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ECOLOGICAL AND GEOPOLITICAL CHALLENGES IN SUSTAINING GLOBAL FISHMEAL SUPPLY FOR AQUACULTURE

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Abstract

Aquaculture plays a pivotal role in addressing global food security, particularly as wild-capture fisheries approach ecological saturation and can no longer meet rising nutritional demands. Fishmeal—valued for its high-quality protein profile—has emerged as a critical feed component, yet its continued use raises pressing concerns linked to ecological degradation and growing geopolitical uncertainty. This paper explores the structural vulnerabilities of the global fishmeal supply chain, drawing attention to the overharvesting of forage fish, climate-induced stock instability—reflected in a roughly 40% decline in production between 2013 and 2023—and the compounding effects of trade restrictions, including U.S.–China tariff escalations (2023–2025) and regional import bans. Unsustainable exploitation of pelagic species threatens marine biodiversity and disrupts ecological trophic networks, while global crises such as pandemics and maritime transport bottlenecks further expose fragilities in the system. In synthesizing these dynamics, the review calls for a transition toward ecosystem-based fisheries governance, geographically decentralized feed production, and strategically resilient supply chains. The analysis concludes with policy imperatives that prioritize international cooperation, anticipatory regulatory mechanisms, and adaptive management strategies to mitigate converging risks to aquaculture's long-term sustainability.

Keywords: Aquaculture, climate change, fishmeal, forage fish, sustainability, trade barriers

Drivers and Implications of Aquaculture Expansion

The rapid increase in the global population has brought with it the pressing need to utilize food resources more efficiently and sustainably (United Nations DESA, 2024). Given the finite nature of natural resources, traditional food production methods have struggled to meet the growing demand. Aquatic foods have historically fulfilled a critical role in global nutrition (Ghamkhar & Hicks, 2020), but wild-capture fisheries are increasingly constrained by ecological and biological limits (Martin, 2017). In this context, aquaculture has emerged as a vital solution for securing global food and nutritional needs (FAO, 2018; Yue & Shen, 2022). Aquaculture's strategic importance is growing, driven by rapid technological advancements. Advances in production technologies have enabled the sector to enhance efficiency, environmental control, and species performance—laying the groundwork for a more resilient and scalable food system. This transition supports a shift toward sustainable, data-driven global food systems.

Cutting-Edge Innovations Enhancing Aquaculture Productivity and Sustainability

In response to these evolving needs, the aquaculture industry has transitioned from extensive systems to intensive and hyper-intensive production, enabled by technological innovations. Practices such as aqua-mimicry, bio-floc technology, integrated multitrophic aquaculture (IMTA), microalgae cultivation, polyploidy, monosex culture, neo-female technology, probiotics-prebiotics, alternative proteins, Internet of Things (IoT), and vaccination have transformed modern aquaculture (Manan et al., 2023). These advances have led to improved species performance, better health management, system automation, and expanded global competitiveness (Figure 1). Collectively, such innovations are reshaping the environmental footprint and economic potential of aquaculture worldwide.

