Together, these regional differences highlight how technology, feedstock availability, and regulatory frameworks shape the pace and direction of marine-ingredient reduction. High-income regions lead in alternative protein adoption, while rapidly growing Asian producers scale cost-effective solutions, often within species-specific constraints.

Alternatives to Fishmeal: A Critical Appraisal of the Evolving Portfolio

The search for alternatives has evolved from simple substitution to holistic feed optimisation. Each alternative category presents unique trade-offs in nutritional adequacy, scalability, cost, and environmental impact (Table 1).

Plant Proteins: The Incumbent Alternative

Soybean meal, corn gluten meal, and rapeseed meal remain the primary plant-based alternatives to fishmeal in aquafeeds, owing to their global availability and cost-effectiveness. Advances in processing, such as toasting, fermentation, and enzyme treatment, have significantly reduced anti-nutritional factors, such as phytic acid and trypsin inhibitors, improving their suitability for fish diets. Nevertheless, these ingredients are inherently limited by imbalanced amino acid profiles, particularly deficiencies in methionine and lysine, as well as the absence of specific marine-derived nutrients essential for optimal fish growth. These nutritional gaps are routinely addressed through precision supplementation with crystalline amino acids, a now-standard practice in modern feed formulation. From a sustainability standpoint, a significant concern is Indirect Land-Use Change (iLUC), especially when sourcing from regions linked to deforestation. Moving forward, the sector is shifting toward certified sustainable supply chains and the use of refined protein concentrates to enhance nutritional quality while minimising environmental impact (Hussain *et al.*, 2024).

Table 1: Comparison of fishmeal alternatives by nutritional profile, scalability, and sustainability trade-offs

Alternative	Crude Protein (%)	Key Amino Acids	EPA/DHA Source	Scalability (Low/Med/High)	Main Sustainability Concerns
Soybean meal	44–50	Lysine high, met low	No	High	Deforestation, land use
Black soldier fly	40–45	Balanced	No (unless oil-enriched)	Medium	Substrate dependency
Bacterial SCP	60–75	Balanced	No (but can co-produce DHA algae)	Medium (scaling up)	Energy input (e.g., natural gas)
Fish protein hydrolysate (FPH)	70–85	Complete	Yes (residual lipids)	High (if waste available)	Limited by seafood processing volume

Insect Meals: The Circular Economy Champion

The larvae of black soldier fly (*Hermetia illucens*), yellow mealworm (*Tenebrio molitor*), and others are rapidly gaining regulatory approval and market traction. Their nutritional profile is excellent, with amino acids comparable to fishmeal, and they contain chitin, which may act as a prebiotic and immune stimulant. Their transformative potential lies in their bioconversion capability: They can be reared on agri-food by-products (e.g., brewer's grains, fruit, or vegetable waste), turning low-value organic streams into high-value protein. Scaling production and achieving cost parity with fishmeal remain ongoing challenges. Furthermore, the nutritional composition of the larvae is directly influenced by the substrate, requiring standardisation protocols. Research is optimising substrate blends to enhance the content of beneficial fatty acids in the final insect meal (Maulu *et al.*, 2022).

Single-Cell Proteins: The Land-Independent Frontier

Single-cell proteins (SCPs), microbial biomasses derived from bacteria, yeast, fungi, and microalgae are emerging as a promising, sustainable alternative to conventional fishmeal in aquaculture feeds. Driven by the need to decouple feed production from finite marine resources, SCPs offer high protein content (typically 30% to 70% on a dry matter basis), balanced essential amino acid profiles, and scalable production independent of arable land (Glencross *et al.*, 2020).

Among the most advanced platforms are methanotrophic bacteria (e.g., *Methylococcus capsulatus*), which convert natural gas or biogas into protein-rich biomass through gas fermentation, a process commercialised under the name "gas-to-protein". This technology exemplifies circular bioeconomy principles, utilising low-value gaseous substrates to produce feed ingredients with a low carbon and water footprint. Similarly, yeasts (e.g., *Candida utilis*, *Yarrowia lipolytica*) and filamentous fungi (e.g., *Fusarium venenatum*) grown on agro-industrial by-products provide additional SCP pathways that valorise waste streams while yielding nutritionally robust ingredients (Pereira *et al.*, 2022).

