

Integrating Aquaculture into Landscapes and Seascapes.

Enhancing aquaculture sustainability with innovations in ecofriendly aquafeeds

PROGREEN PROBLUE



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INTEGRATING AQUACULTURE INTO LANDSCAPES AND SEASCAPES

ECO-FRIENDLY AQUAFEEDS

REDUCING THE CARBON FOOTPRINT OF
AQUACULTURE INGREDIENTS THROUGH
INNOVATION

2025

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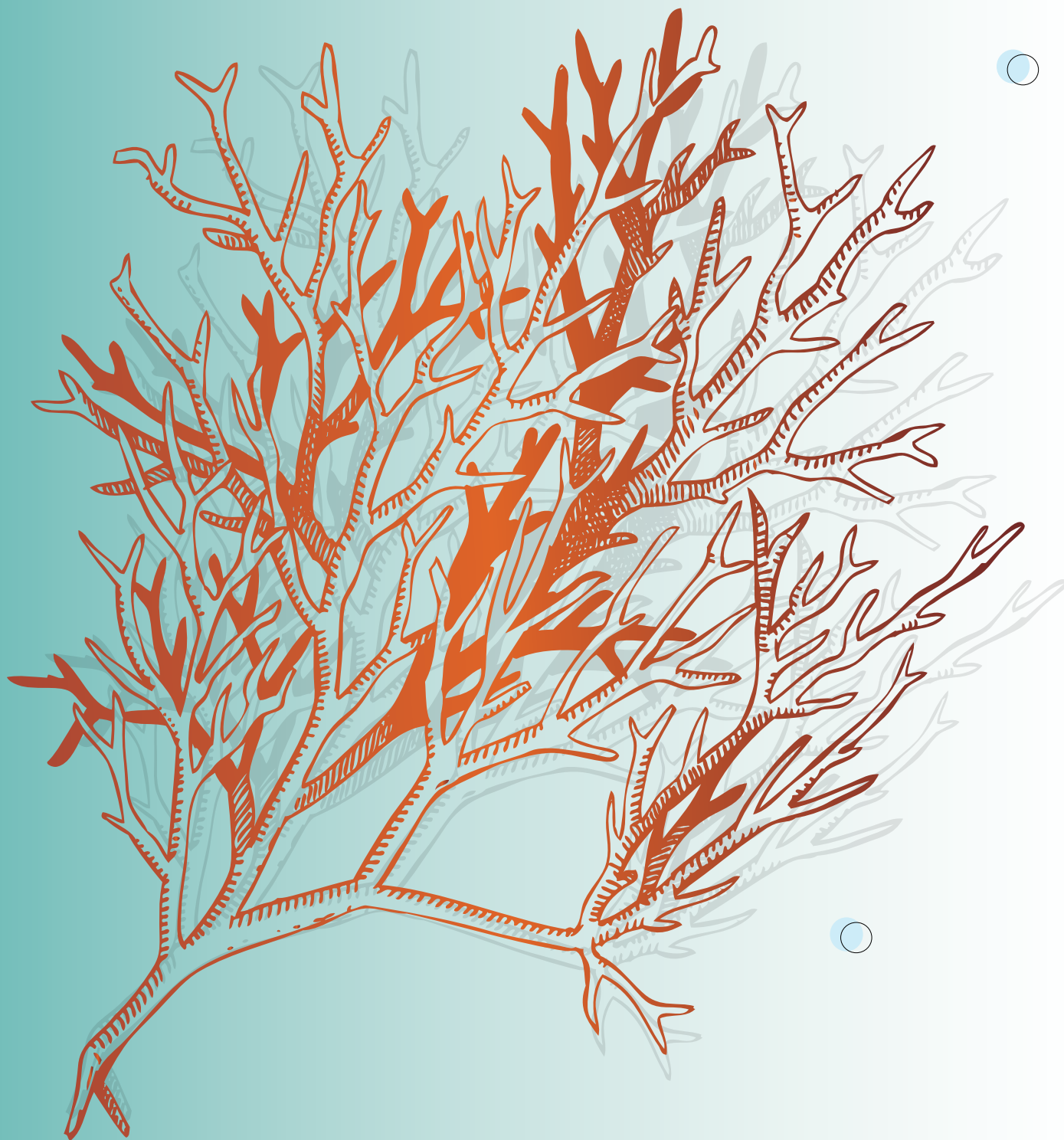
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Gracilaria.

GLOSSARY

Antimicrobial proteins: A diverse class of naturally occurring molecules that are the first line of defense components in the animals. These proteins have a broad activity to directly kill bacteria, yeast, fungi, viruses, and even cancer cells.

Aquaculture: The raising, feeding, breeding, and harvesting of aquatic organisms, including fish, mollusks such as snails, crustaceans such as shrimp, and aquatic plants such as seaweed in a controlled environment, in freshwater or saltwater, for human consumption or other purposes—essentially farming in water.

Aquafeed: Feed given to aquatic farmed animals as part of aquaculture.

Biofloc technology: The use of aggregates of bacteria, algae, or protozoa, held together in a matrix, along with particulate organic matter for the purpose of improving water quality, waste treatment, and disease prevention in intensive aquaculture systems.

Compound feed: A blended mixture of raw materials and additives, formulated according to the specific nutritional needs of a particular animal or fish species, to provide a complete and balanced diet.

Crude protein: A standard measure of the total amount of protein in a feed ingredient, estimated based on its nitrogen content and used to evaluate the protein value of feed materials.

Docosahexaenoic acid (DHA): An omega-3 fatty acid found in fish oil from fatty fish, such as sardines and salmon, and commonly referred to as DHA, it has multiple health benefits, including cardiovascular health, and is crucial for brain and eye fetal development and during infancy. It is also vital for maintaining brain function and cognitive health in adults.

Economic feed conversion ratio (eFCR): A practical measure of the efficiency of feed utilization, is the ratio of the amount of feed consumed to a given increase in harvested weight. Unlike the biological feed conversion ratio, which is the amount of feed a fish needs simply to produce a given amount of body mass, the economic feed conversion ratio is a more real-world measure that compares the total amount of feed an entire pond of fish needs to produce a net gain in their final harvested weight, taking into account production losses like mortality.

Eicosapentaenoic acid (EPA): An omega-3 fatty acid found in fish oil, together with DHA (docosahexaenoic acid), and commonly referred to as EPA, it is known for its anti-inflammatory properties and its role in reducing the risk of heart disease, lowering cholesterol and triglyceride levels, and alleviating rheumatoid arthritis symptoms.

Eutrophication: The gradual over-accumulation of phosphorus, nitrogen, and other plant nutrients in a body of water (typically an aging one) as the amount of organic material in it increases, resulting in the excessive growth of microorganisms like algae and macrophytes, which may then deplete the oxygen in the water. Eutrophication is a condition that certain integrated aquaculture and agriculture systems can mitigate.

Extrusion: An efficient mass-production process, similar to pressure cooking, that offers a high degree of precision and control over the composition, uniformity, particle size, and texture of compacted, pelleted feeds, resulting in

improved durability, greater water stability, flotation capacity (where desired), and enhanced bioavailability of essential nutrients to aquaculture fish and other farmed animals; often an important technology upgrade during the transition of an aquaculture industry from nascent to emerging-sector stage.

Feed conversion ratio (FCR): The ratio of the amount of feed consumed to a given weight gain, it measures how efficiently an aquatic species converts that particular kind of feed into body weight. A lower ratio is therefore better. The ideal theoretical ratio of 1:1 would mean that the fish converts all of the food it eats into body weight.

Feeding level: The amount of feed given to fish relative to their body weight, usually expressed as a percentage per day. Typically, it ranges between 2 and 4 percent, depending on the fish species and farming intensity.

Fingerling: Juvenile fish that are approximately the size of a human finger (hence the name), between 10 and 15 centimeters in length. The fingerling stage is the stage just beyond the fry stage, and the fish at this point are old enough to be used to stock an aquaculture pond.

Fishing pressure: The intensity or extent of fishing activity occurring within the population of a particular species of fish or shellfish, often expressed as a ratio of how much fish is being caught compared to the size of the population or its capacity to replenish itself; it indicates the level of exploitation and is a crucial metric for managing fish populations to ensure their long-term sustainability.

Food security: A condition in which all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for maintaining an active and healthy life.

Frass: Waste material excreted by insect larvae, consisting mainly of droppings, leftover undigested feed particles, shed exoskeletons, and microbial biomass; it is rich in nutrients like nitrogen, phosphorus, and potassium, making it a valuable organic fertilizer or soil amendment in agriculture.

Genetically modified organism (GMO): A plant, animal, or microbe in which one or more changes have been made to the genome, typically using high-tech genetic engineering, in an attempt to alter the characteristics of an organism.

Global warming potential (GWP): A measure of how much heat a greenhouse gas traps in the atmosphere over a specific period, typically 100 years, using carbon dioxide as the baseline reference. GWP conveys how much that gas warms the earth when released, and therefore environmental impact. Some gasses have GWP values tens of thousands higher than carbon dioxide. Methane, from livestock farming, is among the most harmful because of its high GWP, high abundance, and enduring composition. It stays in the atmosphere for a decade before disintegrating, all that while heating the earth. Its GWP is 27–30 times greater than carbon dioxide but also stays in the atmosphere far longer.

Grow-out: The final, longest, and most expensive production stage of aquaculture, following the fingerling stage, during which young fish put on weight and grow to adult market size; it is highly sensitive to the particular husbandry practices employed such as type and amount of feed, feed conversion ratio, stocking density, nutrient content, and health and hygiene factors.

International Aquafeed Feed Formulation Database: A free online tool that offers information on feed formulation for aquafeed formulators, and an open-access database made up of two modules: A feed ingredient composition database with detailed information on the chemical composition and nutritional value of about 300 ingredients, and an aquaculture species database with nutrient specifications for 24 aquatic species that are commercially important in Asia.

International Feed Vocabulary: A standardized system for classifying and naming feed ingredients system using the origin of the feed, part fed, processes, stage of development, cutting, and grade of feed.

International Life Cycle Data (ILCD): An initiative developed by the European Commission in 2005 to provide guidance and standards for greater consistency and quality assurance in applying life cycle analyses. ILCD publications have been established through a series of extensive public and stakeholder consultations.

Infectious Spleen and Kidney Necrosis Virus (ISKNV): A group of viral agents that cause disease in a variety of freshwater fish (particularly cichlids, gouramis and poeciliids), leading to high mortality.

Life cycle assessment (LCA): A method of assessing the environmental impact of a product (although it could also be a service or a process) over its entire life cycle, starting from raw material and following it through production, usage, and disposal, and evaluating both inputs and outputs of materials and energy, in order to optimize resource use efficiency.

Near infrared reflectance (NIR) spectroscopy: A technology for rapidly and non-invasively determining multiple characteristics of various foods, and which is now being used to quickly assess components of oyster tissue such as glycogen levels, lipid and moisture content, nutrient content, and even geographical origin, providing extensive information about the sample—a kind of hi-tech fingerprint.

Net present value (NPV): The value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present.

Proximate composition: The percentage chemical composition of the four basic constituents of tissue—water content, protein content, fat/oil content, and ash content (mainly minerals)—for example, the proximate composition of black soldier fly larvae.

Seascape: A large, geographically bound area that supports integrated management of marine resources to conserve ecosystems that benefit the planet, people, prosperity, and peace.

Specific pathogen free (SPF) animal: A laboratory animal bred, raised, and screened to be completely free of one or more specific disease-causing pathogens to minimize the influence of those diseases in an experiment so that the effects of other variables can be isolated and studied.

Sustainable aquaculture: The practice of cultivating aquatic organisms in a way that meets current needs for food production and economic development while ensuring the long-term viability of industry and the health of ecosystems.

Trophic level: Various levels in a food chain or ecosystem, representing the flow of energy and nutrients from one organism to another.

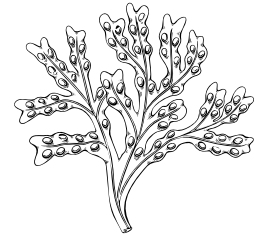
Waste reduction index (WRI): The ability—of larvae, for example—to reduce feeding substrates; a higher value indicates greater ability to reduce the organic matter that is in the substrate.

ABBREVIATIONS

AMPs	Antimicrobial proteins
ANA	Agency for Aquaculture
BFT	biofloc technology
BSF	black soldier fly
BSFL	black soldier fly larvae
CEO	chief executive officer
CO ₂	carbon dioxide
CO ₂ e	carbon dioxide emissions
CO ₂ eq	carbon dioxide equivalent
COVID	coronavirus disease 2019
CP	Charoen Pokphand Foods
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCF	deforestation and land conversion free
DHA	docosahexaenoic acid
eFCR	economic feed conversion ratio
EPA	eicosapentaenoic acid
ESG	environmental, social and governance
EU	European Union
EUR	euro
FAO	Food and Agriculture Organization of the United Nations
FAO-RAPA	FAO Regional Office for Asia and the Pacific
FAQs	frequently asked questions
FAS	Foreign Agricultural Service
FCP	fermented corn protein
FCR	feed conversion ratio
FDA	US Food and Drug Administration
FEFAC	European Feed Manufacturers' Federation
FHF	Norwegian Seafood Research Fund
FRED	Federal Reserve Bank of St. Louis
FSMA	Food Safety Modernization Act

GAA	Global Aquaculture Alliance
GDP	gross domestic product
GFI	Good Food Institute
GFLI	Global Feed LCA Institute
GHG	greenhouse gas
GIFT	genetically improved farmed tilapia
GIS	geographic Information system
GPS	global positioning system
GSI	Global Salmon Initiative
GWP	global warming potential
Ha	hectare
IAFFD	International Aquafeed Feed Formulation Database
ICI	Imperial Chemical Industries
ICIPE	International Centre of Insect Physiology and Ecology
IFC	International Finance Corporation
ILCD	International Life Cycle Data
IMF	International Monetary Fund
INFIC	International Network of Feed Information Centers
INRA-CIRAD	Institut national de la recherche agronomique of the French Agricultural Research Centre for International Development
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
ITA	International Trade Administration
ITC	International Trade Commission
JV	joint venture
kg	kilogram
kg CO ₂ eq	kilogram of carbon dioxide equivalent
LCA	life cycle assessment
LPG	liquid petroleum gas
LVFO	Lake Victoria Fisheries Organization
MARD	Ministry of Agriculture and Rural Development
MJ	megajoules
MT	metric ton
NACA	Network of Aquaculture Centres in Asia-Pacific
NGOs	non-government organizations
NOAA	National Oceanic and Atmospheric Administration

NPV	net present value
NRC	National Research Council
OECD	Organisation for Economic Co-operation and Development
PAPs	processed animal proteins
PL	post-larvae
RAD	Rural Aquaculture Development
RAS	recirculating aquaculture system
SAARC	South Asian Association for Regional Cooperation
SBM	soybean meal
SCP	single-cell protein
SMEs	small- and medium-size enterprises
SPC	soy protein concentrate
SWOT	strengths, weaknesses, opportunities, threats
TBD	to be determined
TNC	The Nature Conservancy
TTL	task team leader
UK	United Kingdom
UN	United Nations
USDA	US Department of Agriculture
WEF	World Economic Forum
WISHH	World Initiative for Soy in Human Health
WRI	World Resources Institute
WSSV	white spot syndrome virus
WWF	World Wildlife Fund
WWII	World War 2



EXECUTIVE SUMMARY

Climate change and environmental degradation are major risks to sustainable development and to how we grow our food. For food production systems such as agriculture, aquaculture, and livestock farming, all of which depend on natural resources and ecosystems, climate change and environmental degradation can also be threat multipliers, exacerbating issues such as habitat decline or poor water quality. The food production systems of the future must therefore be not only sustainable but also climate-resilient, highly efficient and, wherever possible, regenerative and/or restorative. In light of these challenges, there is a growing need to explore innovative and sustainable food production methods, such as integrating aquaculture into broader landscapes and seascapes.