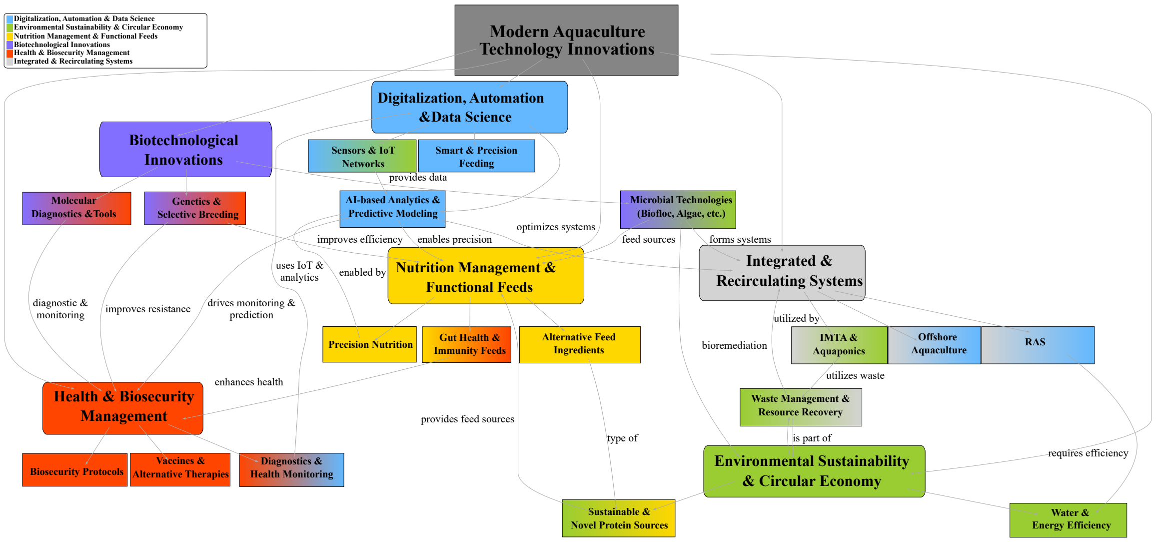

Figure 1. Mindmap of technological innovations in aquaculture, highlighting key advancements in biotechnology, automation, and sustainability

Trends in Global Aquaculture Expansion

In 1987, aquaculture production of fish and shellfish was approximately 10 million tons. By 1997, this had nearly tripled to 29 million tons. The number of cultured species also rose from around 300 to 425 by 2017, with total production reaching 112 million tons (Naylor et al., 2021). According to FAO (2024), as of 2022, global aquatic animal production (excluding algae) reached a record high of 185.4 million tons, with 94 million tons (51%) coming from aquaculture. Marine environments accounted for 115 million tons (62%) of production, of which 31% was from aquaculture, while inland waters produced 70 million tons (38%), with 84% attributed to aquaculture. When algae and other aquatic products are included, the total world fisheries and aquaculture production rises to 223.2 million tons, with 130.9 million tons coming from aquaculture (including 36.5 million tons of algae) (FAO, 2024). This trend is further illustrated in Table 1, which outlines global fisheries and aquaculture statistics between 1990 and 2022, offering a comprehensive snapshot of production, utilization, and employment dynamics. This trajectory demonstrates aquaculture's increasing dominance in global food systems. As aquaculture continues to scale up and diversify, its long-term viability increasingly hinges on the sustainability of key input resources—particularly feed.

Among these, fishmeal remains a foundational component in the diets of high-value, carnivorous aquaculture species due to its exceptional nutritional profile and digestibility. However, the growing reliance on fishmeal has raised critical questions about ecological limits and the resilience of global supply chains. The sustainability of fishmeal sourcing is critical to addressing ecological and supply chain challenges for aquaculture's future.

Table 1. Global fisheries and aquaculture production, utilization, and employment, 1990–2022 (FAO, 2024).

	1990s	**2000s**	**2010s**	**2020**	**2021**	**2022**	**Change (%) (1990 - 2022)**
Capture Fisheries							
Inland	7.1	9.3	9.3	9.3	9.3	9.3	+30.9%
Marine	81.9	81.6	81.6	79.7	79.8	79.7	-2.7%
Total Capture Fisheries	88.9	90.9	90.9	91.0	91.1	91.0	+2.4%
Aquaculture							
Inland	12.6	17.9	25.6	25.6	25.0	59.1	+368.3%
Marine	9.2	14.4	16.9	16.9	16.9	35.3	+284.8%
Total Aquaculture	21.8	21.8	51.2	44.8	44.8	94.4	+332.6%
Total Fisheries and Aquaculture	110.7	110.7	134.3	143.1	143.1	185.4	+67.2%
Utilization							
Human Consumption	81.6	81.6	109.3	143.1	143.1	164.6	+101.0%
Non-Food Uses	29.1	38.3	51.2	60.8	63.8	70.0	+140.9%
Apparent Consumption	35.4	46.6	47.3	54.5	56.4	56.4	+59.2%
Employment							
Aquaculture	6.1	7.2	11.3	11.4	11.4	12.2	+100.0%
Fisheries	5.0	5.1	6.1	6.3	6.8	7.0	+40.0%