Nutritionally, SCPs have demonstrated strong potential to partially or fully replace fishmeal across multiple aquaculture species (Pereira *et al.*, 2022). In whiteleg shrimp (*Litopenaeus vannamei*), diets incorporating up to 50% SCP from bacterial origin showed comparable growth performance, feed conversion ratio (FCR), and survival to fishmeal-based controls, with no adverse effects on immune parameters or gut health (Hamidoghli *et al.*, 2018).

A key advantage of specific single-cell proteins, particularly heterotrophic microalgae such as *Schizochytrium* spp. is their dual functionality. In addition to providing protein, they are rich sources of long-chain omega-3 fatty acids, mainly DHA, which enables the potential to partially or fully replace both fishmeal and fish oil in aquaculture feeds. However, not all SCPs are nutritionally equivalent; amino acid balance (especially methionine and lysine), digestibility, and the presence of residual nucleic acids or cell wall components (e.g., glucans, chitin) require careful evaluation and, in some cases, processing optimisation. Despite technological advances, challenges remain in achieving cost parity with fishmeal, standardising biomass composition across production batches, and scaling biorefinery infrastructure. Regulatory approval and consumer acceptance also vary regionally, though recent European Union authorisations for microbial proteins in aquafeeds signal growing institutional support (Chi *et al.*, 2022).

By-Product Valorisation: Unlocking Circularity within the Seafood Sector

The most direct and efficient strategy for reducing primary fishmeal dependency is the systematic valorisation of seafood processing by-products. The chapter underscores that only about 30% to 40% of a landed fish is used for direct human consumption as fillets, the remaining 60% to 70% (heads, frames, viscera, skins, and trimmings) constitutes a protein-rich biomass stream that has historically been treated as waste. Modern biorefinery approaches transform this "waste" into high-value ingredients, fundamentally closing the nutrient loop within the aquaculture sector and exemplifying circular economy principles.

The conversion pathways are technologically diverse and yield products with distinct functionalities:

1. Fish protein hydrolysates (FPH): Produced primarily via enzymatic hydrolysis using proteases such as Alcalase, Flavourzyme, or papain, FPH is a premier product of by-product valorisation. The process cleaves proteins into smaller peptides and free amino acids, resulting in ingredients with enhanced bioactivity, including demonstrated antioxidant, antimicrobial, and immunomodulatory properties. As noted in the chapter, these bioactive peptides improve feed palatability, nutrient absorption, and stress resistance in farmed fish, making FPH a potent functional supplement in low-fishmeal aquafeeds.
2. Recovered intact proteins and collagens: Beyond hydrolysis, pH-shift or isoelectric solubilisation and precipitation are widely adopted chemical methods for recovering intact, functional proteins from by-products like frames and trimmings. Simultaneously, targeted extraction of collagen and gelatin from fish skins and scales using acid, pepsin, or a novel deep eutectic solvent (DES) yields high-value biomaterials for feed, food, and pharmaceutical applications.
3. Integrated biorefinery outputs: Advanced processing does not target protein in isolation. As highlighted in the case of shrimp waste, sequential biorefining can extract astaxanthin-rich oil via supercritical CO_2, followed by the recovery of chitin or chitosan from shells and high-quality protein fractions, maximising resource efficiency from a single waste stream.

Maximising this resource is not merely a waste-reduction tactic, it is a critical sustainability lever. By redirecting processing discards back into the feed chain as high-quality protein ingredients, the sector dramatically improves its aggregate Fish-In Fish-Out (FIFO) ratio, reduces environmental impact, and creates new economic value from existing material flows.

Emerging and Synergistic Technologies for Precision Feed Systems

The future of sustainable aquafeed lies in the integration of precision management tools with advanced ingredient technologies. This synergistic approach moves beyond simple substitution to optimise the entire nutritional value chain, from ingredient recovery to nutrient utilisation by the animal.

1. Precision nutrition and advanced processing: The chapter emphasises that feed formulation must meet digestible amino acid requirements rather than crude protein alone to avoid inefficiency and nitrogen waste. This requires precision nutritional regulation, integrating knowledge of species-specific life-stage needs, metabolic characteristics, and environmental conditions. Supporting this precision are the advanced mechanical and non-mechanical extraction technologies detailed in the chapter. For instance, ultrasound-assisted extraction (UAE) and pulsed electric field (PEF) treatments are emerging as green technologies that enhance the efficiency of protein and bioactive compound recovery from by-products while preserving their native functionality.
2. Critical feed additives as enablers: The successful inclusion of alternative proteins, including those from by-products is heavily dependent on a suite of specialised feed additives. These additives are essential for overcoming anti-nutritional factors and optimising gut health.