With this in mind, the World Bank Group supports governments toward the development of sustainable aquatic foods through an integrated landscape and seascape lens. Integrating aquaculture—the cultivation of aquatic species in a controlled, optimized environment—into landscape and seascape programs can enhance their design and implementation by upholding cultural and ecological values and bolstering the engagement of women and youth in income-generating activities. Integrated aquaculture projects can also promote the circular economy and encourage novel ways of supporting ecosystem services, including financing approaches that incentivize nature-positive behaviors.

This report, ***Eco-friendly Aquafeeds: Reducing the Carbon Footprint of Aquaculture Ingredients through Innovation***, brings together a set of case studies and analyses designed to give World Bank task team leaders (TTLs) practical examples of the economic value, societal benefits, and ecosystem services associated with restorative aquaculture (practices that enhance ecosystem functions), extractive aquaculture (practices that remove excess nutrients, for example, using seaweed, shellfish, or sea cucumbers), and non-fed aquaculture (the farming of species that do not require external feed inputs, like filter-feeding mollusks) integrated into landscapes and seascapes. The goal is to help TTLs make informed decisions, develop effective project strategies, and contribute to the improvement of food security, nutrition, job creation, climate change mitigation, biodiversity enhancement, and other objectives in their respective aquaculture projects.

Developing sustainable ways of producing aquafeed—essentially, the foods fed to fish and other species in an aquaculture environment—is critical to aligning aquaculture with sustainability principles and ensuring environmental responsibility, economic viability, and social equity. The case studies and analyses of this report uphold at least 8 of the World Bank’s 10 sustainability principles, including improving climate resilience, promoting the efficient use of energy, resources and water, reducing waste and recycling waste byproducts, promoting integrated land and coastal management, and enhancing community rights and empowerment.

The report provides a range of World Bank and other stakeholders with takeaways for different development scenarios, including country contexts where aquaculture is still in its nascent stage. If effectively implemented through World Bank-supported programs, these takeaways could help improve farmers’ access to high-quality aquafeeds—whether locally produced or imported—even in nascent aquaculture sectors. Achieving improved access, however, is more than just a matter of persistence—it also requires innovative and concessional financing solutions that can mobilize resources to help entrepreneurial farmers adopt BSFL-based feed production, utilize urban waste for insect farming, strengthen nascent sector infrastructure, and provide affordable credit for smallholders to purchase from feed aggregators.

To enable farmers and aquafeed producers in nascent markets or even fragile, conflict-affected, and violent (FCV) countries to access and produce aquafeed sustainably, both government and private sector stakeholders will need to strengthen governance and regulatory frameworks at the national and local levels, improve access to suitable financing mechanisms, and implement coordinated strategies to reduce risks such as supply chain disruptions, dependence on imported ingredients, environmental harm, and biosecurity threats. These actions should be developed through collaboration between national governments, local authorities, development partners (such as the World Bank), NGOs, and private sector actors, and in conjunction with capacity-building programs to empower displaced populations, youth, and women, who in many ways already play a very significant role in the aquaculture sectors of the Global South.

Additionally, by exploring public–private partnerships and leveraging digital innovations—such as remote-monitoring technologies and digital platforms for accessing markets—nascent aquaculture sectors in developing economies, including FCV countries, can enhance transparency, improve supply chain efficiency, and create new economic opportunities. These advancements would not only support economic stability but also foster social cohesion and peacebuilding by reducing inequality and enabling more inclusive participation in the aquafeed sector.

Building on these foundational strategies for improving aquafeed access and production in the Global South, it is also essential for policymakers, researchers, and local producers to explore innovative, sustainable raw material options such as insect meal, seaweed, algae-based proteins, and agricultural by-products. As global demand for protein rises and traditional feed sources face increasing environmental and supply challenges, a range of alternative ingredients present a viable pathway to producing reliable, affordable sources of high-nutrition local feeds, ultimately supporting food security and resource efficiency. To elucidate the options, the report offers an in-depth examination of insect meal as one of the most compelling alternatives for both animal and human food production, building on insights from previous World Bank reports, such as *Insect and Hydroponic Farming in Africa: The New Circular Food Economy* (Verner et al., 2021).

Findings

Development of the aquafeed sector

Aquaculture, implemented responsibly, could significantly enhance food security, create jobs, improve nutrition, and reduce poverty while serving as one of the most sustainable sources of animal protein. Some species, such as bivalves, certain carp species, and shrimp, require little to no external feed inputs in an aquaculture setting. But to produce seafood on a scale that could support the global population, many commercially and socioeconomically important finfish and crustacean species need formulated feeds in a farm setting.

Investors weigh this heavy reliance on formulated feed because, in certain country contexts it can constrain the scalability, sustainability, and economic feasibility of aquaculture operations. Communities with limited access to affordable, high-quality feed often struggle to produce seafood at commercial levels. This can reduce the returns on investment and limit the sector’s role in improving food security and livelihoods.

On the plus side, aquaculture production systems tend to be environmentally friendly and resource-efficient. With the exception of shrimp, they generate lower greenhouse gas (GHG) emissions than conventional food production systems. For instance, aquaculture accounts for approximately 245 million tons of CO₂ per year, representing just 0.49 percent of global emissions—significantly lower than terrestrial agriculture, which emits between 400 million and 660 million tons of CO₂ (Macleod et al., 2020).

The challenges and opportunities presented by aquafeed markets depend on their development stage. In a nascent market, where production and supply chains are decentralized, the primary challenge is to scale up aquaculture production to the point where domestic feed manufacturing becomes commercially viable. In an emerging market, where production is centralized but not yet fully integrated, a significant opportunity is that of joint ventures between supply chain actors to reduce investment risks for domestic feed mills.

As aquafeed sectors evolve from nascent into mature markets with fully centralized and integrated supply chains, the gradual and progressive consolidation of capital, resources, and technologies often leads to the emergence of a handful of powerful, vertically integrated, private-sector firms with the reach and capacity to set industry trends, affect prices, dominate their markets, and even influence policy and regulations. The lure as well as the opportunity exist for them to focus their energies on expansion and market domination, but an awareness of global trends and growing interdependency is driving many of these market leaders to shift their focus to assessing how their choices will more broadly affect environmental health, socioeconomic growth, and the needs of communities, including the most vulnerable. Investment strategies must similarly evolve beyond bottom-line gains and prioritize long-term resilience, equitable benefits, and sustainable resource use in order to mitigate the risks of overexploitation and market instability. Indeed, at all three market stages—nascent, emerging and mature—prioritizing environmental, social, and financial sustainability, along with equitable and ethical socioeconomic outcomes, is essential to fostering robust, thriving aquaculture sectors.

Aquafeed ingredients

Good-quality feed is a critical driver of aquaculture growth worldwide, but the sector's increasing reliance on formulated feeds—which often include ingredients like fishmeal, fish oil, and soy—heightens the risk of unsustainable sourcing. The concerns include the limited availability of fishmeal and fish oil, the environmental consequences of soybean cultivation—especially deforestation—and overfishing. Yet despite the technical and scalability hurdles associated with developing novel emerging feed ingredients—like insect meal, microalgae and macroalgae, and single-cell proteins—ongoing innovation in these alternative ingredients at companies and research institutions is helping to mitigate the environmental impacts and reduce dependence on commonly used conventional feed sources.

Insect meal's potential as a new ingredient

Insect meal is emerging as a particularly promising alternative feed ingredient. But its sustainability depends on the choice of feedstock, where it is being produced, and the level of automation. An optimal approach that minimizes carbon emissions is to use underutilized byproducts such as food waste, agricultural residues, and spent grains as insect feedstock, particularly in the tropics, where the hot, humid climate stimulates production. Among insect species, the black soldier fly (*Hermetia illucens*), the house fly, and the yellow mealworm are perhaps the most suited for large-scale farming, but BSF stands out owing to its high nutritional profile, high digestibility, ease of farming, and disease resistance.

Insect and hydroponic crop farming, for both human food and animal feed, have the potential to increase the food supply while creating millions of jobs, mitigating the negative impact of climate change and strengthening national economies. Various production models have emerged, including centralized industrial-scale facilities, decentralized networks involving local farmers, and on-farm models where live larvae are fed directly to farmed fish.

In African countries, a wider range of insects are viable for farming based on substrate availability and historical practice, further expanding opportunities for sustainable production. Insects are increasingly playing a vital role in

animal feed by upcycling food byproducts and other low-nutrient substrates into high-quality protein sources (Pinotti et al., 2019). Sourcing low-cost substrates of consistent quality at scale, however, remains a challenge because of seasonal fluctuations, logistical constraints, and competition with other market sector for raw materials. As the insect farming sector grows, these supply chain pressures will tend to intensify and could impact both sustainability and economic viability. For example, on the demand side, price competition with fishmeal is a hurdle many insect meal producers must clear, particularly before they reach commercial scale.

On the supply side, insect meal producers around the world—including in Africa—find that, at least initially, insect-farming companies often prefer to sell to higher-value markets such as the pet food sector before turning their attention to aquafeed.

With all that, the insect meal industry is nevertheless attracting substantial investment interest because it presents promising business and employment opportunities, including for women and youth in the aquaculture sector. For example, in Kenya, insect meal production has generated employment in the range of 25,000 to 252,000 and now recycles 2–18 million tons of biowaste (Abro et al., 2020). Additionally, producing insect feedstock from waste materials, can have a net positive GHG emissions profile by reducing the release of methane. Repurposing organic materials that would otherwise go unused can also lead to a net positive impact on land use.

Climate resilience and greenhouse gas emissions

The sustainability of aquafeeds can be significantly improved by prioritizing local agricultural byproducts, which help reduce the carbon footprint associated with traditional feed ingredients and mitigate the risks of deforestation and land conversion. Conventional aquafeed ingredients, such as soy and fishmeal, contribute to GHG emissions and other environmental concerns. Although soy can be cultivated sustainably, its production is often linked to deforestation. This results in long-term increases in carbon emission, making careful sourcing essential. Processed animal proteins (PAPs) provide an alternative with potentially lower environmental impacts. Additionally, novel feed ingredients present good opportunities to reduce GHG emissions. The suitability of alternative protein sources for commercial development, along with a summary of opportunities in target countries for alternate protein development, is provided in appendix 1.

Black soldier fly (BSF) insect meal has a notably low carbon footprint, while seaweed aquaculture offers potential environmental benefits since marine macroalgae requires no land or freshwater and emits negligible emissions during growth. Bacterial single-cell protein (SCP) shows varying global-warming potential depending on feedstock and energy sources, but targeted investments in low-emission inputs can reduce its carbon footprint.

Similarly, microbial biomass (biofloc) has potential as a sustainable feed ingredient, though further research is needed before commercial application. Feedstock selection is the most significant factor, contributing 75–90 percent of total emissions (Galán-Díaz et al., 2024).

Sustainable production of aquafeed must prioritize feedstocks that do not compete with the human food supply, aligning with the broader goals of reducing competition for resources and minimizing climate impacts and GHG emissions from the production of feed. Aside from the composition of feed, aquafeed production offers significant opportunities for achieving energy efficiency and sustainability, such as using renewable energy sources, introducing water recirculation systems, and repurposing previously converted land rather than clearing new habitats.

Insect production in tropical regions, for example, requires less energy for climate control than northern geographies. The most energy-efficient application of insects in aquaculture is on-site pond production, where live larvae are fed directly to fish, minimizing processing and transportation emissions. Such strategies can help aquafeed production transition to more sustainable and climate-resilient models.

Guiding principles for investors

Investing in nascent aquafeed industries requires a comprehensive understanding of several factors, including feed mill construction, ingredient availability, and market dynamics. When establishing a new feed mill or aquafeed production line, investors must evaluate the costs and funding options in conjunction with the availability of logistics and infrastructure to transport raw materials and distribute finished feed. Regulatory restrictions and incentives, along with the availability of local agricultural and animal byproducts, can significantly influence the investment outlook of a project. Seasonal variations and competition from other industries, such as human food and livestock feed, should also be taken into account when considering the cost and availability of ingredient supplies.

The economic viability of aquafeed production in a nascent sector depends primarily on projected market demand and sector growth, while social impact considerations—such as the potential benefits to local communities, including job creation and food security—are important but separate from the core economic factors that drive investment decisions. Evaluating the competitiveness of domestic feed against imported alternatives—in price, quality, availability, and consistency—is essential. International trade agreements, tariffs, and supply chain reliability are also factors to consider, as they can affect the cost and availability of key ingredients and ultimately influence the industry’s short- or long-term sustainability.

In emerging aquaculture markets, where operations are often centralized but not fully integrated, a thorough assessment of ingredient availability, market demand, and infrastructure is crucial for ensuring the viability of domestic aquafeed production. Understanding how this fragmented structure influences investment decisions is essential—specifically, whether the primary barrier to aquaculture expansion is inconsistent availability of feed, or if other constraints such as low access to seedstock or gaps in the value chain need to be addressed. Partnerships with international aquafeed mills or joint ventures with seafood producers could facilitate knowledge transfer, while a well-developed logistics network remains critical for supporting raw material procurement and product distribution.

Additionally, understanding the sustainability of key feed ingredients is vital for long-term industry resilience. Investors should assess whether sufficient affordable domestic ingredients are available or if alternative, underutilized ingredients could be adapted for aquafeed. If importing ingredients is necessary, supply chain reliability and cost implications, especially when ingredients are in demand for higher-value uses, must be weighed.

Key takeaways

Developing sustainable aquafeed industries in emerging and mature aquaculture markets requires a strategic approach tailored to the degree of the sector’s maturity and its supply chain integration.

But in the decentralized sectors of a nascent market, where aquaculture production volumes remain low, a more primary challenge is to scale production to justify investments in formulated feed manufacturing and supply chain services.

For example, Senegal’s tilapia industry requires additional feed to expand but has not yet reached the production levels necessary to sustain a profitable feed operation. Investing in ingredient infrastructure, such as fishmeal factories and terrestrial animal-rendering facilities, can create an attractive raw material supply for commercial feed manufacturers while also incentivizing local ingredient importers and suppliers.

Taprobane, one of Sri Lanka’s largest seafood companies and feed producers, has more than 2,000 employees working in 16 processing plants, many of which are staffed entirely by women, and maintains an extensive farmer network. Since aquaculture in Sri Lanka is still at an emerging stage, the company has expressed interest in adding a

tilapia feed line to its poultry feed facility, although profitability remains uncertain. As part of this expansion, Taprobane is considering the use of extrusion technology, which could enhance the quality of its tilapia feed by reducing microbial contamination, improving digestibility, and enabling better feed management. This would be especially beneficial for producing floating feed used in tilapia farming and cage culture, aligning with the company's goal of scaling up its operations in a centralized but not fully integrated supply chain. The risk of capital investment in a domestic feed mill can be mitigated by incorporating aquafeed production into an already existing feed mill or creating joint ventures between complementary stakeholders in the supply chain to spread risk. While such strategies may work well in emerging markets, in mature, fully integrated aquaculture markets, large corporations benefit from economies of scale, although this rapid sector growth does not always align with the socioeconomic needs of communities, as will be discussed in the case of Vietnam. Careful assessment of the impacts of sector expansion is crucial to ensure sustainable development.