All production data in million tons (live weight); employment in millions; per capita consumption in kg. Values for the 1990s, 2000s, and 2010s indicate average figures per year.

Fishmeal as a Critical Aquafeed Component

The success of aquaculture depends heavily on the sustainability of its feeds. Formulating nutritionally balanced feeds tailored to cultured species is crucial for aquaculture success. Among various feed ingredients, fishmeal—recognized for its high energy density, superior digestibility, and high-quality protein content—remains a cornerstone of aquafeed production

(Cho & Kim, 2011; Samaddar, 2018). Moreover, its richness in essential nutrients such as DHA and EPA fatty acids, calcium, phosphorus, vitamins (choline, biotin, B12, A, D, E), selenium, and iodine enhances its value as a critical feed component (Tacon & Metian, 2008).

In recent years, a range of alternative animal protein sources—including slaughterhouse waste meals, rendered animal by-products, and insect-based meals—have been increasingly incorporated into aquafeeds to reduce reliance on fishmeal and to meet the animal protein requirements of farmed fish. Although these substitutes cannot fully match fishmeal in terms of quantity and quality, they play a significant role in decreasing the exclusive dependence on fish-derived ingredients.

However, the growing reliance on fishmeal highlights the urgent need to assess its ecological implications, particularly given the mounting pressure on marine ecosystems. As aquaculture continues to expand, this dependency has placed fishmeal at the forefront of feed sustainability debates. This dependency underscores fishmeal's role in global food security and marine governance, with recent studies indicating that ecological constraints could limit aquaculture scalability without innovative substitutes or improved sourcing (Love et al., 2024). Globally, approximately 15 million tons of fish are used annually for fishmeal production, with production concentrated in South America (e.g., Peru, Chile) and Northern Europe (e.g., Denmark, Norway), forming the backbone of the global supply chain (EUMOFA, 2023; Figure 2). Additional production occurs in countries such as China, Japan, Thailand, Vietnam, and the United States, reflecting the international nature of fishmeal trade (FAO, 2024). However, this geographic concentration also reveals the structural vulnerability of the system to regional environmental and political shocks.