3. Enzymes (e.g., phytases, proteases, carbohydrases): Exogenous enzymes break down indigestible components (e.g., phytic acid in plant meals, complex proteins), liberating nutrients and improving the availability of phosphorus and amino acids.
4. Gut health modulators: Prebiotics (e.g., oligosaccharides) and probiotics (e.g., *Lactobacillus* spp.) are used to stabilise the gut microbiome, enhance intestinal morphology, and improve disease resistance, as demonstrated in fermentation studies using aquatic by-products.
5. Palatability enhancers: Hydrolysates and specific bioactive peptides from FPH are themselves powerful feed attractants, mitigating the reduced palatability of plant-heavy diets.
6. Genetic selection for enhanced Utilisation: A long-term, systemic strategy involves genetic selection for strains of aquaculture species with enhanced metabolic capacity for alternative diets. Breeding programmes are increasingly focusing on traits such as improved starch metabolism, robust gut health resilience, and efficient utilisation of plant-based and microbial protein sources. This biological adaptation works in concert with nutritional and technological innovations to secure the future of low-fishmeal aquaculture.

Hence, the transition to sustainable feeds is not reliant on a single technology but on a synergistic system that couples circular by-product valorisation with precision nutrition, enabled by advanced processing, functional additives, and genetic improvement. This integrated approach, as extensively documented by Esmaeily *et al.* (2026) is key to developing resilient, efficient, and environmentally sound aquafeed solutions.

Case Studies in Transition: From Theory to Practice

The Norwegian Salmon Model: A Managed Evolution

Norway's transition represents the most thoroughly documented case of systematic reduction in fishmeal use in global aquaculture. Enabled by a tightly integrated innovation ecosystem, linking leading feed manufacturers (e.g., Skretting, BioMar), research institutions (notably Nofima), and proactive government support, the Norwegian salmon sector has fundamentally transformed its feed formulations. Today's standard commercial diet contains approximately 15% fishmeal and 10% fish oil, a significant reduction from historic levels that often exceeded 40% fishmeal and 25% fish oil.

This shift was achieved through a multi-component strategy: (1) Base formulation: Relying on high-quality plant proteins such as wheat, soy protein concentrate, and corn gluten as the primary protein foundation; (2) Precision supplementation: Adding synthetic methionine, lysine, and taurine to correct nutritional imbalances inherent in plant-based ingredients; (3) Strategic marine ingredients: Incorporating krill meal (an Antarctic zooplankton) and microalgal oil not as bulk substitutes, but as targeted functional ingredients delivering attractants, phospholipids, and long-chain omega-3 fatty acids; (4) Novel ingredients: Gradually integrating limited but growing amounts of insect meal and bacterial protein as emerging sustainable alternatives.

Critically, this integrated approach has sustained high growth rates, robust fish health, and the prised omega-3 (EPA/DHA) content in salmon fillets, demonstrating that high-performance aquaculture can successfully decouple from direct dependence on wild-capture fisheries, fulfilling the vision of a "fishmeal trap" escape outlined in the case study (Moy de Vitry, 2013).

Vietnamese Pangasius: The Plant-Based Powerhouse

Vietnam's pangasius industry, producing over 1.5 million tonnes annually, relies on a primarily plant-based diet composed of rice bran, cassava (tapioca), soybean meal (imported from Argentina), vegetable oils, and supplements, with only about 3% fishmeal inclusion. This feeding strategy results in a low feed conversion ratio of approximately 1.55, contributing to the species' reputation as a highly efficient and sustainable protein source (Inside Vietnam Pangasius Farming: Every Importer Must Know, n.d.).