Mature aquaculture markets like Ecuador present opportunities for innovative feed ingredients such as insect meal, supported by favorable environmental conditions and industry interest, though pricing challenges persist. By aligning investments with the degree of sector maturity and supply chain integration, aquafeed development can drive economic growth sustainably and equitably.

Conclusion

Aquafeed markets are critical to the growth of fed aquaculture industries and the broader economies they support, and offer a strategic opportunity for both industry and governments to advance sustainable aquatic food systems. Aquafeed's potential to reduce harmful environmental impacts, along with its role in supporting aquaculture's adaptation to climate change, and potential to replace or complement traditional feed ingredients that are placing pressure on ecosystems, is strongly encouraging. But aquafeed markets, be it at the nascent, emerging, or mature stage, present unique challenges as well as opportunities that demand careful analysis if the substantial benefits they can bring are to be fully exploited.

Equally important is the need to assess how aquafeed markets can support the socioeconomic well-being of local communities, particularly in regions where aquaculture already plays a vital role in livelihoods and food security.

Climate resilience and environmental sustainability will remain central concerns in any discussion about the future of aquafeeds. But many alternative feed sources, aquafeed included, currently lack robust data on their climate impacts, underscoring the urgent need for investment in life cycle assessments (LCAs) and related research. Strengthening the evidence base will be essential to ensuring that novel aquafeeds, instead of becoming part of the problem, contribute to a more resilient, equitable, and environmentally responsible aquaculture sector.



Sorting and cleaning food grade seaweed in Tanzania



OVERVIEW

Sustainable food production will be a defining challenge of the 21st century. The world's population reached 8.0 billion in 2022, and by 2050, the UN expects it to increase to 9.7 billion (United Nations, 2022). It is predicted that food demand will nearly double, and that protein demand will increase 50 percent by 2050 (GFI, 2024). Yet food production is one of the largest causes of climate change, accounting for 21–37 percent of total net anthropogenic greenhouse gas emissions (Mbow et. al., 2019). Food production is also a major driver of biodiversity loss and environmental degradation.

Seafood is an important component of the global food supply. Currently, aquatic animal foods (wild capture and aquaculture) provide 15 percent of the animal proteins we eat and 6 percent of all the proteins we consume (FAO, 2024a). Per capita global consumption of aquatic animals has steadily increased over the last 60 years from 9.1 kilograms (kg) in 1961 to 20.7 kg in 2022, driven largely by rising demand—which has prompted an increase in supply—technological advancements, consumer preference, and rising incomes. It is expected to further increase to 21.3 kg by 2032 (FAO, 2024a).

To help meet the growing demand for seafood, many nations are turning to aquaculture, because most capture fisheries are fully exploited or even overexploited. In 2022, aquaculture officially surpassed capture fisheries in the production of aquatic animals. It accounted for 51 percent of the total global production of 94.4 million metric tons, and 57 percent of the aquatic food humans eat (FAO 2024a). Aquaculture is the fastest-growing sector of animal food production and is expected to double in volume by 2050 to meet the increasing demand for aquatic foods (WEF, 2023). With the prices of main fish feed ingredients like fishmeal, maize, and soya bean meal increasing over the years (World Bank, 2025), cheaper alternatives will be needed to keep aquaculture products within the reach of the majority of consumers.

On the basis of a kg CO₂eq (kilogram of carbon dioxide equivalent) per kilogram of harvested protein, aquaculture species have smaller carbon footprints than land-based proteins for human consumption. This difference is most pronounced in the production of lower-trophic species, which often require minimal to no feed inputs. Across many globally traded seafood commodity species—for example, salmon and shrimp—the production of feed and feed ingredients for aquaculture species remains the largest contributor of emissions associated with aquaculture.

The strategic development of a sector requires extensive analysis and planning to meet the socioeconomic, health and nutrition requirements of the region. As the demand for farmed seafood grows, it is therefore increasingly important that developing or expanding aquaculture sectors have access to appropriate tools, research, and guidance to inform these processes, such as sustainable feed production, environmental impact assessments, and effective resource management, all of which are crucial for guiding investments. In addition, there is a need for supply chains and production to operate in ways that are environmentally, socially, and financially sustainable and/or regenerative.

2

HOW AQUAFEED SECTORS DEVELOP: THREE STAGES OF MATURATION

The development of an aquafeed sector generally follows, or runs in parallel with, the development or expansion of a domestic aquaculture industry. The degree of development falls into one of the three categories:

- **Nascent stage: Decentralized production and supply chains:** This is characterized by small-scale, low-intensity farms using little or no feed. Where feed is used, it is typically in limited amounts during certain portions of the production cycle and is prepared on-farm in a rudimentary way, with minimal locally available inputs. The species are typically low on the food chain—carps, milkfish, tilapia, and shrimp, for instance. The supporting supply chains are minimal, and farmers often stock ponds with wild fingerlings or post-larvae.
- **Emerging stage: Centralized but not fully integrated production and supply chains:** Here, production intensity of farms is increasing, driven by higher stocking densities and reliance on supplemental feeds throughout the grow-out cycle. Demand for feed, fingerlings, processing, and marketing is higher. Although on-farm feeds are often still in use, the demand for greater quantities and higher quality of feed stimulates the development of the first commercial feed mills. Other components of the aquaculture production chain emerge, including hatcheries, processing plants, and marketing networks. The mix of species begins to focus on those with the greatest market demand.
- **Mature stage: Centralized and fully integrated production and supply chains:** Mature aquafeed sectors have centralized upstream and downstream supply chains and production. They often include vertically integrated companies and/or other partially integrated supply chain and production models, and are characterized by rapid growth as strong inflow of investment capital scales production to supply robust domestic and international markets. Production focuses on producing consistently high volumes of one or a few key species. As volumes rise, margins tighten, leading to consolidation, vertical integration, and

branding. The production chain deepens and diversifies to supply a full range of supporting products and services. Digital technology plays a more integral role, especially in improving efficiency and traceability.

As a sector evolves from nascent to emerging to mature, following a trajectory of intensification and centralization, its associated industries may not necessarily all evolve in lockstep. Some may shift from one level of development to another sooner than others, pulling the others along. Similarly, not all aquafeed sectors develop along a production intensification trajectory. In some cases, key stakeholders such as policymakers, industry leaders, or development agencies may prioritize strategic goals that do not center on further intensification of production or expansion of fed aquaculture. Instead, they might emphasize sustainability, resource efficiency, or smallholder inclusion. Nonetheless, despite these divergences in the rate and direction of development, certain patterns can be commonly observed. The next section takes a closer look at each of the three development stages. Employing a country example for illustration purposes, it poses and answers a set of questions that should guide investors who are considering entering an aquafeed market at the development stage.

Nascent stage: Decentralized production and supply chains

Feed is the largest driver of aquaculture sector productivity, as illustrated in the progression of productivity in Bangladesh from 1.37 metric tons per hectare per year (MT/ha/year) of fish with the use of no feed, to 3.73 MT/ha/year with farm-made feeds, to 7.28–18.53 MT/ha/year with commercial feeds (table 1).

TABLE 1: Categories of pond fish production in Bangladesh

Culture method	Total area (ha)	Fish productivity (MT/ha/year)	Fertilization	Feed type	Monoculture or polyculture	Stocking density (fish/ha)
Extensive	31,000	1.37	Yes	No feed	Poly	Under 12,000
Semi-intensive	239,100	3.73	Yes	Farm-made feed	Poly	18,000–20,000
Intensive	120,900	7.28	No	Commercial feed	Mono	33,000–35,000
Highly intensive	189,800	18.53	No	Commercial feed	Mono	Over 40,000

Source: Samanta Chandan and Roy (2023)

Note: This is an illustrative example to explain the importance of feed as a driver of aquaculture sector productivity.

At the most nascent stage, the first step has historically been the traditional practice of stocking ponds with wild seed collected from natural waters and stimulating the ponds' natural food chain with organic fertilizer such as animal manure, kitchen scraps, or agricultural byproducts. Pond productivity in such traditional systems typically ranges between 300 and 700 kg/ha/year.

Unfed ponds typically stock species that feed low on the food chain. In freshwater, these include Chinese carp, Indian carp, and tilapia. In saltwater, they include shrimp, oysters, clams, milk fish, and mullet. To increase yields, a complementary mix of species can be raised in polyculture. Farms may also produce aquaculture crops in conjunction or in rotation with agricultural crops (for example, rice). Use of healthy, genetically improved fingerlings instead of wild seed can greatly improve productivity. In the case of carp, stocking large good-quality fingerlings can yield more than 1,000 kg/ha/year of production (Samanta Chandan and Roy, 2023).

The second step on the intensification continuum at the nascent stage is to prepare rudimentary on-farm feeds using locally available ingredients such as soybean meal, palm kernel meal/cake, copra cake, peanut meal, cottonseed meal, rice bran, maize, mustard oil cake, local fish meal, and meat and bone meal. Ingredients are ground, blended, and formed by hand or with simple farm machinery (Wood, 1993; Giri, 2017). On-farm feeds are nutritional supplements intended to complement natural foods in the pond.

As farms intensify their production, they require more complete feed. Farmers shift from on-farm feeds to formulated sinking feeds and, ultimately, to formulated extruded floating feeds. Given the lack of domestic formulated feeds at the nascent aquaculture sector stage, imported feeds are often necessary. Since small, nascent farms may face a variety of inefficiencies from the lack of good-quality seedstock, trained staff, and so on, imported feeds may not be economically feasible (table 2) unless fish prices are high in that market .

TABLE 2: Relative cost of farm-made, sinking, and extruded feeds in Bangladesh

Feed Type	Cost (\$/kg)
Farm-made feeds	0.34
Domestic sinking formulated feeds	0.44
Domestic extruded formulated feeds	0.54
Imported extruded formulated feeds*	0.70

Source: Hazrat et al. (2023)

*The cost is assumed to be 30 percent higher than that of domestic extruded feed (FAS, 2019).

The paradoxical and self-reinforcing circle in which nascent aquafeed sectors find themselves is that justifying the construction of a domestic feed mill requires a sufficiently large market that will purchase that higher level of feed production, but that level of production is hard to achieve without a domestic feed mill.

Ideal investments are those that generate the greatest social and economic impact by addressing the key bottlenecks that limit development. Although this report focuses on aquafeed, feed is not always the primary limiting factor. A variety of other factors that vary by region and over time can limit aquaculture production during the nascent stage. They include hatcheries, processing plants, cold chain distribution, and technical support. For instance, in the case of striped catfish development in Vietnam (box 1), hatchery technology was the main limiting factor.

BOX 1: HATCHERY TECHNOLOGY, FOLLOWED BY FEEDS, WERE THE TWO MAIN BOTTLENECKS LIMITING STRIPED CATFISH PRODUCTION IN VIETNAM

The culture of striped catfish (*pangasiids*) for household consumption in Vietnam started in the 1950s in the Mekong River delta using wild fingerlings in “over-hung latrine ponds” and in floating cages in. In the early 1980’s, a shortage of wild fingerlings led to two decades of research on artificial propagation. Then in 1997, researchers achieved a breakthrough propagation technique that was rapidly disseminated to hatcheries, involving the use of hormonal induction to stimulate fish to spawn (Tri et al., 2021).

Insufficient feed was a second bottleneck to be resolved. This was achieved with the transition from home-made feed to floating extruded feeds, and from culture in cages and pens to high-density deep earthen ponds that can yield 350–400 metric tons of catfish per hectare of pond area, per crop cycle (Ngoc et al., 2016). Currently, Vietnam’s catfish industry is facing climate change-related pressures, including saltwater intrusion. But recent studies assessing the potential for selective breeding for salinity tolerance show promise for the industry to adapt to these changes (Ishimatsu and Utsunomya, 2024).

Infrastructure and regulatory bottlenecks can also hinder the development of nascent aquaculture. Adequate public infrastructure, including good roadways, ports, and energy distribution systems, is required for the efficient transport of goods and energy resources to facilitate development. A suitable legal and regulatory framework is needed to streamline or simplify processes for aquaculture licensing, operation, and investment.

Lack of capital and inadequate access to credit reduces farmers’ ability to build or improve facilities, purchase good-quality fish seed and feed, and buy equipment and services. Despite favorable tailwinds driven by megatrend shifts in the global economy, several investors indicated (AquaSpark, 2021) an unwillingness to invest in nascent tilapia farming projects in Sub-Saharan Africa because of insufficient scale and maturity, excessively long timelines to profitability, an insufficient pool of local talent, and excessive valuations for the level of risk. Institutional or catalytic/philanthropic financing may be needed to accelerate the growth of nascent aquaculture by enabling the development of domestic feed production and other links in the aquaculture supply chain.

Guiding questions for investing in a nascent aquafeed sector

Feed mill construction and production

- What is the cost of constructing a new feed mill or aquafeed line, and what are the funding options available?
- Are there adequate logistics networks and infrastructure to transport raw materials to the feed mill and distribute the feed produced?
- Are there any incentives or regulatory difficulties for establishing feed mills?

Ingredient availability

- How available are local agricultural and animal byproducts for feed? Is the supply of these ingredients subject to seasonal fluctuations?
- Are there local alternative ingredients that can be used in feed production to reduce costs and improve sustainability?
- How reliable is the supply chain for imported ingredients? Are imported ingredients available at competitive prices?
- Does the aquafeed industry compete for the use of local raw materials with the human food and other animal feed industries (for example, poultry or cattle)?

Market and economic factors

- What is the current market demand for aquafeed, and what are the growth projections?
- What are the economic benefits of investing in aquafeed production for the local community?
- Are there any trade agreements or tariffs that could affect the cost and availability of feed ingredients?

Example country with a nascent industry: Senegal

Aquaculture industry. Senegal's aquaculture sector is nascent, with total production of around 1,585 MT/year of tilapia, African catfish, mussels, and oysters (FAO, 2024a). In 2010 the Thai government supported the construction of 10 tilapia hatchery ponds to form a breeding facility. Senegal's Ministry of Fisheries, through the National Agency for Aquaculture (ANA), had developed a national strategic plan for aquaculture development but had lacked the resources to realize it (FAS, 2022).

In 2023, the World Bank initiated a \$100 million Natural Resources Management Project to improve the management of fish and forest resources and access to related economic opportunities in target areas in Senegal. Expected to run until 2028, the project has allocated \$10 million to support the development of aquaculture (World Bank, n.d.).

Aquafeed. The US Foreign Agricultural Service states that domestic feed production is very limited in Senegal, with mostly lower-quality sinking feeds available, which are not optimal for tilapia (FAS, 2022). The lack of good-quality domestic fish feed production, and the high costs of imported feed, limit the near-term growth potential of the country's nascent aquaculture sector (FAS, 2022). Higher-quality feed is available from Nigeria and Ghana, which produce most of the feed in the West Africa region, but cost is a factor. To support domestic fish feed production, a poultry company in Senegal even considered expanding their feed business by producing floating fish feed (WISHH, 2020).