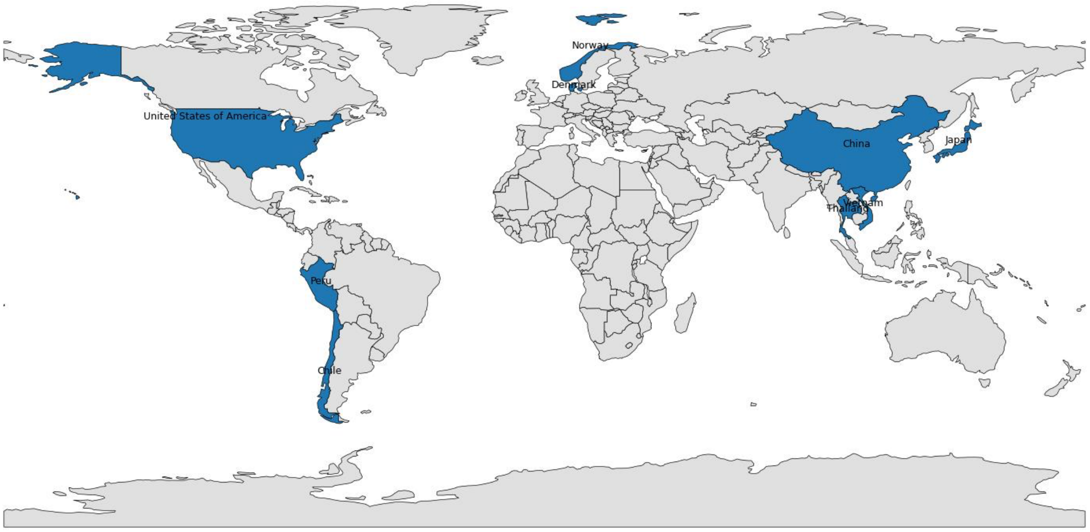

Figure 2. Global distribution of major fishmeal-producing countries (EUMOFA, 2023)

Ecological and Environmental Challenges in Fishmeal Production

Fishmeal is primarily produced from small, oily, pelagic species such as *Engraulis ringens* (Peruvian anchovy), *Engraulis japonicus* (Japanese anchovy) and *Trachurus murphyi* (Chilean jack mackerel), as well as from fish processing by-products (Shepherd & Jackson, 2013; Hua et al., 2019). These forage species, though rarely consumed directly by humans (Cashion et al., 2017), are critical to marine food webs. At the same time, they represent a unique source of high-quality animal protein naturally obtained from marine environments through fishing activities, playing a significant role in food security, especially in regions with limited access to other animal proteins. In addition to fish, macroalgae (seaweeds) are also harvested from the wild by collection methods and are used as a food source in some regions. Their overuse for fishmeal production has the potential to disrupt trophic linkages, particularly by reducing prey availability for top predators, thereby altering ecosystem stability (Pikitch et al., 2014). Therefore, sustainable management of forage fish populations is crucial to avoid exceeding ecological thresholds, which could compromise both marine biodiversity and feed security for aquaculture (Froehlich et al., 2018). Table 2 lists key species used in fishmeal and fish oil production.

Table 2. Key species used in fishmeal and fish oil production, critical to marine ecosystems

Family	**Scientific Name**	**Common Name**
Engraulidae	*Engraulis ringens*	Peruvian anchovy
	Engraulis japonicus	Japanese anchovy
Clupeidae	*Clupea harengus*	Atlantic herring
	Brevoortia tyrannus	Atlantic menhaden
	Brevoortia patronus	Gulf menhaden
	Sardinops sagax	Pacific sardine
	Sardina pilchardus	European pilchard
	Sprattus sprattus	European sprat
Osmeridae	*Mallotus villosus*	Capelin
Carangidae	*Trachurus murphyi*	Chilean jack mackerel
	Trachurus trachurus	Atlantic horse mackerel
Gadidae	*Theragra chalcogramma*	Alaska pollock
	Gadus morhua	Atlantic cod
	Gadus macrocephalus	Pacific cod
	Melanogrammus aeglefinus	Haddock
	Trisopterus esmarkii	Norway pout
	Micromesistius poutassou	Blue whiting
Merlucciidae	*Merluccius spp.*	Hake
	Macruronus novaezelandiae	Blue grenadier
Ammodytidae	*Ammodytes marinus*	Lesser sand eel
	Ammodytes tobianus	Small sand eel
Scombridae	*Katsuwonus pelamis*	Skipjack tuna
	Thunnus albacares	Yellowfin tuna
	Scomber japonicus	Chub mackerel
	Scomber scombrus	Atlantic mackerel
Trichiuridae	*Trichiurus lepturus*	Large head hairtail

Adapted from Miles & Chapman, 2006

According to the FAO (2022), approximately 35% of global marine fish stocks are currently exploited at biologically unsustainable levels. This statistic is particularly relevant for species targeted for fishmeal production. The anchovy stocks (*Engraulis ringens*) off the coast of Peru, for example, are highly vulnerable to climate variability such as El Niño events, which cause sharp interannual fluctuations in yields (Bakun & Weeks, 2008). Overfishing not only endangers target species but also contributes to broader environmental degradation, including disruptions in the marine carbon cycle, nitrogen transport, and overall ocean health (Barange et al., 2014; Link, 2021). Moreover, such disruptions may reduce ecosystem resilience, particularly in regions with limited adaptive capacity (Barange et al., 2014). Climate variability and fishing pressure compound threats to stock resilience, particularly in regions with weak governance.