Insect Meal in Kenyan Aquaculture: A Circular Local Solution

In Kenya, where smallholder Nile tilapia farmers dominate aquaculture, the high cost and import dependency of commercial feed, driven mainly by fishmeal and soy, pose significant barriers to profitability and scalability. Black soldier fly (BSF) larvae meal has emerged as a promising circular solution: Farmers rear BSF on locally abundant organic waste such as market scraps, brewery by-products, and poultry manure, converting low-value residues into high-quality protein for fish feed (Ouko *et al.*, 2023). Research shows that BSF-based diets can reduce feed costs by 20% to 30% while maintaining or even improving growth, feed conversion, and profitability in tilapia (Wachira *et al.*, 2021). Although awareness of insect-based feeds among Kenyan aquaculture farmers is increasing, adoption remains constrained by inconsistent access to quality ingredients, lack of standardised feed formulations, and limited technical knowledge, challenges that are increasingly being addressed through partnerships between startups, research institutions, and government-supported programmes (Munguti *et al.*, 2024). Supported by Kenya's evolving aquaculture policy framework, BSF represents more than a feed alternative; it's a locally rooted, waste-to-value innovation that enhances feed sovereignty, environmental sustainability, and economic resilience in African aquaculture (Brian Mboya, 2025).

Policy, Regulation, and Strategic Future Directions

Accelerating the global transition requires a synergistic framework of regulation, market incentives, and strategic investment.

Strengthening International Governance and Standards

Market-driven certification schemes play a critical role in promoting sustainability in aquaculture, complementing the soft-law guidance provided by institutions such as the FAO's Committee on Fisheries (COFI). The Aquaculture Stewardship Council (ASC) Feed Standard, for instance, establishes precise requirements for the responsible sourcing of feed ingredients, including traceability, the use of by-product meals, and limits on FIFO ratio to reduce pressure on wild fisheries. Certifications like ASC not only incentivise producers to adopt environmentally and socially responsible practices but also create market-driven pressures that encourage wider industry compliance. Expanding the reach of such standards and harmonising them across regions can help level the playing field for producers, enhance consumer confidence, and accelerate the adoption of sustainable practices throughout the global aquaculture sector (ASC Feed Standard, n.d.; Van Putten *et al.*, 2020).

National Policy Instruments for Catalysing Change

Governments possess powerful levers, including research and development funding, economic incentives, and regulatory modernisation.

Public investment should prioritise open-access research on alternative ingredient functionality, gut health, and LCA. Funding for pilot-scale production facilities for novel ingredients (e.g., insect biorefineries) can de-risk private investment. Subsidies or tax credits could be directed not to fishmeal itself, but to feed mills that achieve verified reductions in fishmeal inclusion or incorporate circular ingredients. "Green financing" mechanisms with lower interest rates for sustainable aquaculture projects are another tool. Creating transparent, science-based, and efficient regulatory pathways for the approval of novel feed ingredients (particularly insects and SCPs) is essential to avoid innovation logjams. The European Union's approval process under Regulation (EC) No. 2017/893 is a key reference model.

Envisioning a Circular Bioeconomy for Aquafeed

The transition to a circular bioeconomy in aquaculture fundamentally reconceptualises resource flows, transforming waste streams into valuable inputs rather than disposal challenges. This paradigm shift manifests in diverse contexts: In India, innovative systems increasingly repurpose wastewater from agricultural, food processing, and domestic sources for aquaculture production, simultaneously alleviating pressure on freshwater resources while harnessing nutrient-rich water to enhance fish productivity. These circular approaches enable efficient recovery of critical nutrients such as nitrogen and phosphorus, substantially improving overall resource efficiency. Complementary to water reuse strategies, Integrated Multi-Trophic Aquaculture (IMTA) exemplifies circular design by co-cultivating fed species with extractive organisms, such as seaweed and filter-feeding shellfish, which naturally capture dissolved and particulate nutrients (Das *et al.*, 2023). Together, these approaches represent components of a broader 'fishmeal-smart' transition, where marine ingredients are strategically minimised while maintaining nutritional integrity through diversified feed portfolios. As illustrated in Figure 2, this systems-level vision integrates four interconnected pillars: By-product valorisation, novel protein development, precision nutrition science, and cross-sector synergies, all working in concert to establish resilient, circular aquafeed systems that decouple aquaculture growth from finite marine resources.