Industry experts estimate that an extrusion aquafeed line in Senegal would need to produce and sell at least 10,000 MT of feed to reach profitability (AquaSpark, 2021). Assuming a feed conversion ratio of 1.5, this implies that Senegal's aquafeed industry would need to have at least 6,666 MT of aquaculture fish production to justify building an aquafeed extrusion line. But the country currently produces only 1,585 MT. In short, Senegal is enmeshed in the Catch-22 self-reinforcing cycle that ensnares many a nascent aquaculture sector and holds them in a low-level equilibrium sometimes for years—needing to increase its fish production to make domestic feed production commercially viable, yet not producing enough feed to be able to increase its fish production.

Ingredients. Of the ingredients available or potentially available in Senegal, *fishmeal*, *peanut meal*, *agricultural byproducts*, *processed animal proteins (PAPs)*, and *insect meal* could potentially support the domestic production of aquafeed.

Senegal's main crops (using 2023–2024 approximate production levels) are peanuts (1.73 million MT a year), millet (1.35 million MT a year), rice (1.03 million MT a year), corn (930,000 MT a year), sorghum (450,000 million MT a year),

and palm oil (10,000 million MT a year) (FAS, 2024a). Peanut meal is an excellent protein source for partial replacement of fishmeal in aquafeeds, and its use in aquafeeds could reactivate peanut processing plants in Senegal. Byproducts from millet, rice, and corn can serve as a starch binder and energy source in aquafeeds.

Processed animal proteins, such as feather meal, blood meal, and poultry byproduct meal, are a potential future ingredient in aquafeeds in Senegal. Over the last decade, poultry production has advanced rapidly both in volume and production techniques. The constraints here are that the domestic market relies heavily on live chicken sales. This limits the availability of byproducts like offal for uses such as PAPs because slaughter and plucking typically occur in the live markets and the offal is sold directly for pig production. The volume of live chicken sales is highly variable owing to ad hoc factors such as fluctuating consumer demand, seasonal festivals, inconsistent supply chains, and limited cold chain infrastructure, all of which spell market volatility. But even in a nascent aquaculture sector like Senegal's, supply consistency—in volume, frequency, and quality—is a mission-critical need for feed producers, whose fish-producing customers in turn depend critically on them. For that reason, live chicken sales cannot fit into their business model without creating financial stress (FAO, 2023b). *However, as Senegal's poultry market begins to mature and to offer centrally processed, value-added, and frozen products, opportunities will likely emerge for greater production of processed animal proteins and their inclusion in aquafeed.*

Senegal's tropical climate and freedom from regulatory constraints on the use of local fruit and vegetable waste present an opportunity for insect meal production. NeoFarm is a Senegalese startup company that intends to collect organic waste from various localities and produce meal, oil, and fertilizer for the pet food and animal feed sectors (NeoFarm, 2023). NeoFarm seeks to raise \$3 million to establish a 200 MT/year black soldier fly production facility as a starting point for continuing R&D and future growth.

Emerging stage: Centralized but not fully integrated production and supply chains

At the emerging stage, fed aquaculture production is expanding rapidly, but farms and feed supplies may be at different levels of sophistication and intensity (box 2). Feed commonly accounts for 50-70 percent of total farm operating costs but can be more than 90 percent of the cost for some smallholder farms (Towers, 2013; Hossain et al., 2021; NOAA, 2023).

To take advantage of dealer services such as feed transport, storage, and credit, small farms often buy feed through dealers, rather than directly from the feed. But this incurs an additional expense to cover the dealer's margin. A value-chain analysis in Bangladesh indicated that raw materials account for 73.5 percent of the end price farmers pay for feed. Other cost components include feed processing (15 percent), profit margin for feed miller (5.3 percent), and dealer cost (6.2 percent) (Towers, 2013).

Commercial feed mills are typically the last component of the aquaculture production chain to be developed, because production processes are complex, the costs of raw materials and manufacturing processes require economies of scale, and a diverse array of knowledge and skills is needed to operate them well, including purchasing, logistics, nutrient analysis and quality control, formulation, manufacturing, sales and marketing, distribution, and management.

Programs are needed to train local talent to fill these technical and management roles. The presence of complementary companion industries such as poultry and swine feed facilities, with their corresponding technology (for example, pellet mills or extruders) and trained workers who bring expertise, can be an important source of local technical and management competence. It may also be possible to attract skilled emigrants (Francisco Murillo, CEO of Tropo Farm, Ghana, interview, August 28, 2024).

Formulating diets to meet nutrient requirements

To minimize cost and optimize the nutritional balance of feeds takes understanding the nutrient requirements of target species and their life stages as well as the nutrient composition, digestibility, and antinutritional factors of the ingredients. Skilled aquaculture nutritionists are needed to assemble this information and develop feed formulations for each target species. These specialists often collaborate with ingredient suppliers, research institutions, and farmers to gather data on the optimal use of locally available raw materials.

BOX 2: EXAMPLES OF FEED TRANSITION IN EGYPT, BANGLADESH, AND NIGERIA

Egypt and Bangladesh are examples of emerging-sector aquaculture markets that have chosen two contrasting paths in how they approach aquafeed supply, with distinct consequences for their transition from traditional feed production to commercial aquaculture feed systems.

In Egypt, feed production is fragmented and decentralized. About a million metric tons per year are produced by a mix of 50 registered private mills (67 percent of production), nine government/public sector mills (10 percent), and 200 small, unregistered mills that produce pelletizing units without a drier (13–23 percent) (Kaleem and Sabi, 2021). Many of these smaller mills, with their outdated technology and weak quality control, produce inconsistent, poor-quality feed.

Bangladesh, by contrast, took a more structured, consolidated, centralized, and larger-scale approach to feed production, with the result that commercial feed production now accounts for more than half of all aquafeed production. Between 2008 and 2012, commercial feed production on average grew 32 percent per year, driven by rising demand from pond farmers, technological advances in feed production, and improved supply chains. By 2012, commercial feed production had reached over 1 million MT, with about 100 commercial mills producing aquaculture feeds. Among these, 8–10 large operators account for 60–70 percent of market share (Towers, 2013).

The result of the contrasting feed supply dynamics between Egypt and Bangladesh is that Bangladesh has experienced a much more rapid shift toward commercial production. The country's rapid transformation presents a model for other emerging-market countries such as Egypt, offering evidence that accelerated growth in feed production can drive overall improvements in the aquaculture sector, increasing efficiency and sustainability. The current distribution of feed production in Bangladesh is estimated to be 33 percent highly intensive (commercial feeds), 21 percent intensive (commercial feeds), 41 percent semi-intensive (farm-made feeds), and 5 percent extensive (no feed) (Samanta Chandan and Roy, 2024). The distribution highlights a growing reliance on commercial feed (54 percent of the market) and the intensification of farming practices in Bangladesh. Even though the typical fish pond farm size is only 1–2 ha, pond farming now totals 581,500 ha in Bangladesh.

Transitioning from imported to domestically produced aquafeeds can present a similar mix of initial challenges but eventual benefits for the entire aquaculture sector. When the domestic market first starts producing formulated feeds, the feeds are typically cheaper but lower in quality than the imports—a dynamic observed in Nigeria during the 2000s (Ogugua and Eyo, 2007). While imported European feeds cost more but had superior feed conversion ratios (FCRs) of 1.1 to 1.5, domestic feeds suffered from inconsistent quality and FCRs often exceeding 2.0, reducing fish production efficiency. Initially, this cost vs. quality tradeoff favored the imported feeds, but over time, persistent Nigerian feed producers, responding to farmer demand, improved their quality control and ingredient sourcing. By the 2010s, larger domestic mills had begun investing in better processing technology and partnerships with nutrition experts, narrowing the gap to imported feeds. This shift highlights how emerging aquaculture markets can mature with sustained, patient, persistent investment in local capacity. In short, sector growth and transition are not easy, but eminently achievable.

As ingredient purchasing and formulation systems evolve, managers strive to reduce dependence on marine meals and oils by replacing them with more sustainable plant-based ingredients and with natural and artificial attractants and palatants to stimulate consumption.¹

Manufacturing to achieve consistent pellet quality

To make sure that the full nutritional value of the feed ingredients is delivered in each pellet to the target species, the ingredients must be homogeneously mixed and bound together in a water-stable form that stays intact until the feed is consumed. Water stability can be enhanced by incorporating artificial pellet binders or native protein binders such as wheat gluten, but these increase the cost. It can be more cost-effective to take advantage of the natural functionality of the ingredients themselves (Bortone, 2001).

Extrusion requires higher capital investment and energy costs than pelleting systems, but extrusion is a more versatile process that can reduce ingredient costs and produce either floating, sinking, or slow-sinking feeds.

BOX 3: A JOINT VENTURE BETWEEN A FEED COMPANY, A PRODUCER, AND A CHARITABLE ORGANIZATION

In 2022, Maxim Agri Holding, Victory Farms, and Gatsby Africa formed a joint venture to build a new aquafeed mill, Samakgro (Aquafeed.com, 2022). Each partner in the joint venture brings a different skillset. Maxim Agri, which manages the facility, is a Netherland-based feed company with experience in emerging markets. Gatsby Africa, an English charitable company that supports the development of African economies, is providing financial support and strategic guidance.

Victory Farms, a fish farm based in Kenya, provides practical aquaculture knowledge (Samakgro, 2024). The feed mill operates on sustainable energy sources using high-tech equipment (Aquafeed.com, 2022). Samakgro is also investing in local ingredient trials to tailor its formulations to local conditions. Samakgro is an example of a collaboration between a multinational feed company, a local aquaculture producer, and a philanthropic organization to pool the knowledge and resources needed to develop an aquaculture feed mill.

Potential opportunities to invest in an emerging aquafeed market

1. **Install an aquafeed line within an existing feed mill.** To reduce the capital investment and risk of starting a new aquafeed mill, an aquafeed line can be installed in an already existing animal feed facility such as a poultry mill.
2. **Develop dedicated aquaculture feed mills.** Establishing a dedicated aquaculture feed mill can ensure a consistent supply of high-quality, nutritionally balanced feed tailored to the needs of farmed species. Feed mills can start as joint ventures between seafood producers and multinational feed mills. See case study 3 for an example of a joint venture in Kenya between a seafood producer, a global feed mill, and a philanthropic organization (Aquafeed.com, 2024).

¹ A palatant is something added to food to make it more palatable by enhancing its taste and flavor.

3. **Install extrusion equipment in existing or new feed mills.** Investing in extrusion equipment allows the production of extruded feed, which enables more accurate management of feed consumption and improved efficiency. Investing in extrusion becomes commercially viable when feed demand reaches 10,000 metric tons a year, and optimal when it reaches 30,000 metric tons a year (AquaSpark, 2021).
4. **Produce domestic feed through a philanthropic investment.** With initial feed mills costing several million dollars, direct government or philanthropic investment is often needed in the early stages of aquafeed development because the capital requirements are relatively demanding. After the infrastructure is established, often with the support of public investment, this can then spur outside investment from multinational or transnational corporations to accelerate commercial production and scale.

Guiding questions for investing in an emerging aquaculture sector

1. **Is there strong and growing demand for aquafeed to justify investment in domestic commercial feed production?**
 - Is a lack of aquafeed the primary constraint on aquaculture? Are there other barriers to dismantle (for example, access to seedstock)?
 - What volume of commercial feed is imported at present? Would domestic feed be competitive with imported feed in price and quality?
 - What are the estimated production costs and final costs of locally produced feeds?
 - Will farmers who currently use on-farm feed be able to afford domestic feeds?
2. **Does the country have adequate infrastructure and resources to enable aquafeed manufacturing to succeed sustainably?**
 - Are there existing animal feed mills from which to source skilled professionals, knowledge, and tools?
 - Are there aquaculture feed mills in other countries from which to seek support, such as knowledge and tools?
 - Are there joint venture opportunities with seafood producers or feed manufacturers?
 - Are there adequate transport and logistics networks to procure raw materials and distribute finished products?
 - Are there regulations that may facilitate, or alternatively impede, the development of aquafeed?
3. **What quantities of the necessary ingredients are available to produce feed domestically?**
 - Are affordable domestic ingredients available for feed? Are they available in sufficient quantities?
 - Are underutilized or alternative ingredients available that could be adapted?
 - Will any ingredients need to be imported? If so, are there supply chains to procure them?
 - Are some of the needed ingredients already being used for high-value purposes, such as direct human consumption, that could drive up the price?
 - Are there long-term sustainability challenges to the most promising domestic ingredients?

Mature stage: Centralized and fully integrated supply and production chains

At the mature stage of aquaculture industry and market development, production is accelerating, profit expectations and business confidence are rising, and investors feel encouraged to install additional capacity. As scale and complexity increase, mechanization, automation, and digital technology typically begin to play more important roles. Skilled managers and technology specialists are needed to refine and optimize each growth step.

Potential investment opportunities

Feed research

Feed is the largest component of an aquaculture farm's operating costs, so it is vital that manufacturers control the cost and quality of feeds and that farms optimize feeding management systems. At the mature stage, most feed companies have active research programs. They are typically focused on evaluating new ingredients, refining the nutrient requirements of target species, improving manufacturing methods, and helping farms improve their feed management systems. In 2022, the Norwegian-based company Skretting, the world's largest aquafeed company, opened the Skretting Aquaculture Innovation Guayas Research Station, a EUR 6.1 million shrimp research facility in Guayaquil, Ecuador to focus on a wide range of topics related to shrimp feed (Jimenez, 2022). Such research drives productivity and efficiency and creates a widening gap with nascent and emerging aquaculture sectors.

Feed ingredients

Raw materials constitute about 90 percent of the cost of feeds. Consequently, *research is continually under way to substitute new ingredients and processes that reduce costs or improve performance*—for example, by enhancing nutritional value, digestibility, palatability, and pigmentation, and by improving the immune-enhancing properties of feed. Over the years, systematic persistent research is gradually reducing the reliance on fishmeal and oil in feed because overfishing and shortages have tripled their prices in the past three decades (IMF, 2024). As a result, oilseed meals, protein concentrates, processed animal proteins (PAPs), and vegetable oils have been discovered—and are still being discovered—as effective, high-functioning substitutes.

Alternative and novel ingredients are a focus of research and development. Much of this R&D is directed toward the treatment of low-value agricultural byproducts and food wastes to improve their nutrient composition and digestibility. Seaweed is also in the early stages of consideration as a feed ingredient. (For a further discussion of promising alternative and novel ingredients, see “Aquafeed Ingredients” below.)

Ingredient quality and consistency

Manufacturing consistently high-quality feeds requires using ingredients of consistent quality. In mature aquaculture sectors, many of the larger feed companies, in an effort to build trust and protect their market share, have published ingredient purchasing standards that specify the nutrient composition, digestibility, freshness, and the acceptable

maximum limits of antinutritional factors such as mycotoxins or rancidity in the feeds they sell. These published standards are challenging the companies that produce novel ingredients to raise their nutrition and production standards, improve their feed consistency, and simultaneously lower their costs by scaling up to achieve economies of scale. Small-scale insect larvae facilities, which previously might have sold directly to farms or small-scale feed mills, are now under pressure to consolidate into larger companies to achieve volume and scale while maintaining consistency.

Traditionally, feed mills have checked the nutrient composition of their ingredients and final feeds using wet chemistry in internal quality-control labs.² But as mills modernize and expand, their labs now include high-tech methods like instantaneous nutrient analyses using near-infrared reflectance (NIR), which can also estimate ingredient digestibility. This enables more frequent analyses and more precise formulation adjustments, which improve nutritional performance, reduce waste, and promote species growth.