Industrial fishing operations affect not only the target species but also the broader marine ecosystem. Pelagic trawling, in particular, results in high bycatch rates, where non-target species are often discarded due to their perceived lack of commercial value, causing significant population losses (Shepherd & Jackson, 2013). Ecosystem-based fisheries management principles emphasize the reduction of bycatch and the refinement of fishing techniques as essential practices (Jarvis & Brennan, 2024). In some cases, pelagic fishing activities such as midwater or pelagic trawling, can also impact benthic habitats when gear unintentionally contacts the seafloor, disturbing benthic communities and resuspending sediments, which may alter local habitat structure and benthic biodiversity (Jennings & Kaiser, 1998). Additionally, large-scale forage fish extraction may lead to trophic cascades, weakening the resilience of marine ecosystems to environmental perturbations (Pikitch et al., 2014).

The ecological and environmental challenges in fishmeal (FM) and fish oil (FO) production also stem from the limited availability and unsustainable harvesting of wild fish stocks, which are the primary sources for these aquafeed ingredients (Auzins et al., 2024). As global capture fisheries have stagnated or declined, constrained FM and FO supplies have resulted, with approximately 87% of FM and 74% of FO production in 2021 being directed to aquaculture (FAO, 2024). Overfishing for FM and FO production exerts significant pressure on marine ecosystems and further exacerbates ecological vulnerabilities. This overexploitation threatens both aquaculture outputs and long-term global food security (Barange et al., 2014).

Between 2013 and 2023, total fishmeal production declined from approximately 5 million tons to 3 million tons—a 40% reduction (Table 3). This drop aligns with the FAO's (2024) report of a 23% decrease in 2023, driven by poor anchoveta landings in Peru due to climate variability, such as El Niño events. The proportion of fishmeal sourced from fish by-products has increased, rising from about 20% in 2013 to 30% in 2023, indicating a shift toward more sustainable sourcing practices amid declining whole fish availability. Looking ahead, projections for 2032 suggest production will stabilize around 3.5–4 million tons, with by-product usage continuing to grow (FAO, 2024).

The fishmeal production process involves high levels of energy consumption and greenhouse gas emissions during the capture, processing, and transportation stages. In particular, inefficiencies in industrial operations lead to a substantially elevated carbon footprint per unit of protein produced (Pelletier et al., 2009). Moreover, forage fisheries used for FM production contribute additional carbon emissions through energy-intensive harvesting practices (Majluf et al., 2024).

The heavy reliance on fishmeal and fish oil has driven up raw material costs, with the FM to soybean meal price ratio increasing from 2:1 in the 1990s to 4:1 by 2010, creating economic sustainability challenges for aquaculture (Shepherd & Jackson, 2013). These market pressures underscore the urgent need for cost-effective alternative feed ingredients to sustain the growth of environmentally responsible aquaculture (Turchini et al., 2010).

Table 3. Global Fishmeal Production Trends (2013–2032)

Year	**Total Production**	**From Whole Fish**	**From By-Products**	**By-Product Share (%)**
2013	5.0	4.0	1.0	20%
2018	4.5	3.3	1.2	27%
2023	3.0	2.1	0.9	30%
2032 (Outlook)	3.5	2.3	1.2	34%

All production data in million tons (live weight). Data estimated from FAO (2024) projections, subject to future revisions.