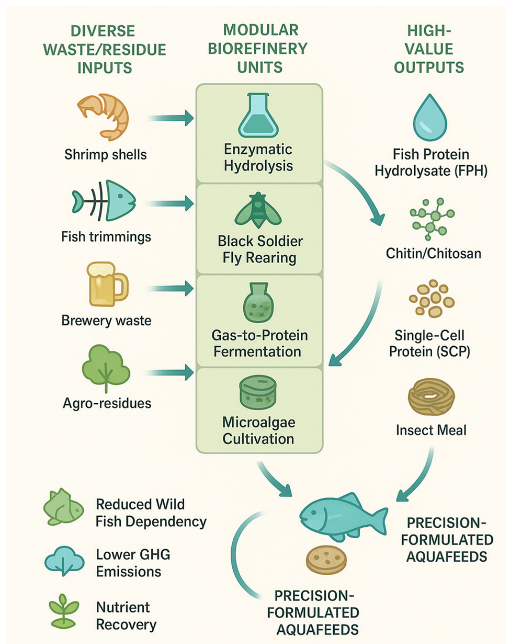

Figure 2: Integrated circular aquafeed system of the future

At a global level, bibliometric and content analyses reveal that the circular economy in aquaculture is increasingly framed around three interlinked strategies: Valorisation of organic by-products, integration of renewable biological resources, and system-level redesign to minimise dependence on external inputs (Masi *et al.*, 2024). Central to this shift is the use of microalgae biomass, which can be cultivated on non-arable land using saline water or wastewater streams, thereby avoiding competition with food crops, while simultaneously delivering high-quality protein and long-chain omega-3 fatty acids for aquafeeds (Ahmad *et al.*, 2022).

The broader vision emphasises resource efficiency across the entire aquaculture value chain, including the recovery of fish processing by-products as fishmeal and oil, the use of crop residues for microbial protein production, and the repurposing of aquaculture sludge for biogas or fertiliser. Critically, circularity extends beyond material flows to encompass cross-sectoral synergies, such as integrating aquaculture with agriculture (e.g., aquaponics) or with renewable energy systems (Verreth *et al.*, 2023).

Together, these approaches aim to decouple aquaculture growth from finite marine and terrestrial resources, reinforcing long-term food security while reducing environmental footprints.

Critical Research Frontiers

To secure the transition, research should focus on: (1) Understanding how alternative diets alter the fish gut microbiome and developing probiotic or additive strategies to maintain symbiosis and health; (2) establishing clear biomarkers for robust health in fish fed novel diets, moving beyond simple growth and FCR metrics; (3) conducting comprehensive environmental and socioeconomic assessments of entire alternative feed systems to avoid unintended consequences (e.g., water use for crops, social impacts of new ingredient markets); and, (4) developing effective strategies to communicate the benefits and safety of aquaculture products fed with novel ingredients to ensure market acceptance.

Conclusions

The evidence presented in this review leads to an unambiguous conclusion. The continued dependence of aquaculture on fishmeal derived from reduction fisheries is a dangerous anachronism. It is ecologically destabilising, economically precarious, and ethically fraught. The overharvest of forage fish undermines the integrity of marine ecosystems and the livelihoods of coastal communities that depend on them for food. The economic model it supports is vulnerable to the whims of climate and commodity markets, threatening the stability of a vital food sector.

Yet, this analysis is fundamentally optimistic. A clear and viable pathway toward independence exists, built on decades of scientific innovation and pioneering industrial practice. The portfolio of alternatives, from optimised plant proteins and circular insect meals to land-independent single-cell proteins and valorised seafood by-products is robust and expanding. The successes of the Norwegian salmon, Vietnamese pangasius, and emerging Kenyan insect-based systems demonstrate that this transition is possible across diverse economic and ecological contexts, for both carnivorous and omnivorous species.

The imperative now is acceleration and scaling. This requires a concerted, multi-stakeholder effort. Industry must boldly commit to ambitious, time-bound fishmeal reduction targets and invest in supply chains for novel ingredients. Policymakers must create the enabling environment through smart regulation, R&D support, and financial incentives that reward circularity. The research community must deepen its work on the frontiers of nutrition, health, and systems analysis. Consumers and retailers must continue to use their purchasing power to support certified, sustainable products.

By decisively breaking its reliance on wild-caught fishmeal, aquaculture can finally resolve its founding paradox. It can evolve from being a net consumer of marine resources to a genuinely sustainable, net-positive contributor to global food security. This transformation is not merely a technical feed reformulation, it is the essential step towards realising a resilient, equitable, and climate-smart Blue Food Revolution. The future of sustainable aquaculture is not fishmeal-free, but rather fishmeal-smart, using this precious marine resource strategically and sparingly within a diversified, circular, and innovative feed system.

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Conflict of Interest Statement

The authors declare no conflict of interest.

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