Feed manufacturing

At the mature stage, as feed manufacturing expands, it typically becomes dominated by a few large-scale domestic feed mills with standardized, high-quality feeds and rigorous quality standards. These mills may be owned by multinational feed companies, integrators, local companies, or joint ventures, depending on the economy of the specific country. Generally, the largest aquafeed companies are integrated or partnered with integrators and are increasingly sophisticated in a range of operational areas like production efficiency, technology, traceability, and sustainability. These more advanced feed mills often shift from steam pelleting to more costly extrusion manufacture because of its greater versatility in accepting a wide range of liquid, dry, or fibrous ingredients, and its greater control over cooking intensity, product density, oil content, size, and form—in short, much greater precision across a broad range of manufacturing parameters.

Feed formulation

At the mature stage, the ingredient mix can be diverse and may be competitively sourced from both domestic and international sources. Feed companies are able to use sophisticated formulation software to evaluate each ingredient not only for their nutrient composition, digestibility, and cost, but also for their long-term sustainability impact (Boissy et al., 2011). For example, to make environmentally informed choices, mature-stage feed companies begin to formulate feeds based on their life cycle assessment (LCA) impact categories, including their carbon footprint and deforestation potential.

Feed management on farm

At the mature stage, on-farm grow-out technologies advance and diversify, enabling expanding production in diverse environments with increasing levels of control and sustainability. Solar-powered, remote-controlled, smart feeder devices equipped with flotation, propulsion, acoustic detection, and GPS technology, along with artificial intelligence

² Wet chemistry is what normally comes to mind when we think of chemistry experiments: conducting reactions in a lab using various liquids in beakers and other glassware. Also known as bench chemistry, modern wet chemistry includes analytical techniques such as titration, distillation, colorimetry, gravimetry, and spectrophotometry.

and machine-learning algorithms, are able to determine precisely when and how much to feed the fish or other species by analyzing water conditions, growth stages, and the movements and behavior of the animals. This makes it possible to automate and optimize the feeding process, minimizing waste, and accelerating growth. Some shrimp smart feeders have underwater microphones to monitor feeding behavior and dispense prescribed amounts of feed.

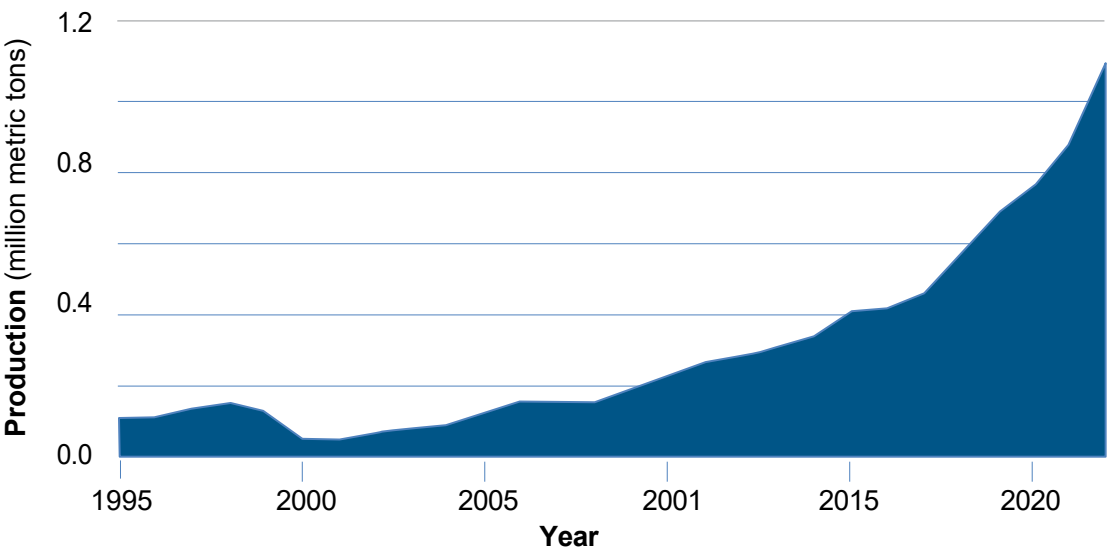
Despite the technological advantage consolidation can bring, in some aquaculture sectors such as shrimp farms in Asia, smallholder farms still dominate and are beginning to access technological innovations through digital solution providers. Companies such as AquaExchange and eFishery are helping farmers gain access to digital technologies, improve their efficiency, streamline processes, enhance productivity, and reduce their environmental footprint. The Nature Conservancy and the Center for Responsible Seafood are linking with digital solution providers to upgrade the performance of small-holder farms and enroll them in an improvement program to enhance their social and environmental practices and provide access to premium markets (Chamberlain, 2024).

Target countries for investors seeking mature aquaculture sectors

The example of Ecuador

Aquaculture industry. Between 1995 and 2022, shrimp production in Ecuador increased 909 percent—from 0.11 million to 1.11 million metric tons (figure 1)—while area stocked increased only 31 percent, from 175,000 ha to 230,000 ha (Seafood Watch, 2021).

FIGURE 1: Shrimp production in Ecuador, 1995–2022



Source: FAO (2024d)

A primary catalyst of this propulsive growth was Ecuador's adoption of a novel shrimp breeding program following the white spot syndrome virus (WSSV) epidemic which devastated the fledgling sector in 1999. After futile attempts by Ecuadorian farms to stamp out WSSV using disinfectants and biosecurity techniques as in smaller ponds in Asia, a few hatcheries began selecting survivors from production ponds as parents of a new generation.

After several years, this mass-selection program resulted in increasing tolerance of not only WSSV but also other viral and bacterial pathogens. This stabilized survival rates and enabled uninterrupted leaps in production for one and a half decades.

The resulting financial stability and explosive growth have attracted major investments all along Ecuador's entire shrimp farming value chain (Rocha 2023). Farms have invested in deepening their ponds and installing smart autofeeder and aerators. Processing plants have invested in value-added lines to reduce reliance on the unpredictable head-on market in China.³ In 2023, Mitsui announced an investment of \$360 million in Ecuador's largest integrated shrimp farm, Industrial Pesquera Santa Priscila (Mitsui, 2023).

Aquafeed. Ecuador's shrimp feed industry is highly consolidated. Four multinational feed companies—Skretting, Vitapro, BioMar, and Cargill—account for 80 percent of feed production (Shrimp Insights, 2022). The feed mills source ingredients from around the world, using soymeal and wheat from the US, Argentina, and Canada, and fishmeal and fish oil from both domestic fisheries and Peru. Given the deforestation and land conversion risk of certain crops sourced from Brazil, Argentina, and Bolivia, there is a major opportunity for local agricultural byproducts to play an important role in improving the carbon emissions profile of the feed.

Feed ingredients. Local ingredients face stiff competition from imports, often sold by large commodity traders with significant economies of scale. In Ecuador, rice is the most cultivated agricultural crop by far, at 27 million metric tons annually. Domestic broken rice is therefore abundantly available for use in shrimp feeds (FAS, 2024b). Rendered animal proteins are also already being used in shrimp feed. For example, Ecuador imported 40,000 tons of American rendered animal proteins in 2021 (USAEDC, n.d.). The large and mature global processed animal proteins (PAPs) industry makes it difficult for new entrants to compete (for example, a significant volume of PAPs comes from Brazil).

Insect meal use, by contrast, is quite small today, potentially creating an opportunity to establish a local sector. There is interest in insect meal from feed companies and downstream US and EU buyers (Alando, 2023), but it is currently too expensive for mainstream feeds compared to fishmeal, which has higher protein, palatability, and essential fatty acids content. Hadas et al. (2024) estimate that insect meal prices would need to be declined from \$3,500–4,000/MT to about \$1,100/MT to justify inclusion in aquafeeds. Ecuador-based Bioconversión started trials in 2019 and opened Latin America's first insect meal plant in 2021. In addition, a joint venture between Lukmar, a shrimp-farming company, and Mutatec, a bioconversion specialist, is looking to conduct a second on-farm pilot with the potential to use insects directly in ponds.

Ecuador has good fundamentals to build an insect meal industry. It produces \$61.4 million of processed fruits and nuts a year, the byproducts of which could be used to feed insect larvae. The International Trade Administration notes that fruit and vegetable processing is a significant market opportunity for growth, since only 4 percent of current fruit and vegetable production is processed in Ecuador (ITA, 2022). In Costa Rica, ProNovo recently received a \$2 million investment from the World Bank to complete construction of a 4,000 MT/year insect meal plant that will use banana peels from the production of banana puree to feed insects (Feed Strategy, 2024).

3 Head-on shrimp are shrimp sold with their heads attached and shells intact, as opposed to peeled or deveined shrimp. Head-on shrimp are preferred by some because the head's flavorful juices and fat give the shrimp a richer, more complex flavor, but this market, particularly in China, can be less predictable, leading Ecuadorian shrimp-processing plants to diversify their offerings and lessen their dependence on this less segment.

The example of Vietnam

Aquaculture industry. Vietnam, currently the world's fourth-largest aquaculture producer, behind China, Indonesia, and India (FAO, 2024a), has a large and diverse aquafeed industry. In 2022, it produced 5.8 million MT of aquaculture species, dominated by catfish, shrimp, carp, tilapia, and bivalves. In 2019, aquaculture contributed 3.4 percent of Vietnam's GDP. Striped catfish (*Pangasius*) and marine shrimp (*L. vannamei* and *P. monodon*) dominate aquaculture production—1.7 million and 1.1 million MT in 2022, respectively (FAO, 2024a).

Vietnam has 1.7 million hectares of land potentially suitable for aquaculture, of which about 1 million hectares are currently in use in eight zones with different geographical and climatic conditions (Tri et al., 2011). The Mekong River delta accounts for around 71 percent of fish and 84 percent of shrimp production.

But the delta faces several challenges associated with the rapid diversification of an aquaculture sector in the mature phase. They include subsidence,⁴ sea level rise, saltwater intrusion, and pollution from effluents generated by the intensive culture of *Pangasius* and shrimp (van Beijnen and Yan, 2024; Nguyen, 2017). Numerous projects are trying to address the unsustainable expansion of the aquaculture sector in the delta, with varying levels of success. Nevertheless, Vietnam offers many advantages for investors, including its warm climate, proximity to raw materials, and government interest in sustainable practices.

Aquafeed. Vietnam's aquafeed industry produced an estimated 5.7 million MT in 2024 (FAS, 2024c). European and American multinational companies such as Cargill, Skretting, Biomar, and De Heus are active in the country, but the top producers are Asian companies: CP (Thailand),⁵ Sheng Long Biotech, a subsidiary of Guangdong Haid Group, China, Uni-President (Taiwan), and Evergreen (China) (Shrimp Insights, 2022).

Vertical integration is common. Several shrimp feed companies—Sheng Long, Grobest, CP, and Viet Uc Seafood Corporation—own hatcheries that provide post-larvae. Viet Uc, the country's largest post-larvae producer, with nine hatcheries, recently joint-ventured with Biomar to produce shrimp feed. It also owns a processing plant and a super-intensive shrimp farm.

Vietnam has established minimum standards for the composition of formulated feeds for shrimp, *Pangasius*, and tilapia (FAO, 2024b). The standards specify pellet size for various life stages, proximate composition, key amino acids, macro-minerals, the maximum content of contaminants such as ash and sand, and the permitted levels of *Aspergillus*, *Salmonella*, and aflatoxin.

Feed ingredients. Vietnam imports 75 percent of its aquafeed ingredients (19.8 of 26.5 million MT). The highest volumes are of soybean meal, corn, and feed wheat, at 5.8 million, 7.8 million, and 2.3 million MT, respectively (FAS, 2024b). It has established standards for major feed ingredients such as fishmeal, bone meal, meat and bone meal, rice bran, and soybean meal (FAO, 2024c). Rendered animal proteins are already being used there, and standards have been set for maximum inclusion thresholds. The country has a large agricultural sector with suitable byproducts for aquafeeds, many of which are already in use. In Vietnam, rice is easily the most cultivated crop, at 27 million metric tons annually. The local supply of rice bran and broken rice is 4.2 million MT, but 0.7 million MT is also imported (FAS, 2024c). Government standards limit broken rice inclusion in aquafeed to less than 2 percent for shrimp, tilapia, and *Pangasius* (FAO, 2024b).

4 Subsidence is the gradual sinking of the ground, or the settling of the earth's surface, often due to the natural compaction of sediments or human activities such as groundwater extraction.

5 CP is Charoen Pokphand Foods.

Given its level of development, Vietnam is an attractive candidate for the near-term development of the more advanced capital-intensive feed ingredients used in commercial feed mixes, such as microalgae oil and insect meal. But new ingredients will have to compete with low-priced, high-volume commodity ingredients from domestic and international sources. This could make it difficult for these new ingredients to gain traction and build up the quality and quantity demanded by large-scale feed producers. There is some insect meal production, such as in *Pangasius* feed—led by companies such as Entobel, which produces 10,000 MT/year of black soldier fly meal through a collaboration with Heineken to use the byproducts of its beer-brewing operations. But overall, the insect meal industry is still nascent, and production is minimal compared to agricultural byproducts and processed animal proteins. Nevertheless, *Vietnam is very well suited for insect meal production because of its warm climate and ample quantities of agricultural waste.*

Entobel, the insect meal production leader, is looking to expand both in Vietnam and to nearby countries such as Malaysia and Indonesia. There are also smaller black soldier fly larvae (BSFL) operations in Vietnam that are often collocated with agricultural production. Possible feedstocks for insect meal in this region are bioethanol byproducts, brewers' byproducts, peels of crops such as cassava and oranges, livestock waste, and other food waste streams.

Similar to other low-income countries, Vietnam has challenges with organic waste collection and utilization, so insect meal companies that can provide collection services in urban areas to use as feedstock would be serving a dual purpose, so long as they comply with local regulations. Despite the promise of the region, some insect-producing companies say they have encountered some challenges upon entering the Vietnamese industry, including the relatively high cost of quality agricultural byproducts, difficulty navigating the regulatory environment and building up the necessary policy infrastructure for a new industry, and difficulty obtaining outside financing.

Key takeaways

Nascent: Decentralized production and supply chains

1. In decentralized, nascent aquaculture industries such as those in Ecuador, the aquaculture production volume is typically inadequate to justify domestic production of formulated aquafeeds and other supply chain services. The challenge here is to increase aquaculture production to stimulate and enable the development of an efficient supply chain, yet at the same time increase the supply chain to meet the needs of that expanding aquaculture production sector. During that growth stage, each side of the sector might need to encounter, and absorb, a certain amount of productive inefficiency as it waits for the other side to catch up. But this is not an unprecedented challenge unique to aquaculture. Historically and globally, it has been faced during the growth stage of every industry.

For example, in many countries, at some point there were not enough prospective car owners to increase production volumes to take advantage of economies of scale, yet simultaneously, cars were not being produced in sufficient volume for the companies to be able to offer millions of customers vehicles at prices they could afford. Buyers were waiting for prices to fall, while companies were waiting for consumers to buy enough cars. Both sides of the market were, in a sense, waiting for the other side to make the first move.

- Case in point: Senegal needs more aquafeed to expand its production of tilapia, yet it is not currently producing enough tilapia to make it commercially viable to create a large, profitable feed operation.