An increased inclusion of terrestrial animal by-products in aquafeeds has been linked to elevated phosphorus discharge into aquatic systems (Shaw et al., 2024), potentially contributing to environmental degradation through eutrophication, as phosphorus is a well-established driver of such processes (Smith et al., 1999). As such, monitoring and optimizing phosphorus excretion from feed components is essential for maintaining water quality and preserving ecosystem integrity (Majluf et al., 2024). Nutritionally balanced feed formulations are therefore critical in reconciling ecological sustainability with aquaculture nutrition goals (Glencross et al., 2020).

Comparative life cycle assessments indicate that conventional feeds containing fishmeal and fish oil tend to exert significantly greater environmental burdens than marine-free alternatives, particularly in terms of global warming potential, eutrophication, and fossil energy demand (Ghamkhar & Hicks, 2020). In contrast, the valorization of by-products, utilization of microbial biomass, and incorporation of insect-based proteins are increasingly promoted as foundational innovations for the long-term resilience of aquaculture (Majluf et al., 2024). To mitigate environmental impacts, circular economy approaches and reduced dependence on wild fisheries are imperative (Pikitch et al., 2014; Majluf et al., 2024). A transition toward alternative protein sources and circular feed production systems is thus central to building resilient aquafeed value chains (Love et al., 2024). Collectively, these trends highlight the pressing need for sustainable fisheries governance, innovative feed strategies, and diversified resource inputs to secure the future of global aquaculture.

Socio-Economic and Geopolitical Risks Affecting Fishmeal Supply Chains

The fishmeal supply chain encompasses far more than just production costs; it is a multidimensional system shaped by global crises and evolving geopolitical dynamics. As food security becomes an increasingly strategic concern, exceptional disruptions—such as pandemics, logistical bottlenecks, and market shocks—have exposed the fragility of fishmeal supply and underscored the rising importance of alternative protein sources (Vasilaki et al., 2023).

The COVID-19 pandemic triggered widespread disruptions across fisheries and aquaculture sectors, adversely impacting production, supply chain continuity, and market stability (Ahmed & Azra, 2022; OECD, 2020). Factory closures, labor shortages, and logistical constraints coincided with a dramatic collapse in demand from the hospitality sector, contributing to pronounced price volatility and financial instability for producers (FAO, 2020). Concurrently, border closures and a sharp reduction in air freight capacity significantly hindered the distribution of fresh seafood, while rising operational costs—driven in part by health and safety compliance requirements—placed additional financial strain on enterprises (Lennane et al., 2020; Gosh et al., 2022).

Despite a long-standing upward trend since the 1950s, global aquaculture output experienced a marginal decline in 2019 and stagnated in 2020, dampening demand for fishmeal (FAO, 2024). The pandemic also revealed structural vulnerabilities: disruptions in seed supply threatened future aquaculture output, while the suspension of fisheries observer programs heightened the risk of illegal, unreported, and unregulated (IUU) fishing activities (OECD, 2020). Collectively, these cascading impacts have reinforced the urgency of developing more resilient and diversified supply chains and have accelerated discourse around reducing reliance on conventional fishmeal sources.

Beyond pandemic-related disruptions, logistical vulnerabilities were further exposed by events such as the 2021 Suez Canal blockage—an incident that affected approximately 12% of global trade and highlighted the susceptibility of fishmeal and seafood logistics to unexpected shocks (Özkanlısoy & Akkartal, 2022). The broader seafood trade, with an estimated annual volume of $150 billion, includes fishmeal as a significant component (FAO, 2021). One notable trade relationship is between China, the world's top producer, and the United States, a major consumer. By 2023, according to the United States Department of Agriculture (USDA, 2024), the bilateral seafood trade volume was estimated at $6 billion, underscoring the mutual dependence of both nations. In this context, bilateral agreements—such as free trade deals between China and Ecuador, and between Peru and China—have restructured import dynamics by offering preferential tariff reductions of up to 95% on fishmeal and related products (Ministry of Commerce of the P.R.C., 2023, 2024).