2. Investing in ingredient infrastructure, such as fishmeal factories and terrestrial animal-rendering processing plants that transform animal byproducts into other products, would provide a supply line of raw materials that would attract commercial feed manufacturers. Investments could also build the capacity of local ingredient importers, traders, and suppliers.
- Taprobane Seafoodsm, in Sri Lanka, is interested in creating a tilapia feed product line in its poultry feed facility, but the plan is not yet profitable to launch.

Emerging: Centralized, not fully integrated production and supply chains

3. Extrusion reduces microbial contamination, gelatinizes starches, and introduces high levels of precision and control in the manufacturing process, which improves pellet binding, water stability, and digestibility. Floating extruded feeds are preferred for tilapia and other surface-feeding fish to enable observation of feed consumption and more efficient feed management. Floating feeds are the preferred choice for floating cages, because sinking feeds may pass through the bottom of the cage before being completely consumed by fish.
4. The risk of capital investment in domestic feed mills can be reduced by adding an aquafeed line to an already existing feed mill, or through a joint venture between complementary stakeholders in a commodity supply chain.

Mature: Centralized, fully integrated production and supply chains

1. Mature aquafeed sectors can generate significant economic gains for large corporations that are part of a well-integrated supply chain. But even as production within the aquafeed sector grows and efficiency rises, mature markets, which are typically dominated by powerful profit-seeking private firms, may not necessarily meet the socioeconomic needs of communities. Care must be taken to understand how the rapid growth of the aquaculture sector, or subsectors within it, impacts society, as seen in Vietnam, where aquaculture expansion has boosted exports and corporate profits but often left small-scale producers and local communities with limited benefits.
2. Ecuador's aquaculture sector offers an opportunity for the development of an insect meal industry. Environmental conditions are favorable, and there is interest from major feed companies operating in the sector, but finding the right pricing has remained a challenge.

3

AQUAFEED INGREDIENTS

Good-quality feed promotes the growth of the aquaculture industry across the board. But the vigorous growth of an aquaculture sector that needs more and more reliance on feeds can exacerbate some of the undesirable impacts of unsustainable feed ingredient sourcing, such as overfishing of wild-caught fish for fishmeal, deforestation for soy production, or excessive use of land and water resources. Three adverse impacts of unbridled feed ingredient production and milling are land use change and subsequent biodiversity loss, overfishing of already fully exploited wild stocks, and greenhouse gas emissions.

In response to these risks, companies and research organizations around the world are developing and scaling up alternative, novel replacement feed ingredients to safeguard the availability of conventional, traditional ingredient supplies such as fishmeal and fish oil, and to mitigate environmental effects like deforestation (an impact of, for example, soy production). Feeds fall into three categories:

1. **Traditional or conventional feed ingredients (examples: fish meal, fish oil, and soy):** These are currently used in significant volumes in most aquafeeds.
2. **Alternative ingredients (example: vegetable protein concentrates):** These are new variations of existing byproducts that have the potential to become mainstream ingredients.
3. **Novel ingredients (example: single-cell protein):** These are currently not produced at scale but could replace a portion of supply-constrained, less sustainable traditional ingredients.

Traditional feed ingredients: Marine, agricultural, and processed animal proteins

This section provides a detailed description of traditional aquafeed ingredients and their environmental impact.

Traditional feed ingredients include

- **Marine ingredients** such as fishmeal and fish oil produced from wild forage fish, fish trimmings, crustacean heads and shells, squid, and bivalves.
- **Agricultural byproducts** including de-oiled meals and oils from oilseeds such as soybeans, rapeseed, and cottonseed; grains and or their byproducts, principally wheat, corn, and rice (included here are fermented plant products); and protein concentrates from oilseeds, grains, and other plant proteins.
- **Processed animal proteins (PAPs)** produced from byproducts of livestock and poultry processing, mainly meat & bone meal and poultry byproduct meal, and products such as blood meal, blood plasma meal, and feather meal.

TABLE 3: Percentage composition (by ingredient inclusion) of conventional feed formulations for tilapia, shrimp, and catfish in Senegal, Tanzania, Sri Lanka, Ecuador, and Vietnam

	For tilapia (range)	For tilapia (median)	For shrimp (range)	For shrimp (median)	For catfish (range)	For catfish (median)
Marine ingredients	4–15%	8.5%	5–26%	20%	4–32%	4%
Processed animal proteins (PAPs)	6–48%	27%	0–12%	10%	0%	0%
Agricultural products	51–87%	85%	32–76%	28%	60–97%	94%
Other	2–3%	2%	14%	14%	0.6–8%	0.85%

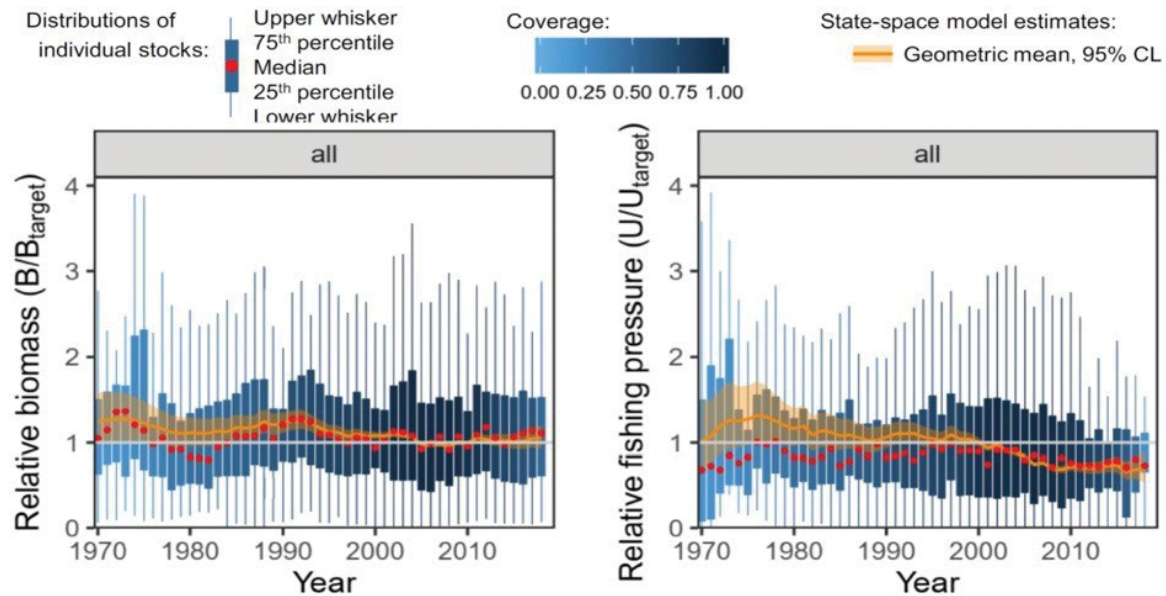
Sources: Tilapia: FAO (n.d.-a); Shrimp: TCRS (2023); Catfish: The Fish Site (2006); Victor Pellet Mill (n.d.)

Marine ingredients

Marine feed ingredients are excellent sources of protein and oil in aquafeeds, but around the world, many sources are already fully exploited, with relatively little scope for growth except for increased recovery rates and utilization of processing discards. Approximately 4 million metric tons (million MT) of fishmeal are produced annually, and about 82 percent is used for aquafeeds.

Of the current global fishmeal production volume, about two-thirds comes from whole fish in forage fisheries and one-third from byproducts of aquaculture and food fisheries (Glencross et al., 2024a). Forage fisheries are finite resources that cannot scale with the growth of aquaculture without dangerously overfishing small pelagic fish, which are crucial to marine ecosystems. The only scope for growth in fishmeal supply will come from additional byproduct volume from the growing aquaculture sector and from underutilized byproducts from food-grade fisheries. It is estimated that, by 2050, this will amount to no more than an additional 3 million metric tons. Aquafeed companies have responded by reducing the proportion of fishmeal in their feeds (figure 2), replacing them principally with vegetable meals and oils.

FIGURE 2: Global estimates of the relative abundance of, and fishing pressure on, small pelagic fish, 1970–2018



Source: Hilborn et al. (2022)

Note: Abundance has consistently remained above targets, while fishing pressure has declined.

The relative abundance (or biomass) is measured relative to the maximum sustainable yield-based or other target reference points

Projections of global aquaculture growth, assuming a flat supply of fishmeal, indicate that the proportion of fishmeal in aquaculture feeds must decline from an average of 6 percent to 2 percent by 2050 (Jones et al., 2020). Of note, these figures reflect fishmeal consumption by fed *carnivorous* and *omnivorous* species. Table 3, above, presents the proportions of marine, agricultural and PAP ingredients used in conventional feeds for fed tilapia, shrimp, and catfish. Because tilapia and catfish are omnivorous, they need relatively lower proportions of fishmeal and other marine ingredients than purely carnivorous species such as shrimp.

TABLE 4: SWOT analysis: Marine ingredients (fishmeal and fish oil from wild forage fish, fish trimmings, crustacean heads and shells, squid, and bivalves)

STRENGTHS • Excellent nutritional composition, amino acid profile, long-chain n-3 fatty acids, and no antinutritional factors • Excellent digestibility • Effective fisheries management of major pelagic fisheries such as Peruvian anchoveta • Stable monthly pricing in comparison with soybean meal over the last 20 years (Glencross et al., 2024b)	WEAKNESSES • Public perception of unsustainability, not deserved in the case of modern dedicated pelagic fisheries, but a continuing challenge with poorly managed multi-species fisheries • Limited capacity to increase supply, except through enhanced product utilization, for example, improved by-product use and higher processing efficiency to increase the effective yield
OPPORTUNITIES • Processing and drying sequence lends itself to value addition through enzymatic hydrolysis (Glencross et al., 2024b) • Use of life cycle assessment tools to demonstrate the low environmental impact of fishmeal (especially its low global-warming potential and its small water and land footprint) compared to plant protein ingredients, although the tradeoff there is limited volumes	THREATS • Climate change impacts such as anomalously high sea surface temperature events (Halpern et al., 2019) • Poor fisheries management • Regulatory constraints

Agriculture-based feed ingredients

The processed and unprocessed byproducts of agricultural operations are well characterized and have long been accepted in aquafeeds. Their use in feeds varies with the target species and with price relative to other alternatives.

Byproducts from grains and oilseeds provide protein, carbohydrates and fiber that can be further processed and refined to produce protein-rich feed ingredients such as soybean meal, corn gluten meal, soy protein concentrate, and wheat gluten meal. Starchy secondary products such as wheat bran, maize bran, rice bran, and broken rice are also important aquafeed ingredients that provide energy for omnivorous farmed fish species.

Oilseed meals

The most important plant protein supplements for fish feeds are oilseed meals, produced from press cake that remains after edible oil has been extracted from soybeans, cottonseed, rapeseed or canola, peanuts, sunflower seeds, safflower seeds, linseed, or palm seed. The edible oils are commonly extracted using solvents, and this leaves a small amount of residual oil in the protein-rich press cake. Soybean meal is the most common oilseed protein supplement used in livestock, poultry, and fish feeds. Cottonseed meal has been used in semi-moist pellets for juvenile salmon and grower diets for catfish to supply protein and act as a pellet binder. Oilseed meal levels are limited in feeds for carnivorous species because of their fiber content but are used in feed for omnivorous species when availability and price are favorable.

Protein concentrates

Protein concentrates are feed ingredients that have been processed to increase their protein content by removing much of the non-protein material. They typically contain at least 65–70 percent protein. Many agricultural byproducts can be used to create protein concentrates for use in aquafeeds. Soy protein concentrate, rapeseed protein concentrate, wheat gluten and corn gluten are common in aquafeeds. Soy and rapeseed protein concentrate are produced from press cake remaining after oil is removed. Wheat gluten is considered one of the best plant protein concentrates to use in fish feed owing to its high levels of digestible protein and the fact that it lacks antinutritional factors, with the exception of phytic acid (Glencross et al., 2024b). Corn gluten meal is likewise a high-protein (60 percent) byproduct of corn, processed to remove the oil, starch, and bran.

Protein concentrates are also produced from peas and sometimes beans by partially removing other fractions, namely, the hulls and some fibrous starch constituents, by a process called air classification.

Distiller's and brewer's byproduct meals

Brewery and distiller's byproducts are the dried materials that remain after brewing or distilling corn, rye, rice, and other grains to make beer, distilled spirits, or ethanol for biofuel. Starch in the grains is fermented into alcohol (ethanol), which is then removed, leaving behind nonfermentable carbohydrates, protein, and fiber. These byproducts can either be used as a direct feed ingredient or as a feedstock to support the growth of alternative feed ingredient raw materials such as insects or fungi. Upcycling with insects or fungi can upgrade the brewer's byproducts to increase their crude protein and amino acid levels and, in the case of fungi, add functional components. Three main byproducts are available as feed ingredients:

- Distillers' dried soluble (dried stillage fraction)
- Distillers' dried grains (the fraction remaining after removal of stillage)
- Distiller's dried grains with soluble (combination of stillage and grain sediments).

Brewer's grains have limited direct use in fish diets because of their bulk and the difficulty in grinding to a consistent particle size. The protein content of these products ranges from 26–28 percent, while the crude fiber level is higher in the dried grains (9–11 percent) than in the dried soluble (4–5 percent). The protein and fiber contents of brewer's dried grains specifically are 27 percent and 13 percent, respectively.

Brewer's dried yeast can be isolated after ethanol production and contains about 44 percent protein and only 3 percent fiber. Brewer's yeast acts as a binder in some formulations, but its use is limited because of its relatively high cost of production.

Industry status

Current companies: Globally, the agricultural byproduct industry is mature. Large global commodity traders—ADM, Bunge, Cargill, LDC, and others—sell and buy much of the meal and concentrate created from agricultural byproducts, along with local companies. Ingredient companies are now developing production processes to upcycle agricultural byproducts into more nutrient-rich forms using organisms such as microalgae, yeast, fungi, and insects or, in some cases, directly using unaltered pre-consumer byproducts in feed such as broken rice grains. These Ingredient companies include Green Plains, Montana Microbial, Menon Renewable Products, Houdek, and Jiangsu Fuhai Biotech Co.

TABLE 5: SWOT analysis of the agricultural feed ingredients business *

STRENGTHS • Large-scale production and infrastructure and economies of scale • Shares production costs and impacts with foods for human consumption • Well-established processing systems, for example, for fermentation, add value • Well accepted from both the regulatory and social perspectives • Less harmful impact on marine biodiversity than fishmeal • Potentially lower GHG emissions than fishmeal or SBM • Nutrient recycling and promotion of the circular economy	WEAKNESSES • Poor palatability of grain proteins • Diverse nutrient composition, which makes it challenging to formulate a consistent, balanced diet for various fish species • Nutrient profile composition is often limited in one or more essential amino acids • High levels of indigestible starch—cellulose, lignin, non-starch polysaccharides • Contain one or more antinutritional factors • Large environmental footprint due to extensive need for water, pesticides, herbicides, and energy • Some feedstock could be more efficiently used directly in feed • In some regions, a risk of supporting deforestation and land conversion
OPPORTUNITIES • Adding value through air classification (a process that separates particles based on size and weight) and fermentation to improve nutritional value and reduce antinutritional factors • Genetic improvement of plants (both conventional and transgenic) to improve their nutritional value	THREATS • Climate changes such reduced rainfall • Imbalances between food and feed demand due to fuel demands, geopolitical conflicts, supply chain disruptions

* Oilseed meals, protein concentrates, and distiller's and brewer's byproduct meals

Processed animal proteins

PAPs consist of dried meals made by processing non-edible portions of livestock and poultry. The protein content of rendered protein products after drying ranges from 50 percent to over 85 percent. There are established standards for the quality of the proteins, generally a minimum pepsin digestibility value. Animal byproduct meals are excellent sources of essential amino acids for fish. The essential amino acid composition of animal byproducts meal is like that of whole-egg protein, the standard by which all protein quality is judged in general. Rendered protein ingredients are less expensive than fishmeal per unit of protein, but digestibility issues and excessive mineral content from bone limit the levels that are added to fish feed formulations (table 6).

TABLE 6: Comparison of fishmeal and two commonly used PAPs

	Fishmeal	Meat-and-bone meal, porcine meal	Poultry byproduct meal (regular)
Protein (%)	67	51	65
Lysine (%)	5.1	1.1	1.5
Methionine (%)	1.96	1.7	0.8
Price (\$/MT)	1,562	404	297
Cost per MT of protein (\$)	2,331	792	457
Global warming potential (kg CO ₂ eq/MT of product)	1070 (Peru)	562	741

Sources: GFLI (2022), NRC (2011), Feedstuffs (2024), Hatch (2024), and Tanga et al. (2021)

Products created from land animal byproducts

Meat meal and meat-and-bone meal: These are made of dried mammalian tissues, without hair, hooves, horn, hide trimmings, manure, and stomach contents. Their protein content is about 50 percent and fat levels average 9–10 percent. The principal difference between the two products is their phosphorus content: meat meal must have less than 4.4 percent phosphorus. The calcium content of meat-and-bone meal ranges from 8.8 to 12 percent, while meat meal typically contains about 3 percent less calcium. Both ingredients have relatively high ash content, about 27 percent and 31 percent for meat meal and meat-and-bone meal, respectively.

Blood meal: Blood meal is a dry product made from clean, fresh animal blood, exclusive of all extraneous materials. The most common blood meal product used in fish feeds is blood meal that is spray-dried after the moisture content has been reduced to about 70 percent through low-temperature vacuum evaporation. Other processes of drying blood include flash-drying and drum drying. Blood meal has a minimum protein content of 85 percent and is rich in the essential amino acids lysine and histidine. This makes it a valuable ingredient to combine with low-lysine protein concentrates from wheat or corn. Blood from animal processing can be refined further by separating the red blood cells from the plasma to produce higher-value products.

Feather meal: Feather meal is made from poultry feathers that are hydrolyzed under pressure in the presence of calcium hydroxide, or Ca(OH)₂, also called slaked lime, and then dried. It has a protein content of 80–85 percent; no less than 75 percent of this protein must be digestible by the pepsin digestibility method. Digestibility of feather meal products can vary depending on the processing method and conditions. The *crude protein apparent digestibility coefficient* of individual feather meal products—a measure of how much of the crude protein in the meal product is actually digested, absorbed, and used by the animal (essentially, how well the protein in the meal is utilized)—dictates the appropriate levels used in fish feeds.

Poultry byproduct meal: Poultry byproduct meal is made from byproducts of poultry processing, exclusive of feathers and the contents of the gizzard and intestines. Blood may or may not be included. The material that remains after chickens are dressed is rendered (cooked), most of the fat is removed, and the residue is dried. The ash content can be no higher than 16 percent, of which not more than 4 percent can be acid-insoluble ash. Poultry byproduct meals are available in regular, low-ash, and pet-food grades. Higher grades have more protein and less ash, and cost more. An additional measure of quality is considered to be the cysteine content. If the cysteine levels are much higher than usual, then the alleged poultry byproduct meal may very well contain feather meal. This is easily confirmed by feed microscopy.

Milk byproducts: Milk byproducts, for example, dried whey, dried whey product, casein, and dried skim milk, are sometimes used in feed formulation for fish but mainly in specialized feeds. Dried whey *product* is the residue obtained when a portion of the lactose is removed. By contrast, dried whey has a minimum of 65 percent lactose. The protein content of whey products is relatively low (13–17 percent), yet these products are often classified as protein supplements. Dried skim milk is sometimes used in livestock starter diets primarily due to its excellent digestibility and amino acid balance. Its protein content is about 34 percent. Casein is the residue obtained by acid or rennet coagulation of defatted milk. By definition, it contains at least 80 percent protein. Vitamin-free casein is the standard protein used in semi-purified diets.

Gelatin: Gelatin is an important ingredient in semi-purified feed formulations. It is a glutinous material obtained by the partial hydrolysis of collagen from animal skin, tendons, and ligaments. It is hard and brittle when dried but dissolves in hot water and forms a gel when cooled. It contains 88–92 percent protein but lacks tryptophan. It serves as a protein source and binding agent in semi-purified diets.

Production of PAPs

The primary technology needed is a centralized meat-processing facility that slaughters poultry, pigs, and/or other livestock. The byproducts produced from meat processing can then be rendered via machinery that heats and compresses the materials into a shelf-stable meal for use in aquafeeds. Like the equipment used for making agricultural byproducts, this technology is not new and is used worldwide. In many cases, PAP facilities exist but the quality is not suitable for aquafeed. The knowledge and technology needed to upgrade facilities, however, are easily available if the budget is there (BOX 5).

BOX 4: THE NEED TO UPGRADE PAP QUALITY FOR AQUAFEEDS

Several countries in the Global South, such as Chile, Mexico, and Thailand, have developed stable, mature rendered protein ingredient industries.

In **Chile**, the poultry industry underwent modernization and expansion in the 1970s, coupled with the construction of factories to convert the byproducts of poultry-processing into poultry byproduct meal, feather meal, and blood meal. These ingredients were recycled in poultry feeds and used to feed pigs. Salmon farming in Chile began in the 1980s and expanded rapidly in the mid- and late-1990s, with a parallel development and expansion of fish feed production. These feeds were fishmeal-based because Chile had a well-established fishmeal industry, but annual fishmeal production declined and, ultimately, was no longer sufficient to supply the protein needed in salmon feed. A rendered animal protein ingredients industry arose to fill this gap, but the products had to be improved in quality through upgrades in the manufacturing process to be acceptable as salmon feed components. Today salmon feed in Chile contains substantial percentages of rendered animal proteins.

A similar developmental process occurred in **Mexico**. There, livestock rendered products, rather than poultry, were the focus of ingredient development for aquafeeds for warm-water marine fish and shrimp. Feed ingredients from the rendering industries were already being produced but they were of substandard quality as fish feed. Improvements in manufacturing led to production of higher-quality feed ingredients from animal processing byproducts, which led to the greater incorporation of these products into fish and shrimp feeds.

Thailand followed a similar route as Chile (poultry rendered products) except that product development focused on creating ingredients to be used in shrimp feeds.

BOX 5: CONSUMER RESISTANCE AND OTHER BARRIERS TO SCALING UP PROTEIN FEEDS FROM ANIMAL BYPRODUCTS AND INSECTS

Consumer acceptance and attitudes toward protein feeds derived from animal byproducts and insects can present significant barriers to scaling up these alternative feeds. Religious and cultural factors constraining consumer acceptance of livestock reared on animal and insect-processed animal proteins—in particular swine or beef PAPs—could substantially limit market availability.

Biases, such as disgust, stemming from a lack of understanding and sociocultural misinformation can create attitudinal biases and even feelings of disgust that generate distrust, hindering the adoption of livestock feeds that include alternative proteins. Research gaps still exist in understanding public perceptions and the factors influencing the acceptance of circular agriculture alternatives. More focused efforts are needed to explore whether insects and other alternative proteins are more likely to be accepted as feeds rather than food. Additionally, retailer requirements, livestock certification standards, and stringent safety regulations to prevent food safety issues and mislabeling may also impede, or at least slow, the adoption of these protein feeds. In some cultures, including some western ones, insects reared for feed are perceived by some as livestock, which has led some consumers to call for insect-rearing systems to comply with high animal welfare standards.

In Europe, new regulations have been approved that define what PAPs are and they can be used in animal and fish feed. Specifically, category 3 animal byproducts are approved for, and considered safe to, use in feeds because they do not contain fallen or sick animals, or otherwise contain material unfit for human consumption. They have been evaluated and deemed low-risk for use in animal feed and not a risk to animal or human health. However, it raises broader concerns about consumer acceptance and the potential rejection or adoption of PAPs in animal feed because public perception of safety and ethical considerations will likely influence their widespread use.

TABLE 7: SWOT analysis: Processed animal products

STRENGTHS • Shares production costs and impacts with foods for human consumption • Widespread availability with little competition from direct human consumption • High levels of protein rich in certain essential amino acids • Immunomodulator effect with PAP hydrolysates (Glencross et al., 2024b) • Lower impact on marine biodiversity than fishmeal • Nutrient recycling and circularity	WEAKNESSES • Requires the presence of significant livestock or poultry industries • Lack of long-chain n-3 fatty acids • Nutritional profile can be variable • Low acceptance in some regions (European concerns with history of mad cow disease and other health threats), with some religions not allowing consumption of porcine or blood products, and consumer perceptions (“yuck factor”) (Glencross et al., 2024b) • Risk of disease if proper sanitary measures are lacking
OPPORTUNITIES • Availability will increase with the global megatrend toward higher levels of meat consumption • The environmental footprint identified in the LCA is largely due to the energy consumed during the rendering process; this could be addressed by switching to renewable energy • The value addition potential of various PAP ingredients such as hydrolyzed feather meals, poultry protein concentrates	THREATS • Perceptions about the use of PAPs in aquaculture feeds continue to limit use in Europe, despite enabling legislation • Adulteration of PAPs • High energy costs associated with rendering and drying

Environmental impact of traditional feed ingredients

Traditional ingredients used in aquafeeds have a range of environmental impacts, including freshwater and land use, greenhouse gas emissions, and eutrophication. Each type of ingredient has tradeoffs between environmental impact, digestibility, bioavailability, and other attributes. Environmental impacts are often nuanced and vary based on the geographic location of production, the complexity of the supply chain, and the availability of technology.

TABLE 8: Environmental impact per kilogram of feed ingredient type

Ingredient category	Impact	kg CO ₂ eq	Degree of impact (average kg)			P
			m ³ kg N eq	kg P eq	depriv	
Marine	Freshwater eutrophication			0.0002		
	Marine eutrophication		0.005			
	FLAG climate change—LUC (includes peat ox)	0.0007				
	Land use					3.41
	Non-FLAG climate change—excludes LUC, peat ox, land management	1.74				
	Water use				0.09	
Agricultural byproducts	FW eutrophication			0.0008		
	Marine eutrophication		0.008			
	FLAG climate change—LUC (includes peat ox)	1.3				
	Land use					313.84
	Non-FLAG climate change—excludes LUC, peat ox, land management	0.63				
	Water use				1.13	
PAP	FW eutrophication			0.0002		
	Marine eutrophication		0.002			
	FLAG climate change—LUC (includes peat ox)	0.16				
	Land use					36.10
	Non-FLAG climate change—excludes LUC, peat ox, land management	0.55				
	Water use				0.21	

Source: Data aggregated from Mérieux NutriSciences, Agri-footprint database

Note: depriv = deprivation; FLAG = forest, land, and agriculture; FW = freshwater; LUC = land use change; peat ox = peat oxidation.

Within the categories included in table 8 above, common agricultural byproducts in aquafeeds include various soy and wheat products and oilseeds. Marine ingredients are largely comprised of fishmeal and fish oil from both primary wild capture and trimmings from processed fish. Processed animal product ingredients are often poultry meal and blood meal. Table 9 presents a further description of the environmental impacts of conventional feed ingredients.

TABLE 9: Environmental impact of producing a kilogram of various aquafeed ingredients

Ingredient category	Ingredient type	FLAG kg CO ₂ eq (LUC, peat ox)	Non-FLAG kg CO ₂ eq (excl LUC, peat ox, land man)	m ³ depriv.	P
Marine	Fishmeal	0.0007	1.83	0.1	3.6
	Fish oil	0.0008	2.02	0.1	3.91
Agricultural byproducts	Soybean meal	2.31	0.41	0.75	255.06
	Maize (average gluten meal, fiber and bran, gluten feed, solubles, slurry)	0.07	0.39	0.95	43.92
	Soy protein concentrate	4.83	1.24	0.3	441.91
	Wheat gluten (meal)	0.37	1.94	0.84	346.98
	Broken rice	0.0001	0.55	3.85	60.49
	Soybean oil	4.11	0.71	1.94	467.08
	Rapeseed oil	0.61	0.78	0.1	355.9
	Maize distiller's grains	0.01	0.6	0.73	30.65
	Brewer's grains	6.78	0.008	7.63	0.01
Processed animal proteins	Animal meal	0.07	0.41	0.28	26.32
	Blood meal	0.37	1.29	0.17	68.84
	Chicken coproduct	0.11	0.09	0.13	22.92

Source: Data aggregated from Mérieux NutriSciences, Agri-footprint database

Note: depriv = deprivation; FLAG = forest, land, and agriculture; LUC = land use change; peat ox = peat oxidation; land man = land management

Marine ingredients

Overfishing of marine resources has long been a substantial concern of conservationists. In 2021, the fraction of marine fisheries that are within biologically sustainable levels continued to decline, falling to 62.3 percent, 2.3 percent lower than in 2019 (FAO, 2024a). However, because of the adoption of more scientifically based fisheries management practices, 78.9 percent of the 10 marine species with the highest landings in 2021 (representing 27.4 percent of total landings) were fished within biologically sustainable levels.

As much as 70 percent of fishmeal and fish oil is produced from small, open-ocean pelagic fisheries species—anchovies, herring, pilchards, mackerel, sardines, and so on—that are among the world’s most abundant. These fisheries species, although variable in their individual abundance, show remarkable stability across stocks (Hilborn et al., 2021). Plots of relative abundance (estimated biomass/target biomass based on maximum sustainable yield) and the fishing pressure of these stocks indicate that abundance has consistently remained above the target, while fishing pressure has declined over the last 20 years.

Given the high global demand for fishmeal and subsequent high prices, it is critical that the economics of fishmeal are managed in a way that does not compromise local food security needs. Well-enforced fishing and aquaculture regulations must ensure that although the prospect of income from a fishmeal sector is attractive, it does not come at the expense of local coastal communities who may be reliant on these fish species for subsistence. This risk is currently being played out in West Africa, where fishmeal is exported for use in the salmon industry in the Global North, to the detriment of local food security (Reichling, 2024).

Agricultural products

The environmental impact of land use change has emerged as an important concern, especially in light of the conversion of the Amazon rainforest in Latin America and other forests in Asia to agricultural land. This is increasingly an issue in nascent and emerging aquafeed industries. Soybean cultivation is a case in point: Soybean meal was originally heralded as a cheap, sustainable alternative to fishmeal, and its use has increased in aquafeeds over the last few decades. It now makes up more than 50 percent of feed ingredients for some species. But although soy can be grown sustainably, its production has led to the substantial deforestation of environmentally significant habitats, causing long-term increases in GHG emissions from the loss of vegetative biomass, the loss of soil carbon, and the loss of ongoing carbon sequestration potential. When rainforests are converted to crop production, about 75 kg of CO₂ sequestration is lost per square meter of land over a 30-year period (2.5 kg/m²/year) (Nguyen, Hermansen, and Mogensen, 2010).