However, rising protectionism and geopolitical tensions have increasingly disrupted international seafood trade and fishmeal availability. For example, a 2023 U.S. regulation (EO-14068) banned imports of certain seafoods (e.g., salmon, cod, pollock, crab) if they originated from Russian vessels or were caught in Russian waters—even when processed in third countries (U.S. Treasury, 2023). That same year, China suspended all seafood imports from Japan in response to its release of treated radioactive water into the Pacific Ocean (General Administration of Customs of the P.R.C., 2023). In 2025, tariff conflicts intensified when the U.S. raised duties on certain seafoods up to 125%, prompting China to reciprocate by increasing its tariffs on U.S. goods from 84% to 125% (The White House, 2025; State Council Tariff Commission of the P.R.C., 2025).

Such restrictive trade policies not only affect the countries directly involved but also reverberate throughout highly integrated global supply chains. Events like the 2018 U.S.-China trade war (U.S. Department of the Treasury, 2023) or the European Union's implementation of CBAM taxes under the Green Deal—targeting imports that fail to meet environmental standards (Smith et al., 2024)—have created instability and cost inflation in fishmeal sourcing. These challenges threaten aquaculture's operational sustainability, increasing production fragility and unpredictability. Localized, sustainable production strategies are essential to reduce external dependence and build resilient supply chains capable of withstanding global trade volatility. Assessing alternative proteins requires considering ecological, geopolitical, economic, and structural risks.

Synthesis and Policy Recommendations for Sustainable Aquaculture

The global aquaculture sector stands at a critical juncture, navigating the tension between its essential contribution to food security and the mounting ecological and geopolitical challenges that threaten its long-term sustainability. While fishmeal remains indispensable for the production of high-quality aquafeeds, its availability is increasingly constrained by the overexploitation of forage fish, environmental degradation, and volatile global trade dynamics. Climate change further exacerbates these pressures by disrupting fish stock productivity, while recent trade restrictions and tariff disputes underscore the growing uncertainty introduced by geopolitical tensions. To address these challenges, a multifaceted approach is essential:

1. Prioritize the use of wild-caught biomass for direct human consumption. Redirecting fish biomass from reduction to fishmeal and fish oil toward direct human consumption can significantly enhance food security and nutritional outcomes at the global level.
2. Promote the cultivation of low trophic level omnivorous and herbivorous species. Focusing on such species reduces the demand for animal-based feed ingredients, supports efficient resource use, and has proven effective in countries like China, where low trophic aquaculture underpins much of the sector's success.
3. Implement ecosystem-based fisheries management. Adopting ecosystem-based approaches can mitigate the ecological impacts of forage fish harvesting, safeguard biodiversity, and preserve trophic stability within marine ecosystems.
4. Accelerate the development and adoption of alternative protein sources for aquafeeds. Investments and regulatory support are needed for the commercialization of insect-based, plant-based, and microbial proteins, ensuring their scalability and nutritional adequacy as substitutes for fishmeal and fish oil
5. Foster localized production strategies and regional trade agreements. Strengthening local supply chains and regional collaborations can increase the resilience of aquaculture systems to global market volatility and trade disruptions.
6. Enhance international cooperation. Greater harmonization of environmental regulations, reduction of trade barriers, and global promotion of sustainable aquaculture practices are critical for sectoral resilience and long-term sustainability.
7. Encourage further research into alternative feeds and sustainable farming systems. Continued interdisciplinary research is needed to assess the long-term viability, safety, and scalability of novel protein sources, particularly insect-based feeds, across diverse aquaculture species and production systems.

By integrating these strategies through collaborative, evidence-based frameworks, the aquaculture industry can transition toward a sustainable trajectory—ensuring environmental integrity, economic viability, and global food security.

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Ethical approval

No ethical approval needed for this study.

Informed consent

Not applicable

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Conflicts of interest

The author declares that there is no conflict of interest.

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Contribution of authors

The author solely conducted all aspects of the study, including conceptualization, literature collection, critical analysis, interpretation, writing, and final revision of the manuscript.

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