Similarly, the use of agricultural byproducts in aquaculture may start out small in a nascent or emerging market, in tandem with a small aquafeed industry, and generally be positive for the environment using material that would otherwise have gone unused. Yet it is important to consider what might happen if aquaculture were to reach scale in that particular geography. Could it, for example, drive crop expansion? What environmental pressures might emerge with for each ingredient? From a business economics perspective, could aquaculture usages become more profitable than direct human consumption of the non-waste streams, and how might this impact local food availability? Such early forecasting can help new aquaculture industries build an ingredient and feed infrastructure that avoids some of the pitfalls associated with global aquaculture, in particular, overreliance on limited resources, unintended competition with food systems, and the amplification of environmental and social pressures as demand rises. Aquaculture producers must carefully assess whether using ingredients that are also suitable for direct human consumption risks creating competition with local food systems, recognizing that in some cases there may be enough supply for both uses, but in other cases it may heighten food security or sustainability concerns. Similarly, aquaculture producers need to avoid cultivating or sourcing agricultural products from areas at risk of deforestation.

Processed animal products (PAPs)

The life cycle assessment characteristics of many PAPs are quite favorable when the environmental impacts are allocated according to the economic value of the coproducts. In other words, the economic allocation method

distributes the environmental burden of animal production primarily to the human food components, based on their market value. This approach allows for a more accurate representation of the environmental impact by considering the relative value of each coproduct. Only a nominal portion—related mainly to the rendering process—is allocated to byproduct meals. For example, Tetteh et al. (2022) estimate that the edible offal of poultry production account for just 2 percent of the environmental impact of poultry production. This means that by far the greatest proportion of the environmental impact of poultry and other livestock production can be blamed on the chicken meat people eat; rendered animal byproducts are not the driving economic force of these negative environmental outcomes. Under the economic allocation approach, rendered porcine meal and rendered poultry meal have GHG emissions profiles of 0.6 and 0.7 kg of CO₂eq per kilogram produced, respectively, much lower than fishmeal's roughly 1 kg of CO₂eq per kilogram produced.

Current companies: The largest land animal byproduct companies—such as JBS, BRF, and Tyson Foods—are typically the same as the largest land protein processors. The Brazilian company BRF, for example, is one of the largest pork and poultry producers globally and supplies a variety of animal meals, including pork meals, poultry meals, feather meals and oils. BRF both uses these ingredients for its internal consumption (that is, feeding its own animals) and sells these ingredients to external partner industries such as aquaculture (BRF, 2022). Tyson Foods employs a similar model, offering a variety of chicken byproducts, including chicken meal, chicken fat, feather meal, and chicken blood meal (Tyson, 2022).

Location considerations: Rendered animal proteins are a mature industry worldwide, and meat processors produce millions of tons of it every year. These proteins can be used in any country sector that has centralized meat-processing facilities, but their potential in each target region varies with the scale of existing livestock and poultry production. Investments to increase the productivity of poultry and livestock could therefore also support the development of aquafeed businesses. Local and end-market regulation plays a large role in the viability of processed land animal protein use in feed. For example, Chile allows the use of PAPs in feed, while Norway does not. Norwegian salmon feed therefore uses substantially more marine ingredients than in Chile, where a significant portion can be substituted with PAPs. The use of any ingredient in feed must consider both local and end-market regulation.

Price: Processed animal proteins are usually cheaper than fishmeal and can even be cheaper than soybean meal per unit of protein. The prices of fishmeal can vary widely but have recently reached \$2,500 per MT of protein (\$1,600 per MT total) (IMF, 2024). Although the prices of rendered animal proteins can vary based on geography, rendered processed animal proteins range from \$400 to \$800 (Hatch, 2024). For comparison, the prices of soybean meal per unit of protein have recently (year 2023) been quoted at \$700–800 per ton of protein. Although PAPs offer a cost advantage, new producers looking to enter the market must also consider international competitive pressures. Established exporters, such as BRF in Brazil, already supply PAPs to major markets in Europe and Asia. As a result, new PAP industries aiming to export to these or similar regions will need to assess how factors like import tariffs, logistics, and the cost efficiency of their initial production affect their ability to compete internationally.

Aquafeed use: Feed manufacturers generally favor the increasing use of processed animal proteins because of their high nutrient content and relatively low costs, but adoption levels vary from area to area because of regulations and consumer acceptance. In the European Union, feed manufacturers face regulatory restrictions on the use of PAPs in aquafeeds: PAPs from ruminants (for example, cows) are banned but regulations allow the use of pork protein in poultry feed, poultry protein in pig feed, and insect protein in both pig and poultry feed (FEFAC, 2021). Feed companies such as Skretting have publicly reiterated both the environmental benefits and safety of using rendered land animal byproducts in aquafeed (Skretting, 2024). Even where regulation does not prohibit the use of PAPs, there may still be hesitation in some markets based on customer perception, as in Norway. There may also be limitations on where PAPs can be sourced from, as in Japan.

Alternative feed ingredients

Alternative ingredients are new variations of existing byproducts such as insect meal, microalgae and macroalgae, single-cell protein, and vegetable protein concentrates such as soybean meal, soy protein concentrate, corn gluten, and wheat meal. In some contexts, they are used to replace a portion of traditional ingredients to improve the sustainability profile of feed, or because of traditional ingredient price increases. The useability and effectiveness of alternative ingredients vary. In comparison to other products, they have limitations in nutrient content, profile, and availability, digestibility, cost, lack of year-round market availability, the presence of antinutrient compounds, toxic compounds, and compounds that reduce palatability, and physical properties that interfere with material handling and transport. Among the growing category of alternative feed ingredients, high-protein fermentation products have emerged as a promising subset, offering potential solutions to some of the nutritional and functional limitations associated with more conventional alternatives.

TABLE 10: Nutritional value, price, and global warming potential of fishmeal vs. agricultural byproducts commonly used in aquafeeds

	Fishmeal	Soybean meal	Soy protein concentrate	Corn gluten meal	Wheat gluten meal
Protein (%)	67	48	62	63	81
Lysine (%)	5.1	3.2	3.9	1.1	1.1
Methionine (%)	1.96	0.7	0.8	1.9	1.7
Price (\$/MT)	1,562	398	1,210	917	1,458
Cost per MT of protein (\$)	2,331	830	1,952	1,455	1,800
Global warming potential (kg CO ₂ eq/MT of product)	1,070 (Peru)	503	1,590	743	3,205

Sources: GFLI (2022); NRC (2011); Feedstuffs (2024); Hatch (2024)

High-protein fermentation products

These ingredients are often produced by upcycling traditional ingredients such as brewery byproducts and distiller's dried grains and solubles from the ethanol sector. Additional fermentation and processing produce such products as fermented corn protein, fermented soybean meal, and barley protein concentrate. These are examples of emerging agricultural coproducts that have the potential to directly substitute for fishmeal and soybean meal.

Fermented corn protein, a nutrient-rich, high-protein, upcycled, digestible coproduct of ethanol production, has average crude protein of 54 percent. Global production is estimated to be greater than 12 million tons, with prices ranging from \$500/t to \$1,200/t. Production is centered in the United States and China. Estimated capital investment for a plant that can produce 100,000 t a year is \$45–89 million (Hatch, 2024). Such a plant would require 1.5–2.0 million tons of fuel corn.

Corn is not a staple crop in Vietnam, but the country may be able to upcycle traditional products from its cassava-based ethanol plants (Do and Vu, 2024). Ecuador, Sri Lanka, Senegal, and Tanzania have developed sugar-cane-based ethanol plants to produce biofuels. These too might be considered as upcycling opportunities.

Soybean meal is available to varying degrees in key aquaculture-producing countries. Fermentation of soybean meal breaks down fiber and converts indigestible oligosaccharides into proteinaceous microbial biomass, which increases soy’s protein content from 48 percent to an average of 56 percent (Hatch, 2024). It also reduces antinutritional factors and improves its protein digestibility, but the cost rises because of the fermentation process and the need to dry the product (Mukherjee, Chakraborty, and Dutta, 2016). Fermented soybean meal is being adopted in some markets as a fishmeal replacement. It is typically priced 10–20 percent below fishmeal, depending on protein level (Hatch, 2024).

Industry

Several companies are upcycling ethanol byproducts or distiller’s byproducts for feed. For example, Green Plains is a corn-based ethanol producer that uses its corn protein byproduct streams from ethanol production to create fermented corn protein. Although this is lower in crude protein than other ingredients, Green Plains has developed a new product, Sequence, that combines corn and yeast protein to yield a minimum of 60 percent crude protein concentration (Sequence, 2024).

Another company, Montana Microbial, is currently the leading producer of high-protein barley concentrate, with 65 percent crude protein content. Montana Microbial has partnered with Scoular and Pannonia Bio to produce barley protein concentrate for North American and European markets, respectively.

Additionally, several companies—including Menon Renewable Products, Houdek, and Jiangsu Fuhai Biotech—produce fermented oilseeds as a protein-rich ingredient using large bioreactors. The largest facilities are in China, the US, and Europe. Like those of its competitors, Menon’s MrFeed is a soy protein hydrolysate made by converting soybean meal into a higher-protein feed ingredient with reduced antinutritional factors, using a proprietary hydrolysis process (Menon, 2018).

Houdek (formerly Prairie AquaTech), another fermented soybean product made in the US, has is over 70 percent protein, making it one of the most protein-rich fermented proteins (Houdek, 2024). Jiangsu Fuhai Biotech, based in China, uses fermented, dehulled, full-fat soybean as a raw material for use in aquafeeds.

TABLE 11: SWOT analysis: High-protein fermentation products

STRENGTHS • High-protein • Reduced antinutritional factors • Beneficial bioactive compounds may improve health and resistance to infection	WEAKNESSES • The maximum proportion of FCP allowable in shrimp feeds (10–18 percent) less than the maximum allowed for finfish species (37.5–50 percent) • Amino acid digestibility of FCP is lesser than that of fishmeal
OPPORTUNITIES • Production of high-protein fermented ingredients at ethanol plants in certain countries	THREATS • The viability of ethanol coproducts is highly dependent on ethanol demand and pricing.

Novel feed ingredients

Novel ingredients are either traditional ingredients that have been further developed to offer improved nutrition, or unconventional ingredients that have been scaled up to commercial quantities. They include algal oils, single-cell protein, fungal proteins, seaweed, biofloc, and insect meal (see Appendix 3: *Market Potential and Production Models*

of the Insect Meal Industry: Insights from Case Studies and Emerging Trends). They are ingredients that are currently not being produced at scale but could theoretically replace a portion of certain supply-constrained or less sustainable traditional ingredients. One challenge is that niche, low-volume ingredients face resistance gaining acceptance. A second challenge has to do with economies of scale because feed manufacturers require secure, consistent, competitively priced supplies (Glencross et al., 2024a).

Seaweed derivatives

Although some seaweed is farmed for human consumption, most of it is grown for extraction of hydrocolloids such as carrageenan, alginate, and agar, used as gelling and thickening agents in the food industry. As an aquafeed ingredient, seaweed's benefits include potentially nutritious composition, including long-chain n-3 fatty acids, and high levels of macro and microminerals, carotenoid pigments, immunostimulatory compounds, and bromophenols that give seaweed a pleasant sea-like flavor profile (Wan et al., 2019).

A major disadvantage of macroalgae is their high-water content, ranging from 64.9 to 94 percent, which greatly adds to the cost of drying compared to terrestrial plants. Seaweed species are highly variable in their nutrient composition, but the majority have relatively high carbohydrate content (for example, 50–60 percent in kelp) and relatively low protein and lipid content. The carbohydrate fraction consists primarily of non-starch polysaccharides and structural carbohydrates in the algal cell walls. These are not easily digestible for most fishes. Finally, some seaweed can accumulate harmful levels of heavy metals such as arsenic and cadmium.

Trials conducted to assess algae for inclusion in aquafeed have found that there is a decrease in fish performance if inclusion rates exceed 10 percent (Hasan and Chakrabarti, 2009; Serra et al., 2024). Although seaweed and seaweed byproducts have not been extensively tested as feedstock for insects, some early studies have found positive results. For example, black soldier fly larvae that were fed 50 percent with the brown macroalgae *Ascophyllum nodosum* had better growth performance than the control (Biancarcosa, 2020).

Nutrition considerations

Based solely on the chemical or nutritional content of seaweeds, they are not potentially great sources of direct ingredients for fish feed use because of their high moisture, low protein, and high concentrations of non-digestible polysaccharides. But a review by Mwenda et al. (2023) indicates that many aquaculture species benefit from low inclusion levels (2–10 percent) of seaweed, although they experience low digestibility and slowed growth at higher levels. For example, Nile tilapia fed with seaweed exhibited slow growth and significant decrease in intestine diameter and villi length, indicating that digestibility was the issue. Qui, Tian and Davis (2017) found that *Ulva* meal could be included in shrimp (*L. vannamei*) diets at levels up to 6.35 percent to replace 2 percent fish meal, but higher inclusion levels depressed their growth. The principal value of seaweed meal in fish feeds may be as a functional ingredient—providing health or performance benefits such as improved immune function, gut health, and stress resistance—when used at low levels in feeds for marine carnivores. There are two important caveats to this conclusion:

1. Fresh seaweed is the principal food for macroalgae herbivores such as abalone, sea urchins, and rabbitfish (*Siganus spp.*).
2. Physical treatment, fermentation, or enzyme treatment can increase the nutritional value and digestibility of seaweed.

Industry status

The global aquaculture production of aquatic plants has steadily increased from 20 million MT in 2010 to 37 million MT in 2022. This production volume is consistently led by Japanese kelp, *Gracilaria* species in China, and *Eucheuma*

species in Indonesia (FAO, 2024a). The largest producers of seaweed are Chinese companies such as Leili, Gather Great Ocean Algae Industry Co., and Shandong Jiejing Group. In the Shangdong and Dalian regions of China, large companies may cultivate farms of up to several hundred or thousands of hectares. In other regions, farms are often smaller and more labor-intensive (Hatch, 2022). Roughly 40 percent of harvested seaweed is directly consumed by humans and another 40 percent goes into additives to consumer products and foods (TNC, 2023).¹ Its use in aquafeed is currently limited, and typically only for selected species.

Environmental impact

Seaweed aquaculture is one of the most sustainable forms of farming today. In some cases, it may even have a positive environmental impact, such as buffering ocean acidification (Xiao et al., 2021). Marine macroalgae require no land or freshwater to grow and emit negligible GHG emissions during growth (TNC, 2024). Most Scope 1 emissions² from macroalgae comes from the drying process in areas that lack adequate heat and sunlight.

If farmed seaweed is managed in a way that maintains a consistent biomass level in the oceans, farmed seaweed could contribute to carbon sequestration (via lost fronds becoming buried in the seabed), and could create habitats for wild species, increasing biodiversity in those farmed areas. Additionally, macroalgae absorb nitrogen from the surrounding water, helping to reduce nutrient levels that could otherwise contribute to eutrophication (TNC, 2024). For the best chance for seaweed’s impact to be net-positive, farming should be sited in areas where seaweed’s capacity for nitrogen removal can be employed and where it can create a habitat for vulnerable wild species to conserve biodiversity.

TABLE 12: SWOT analysis: Seaweed species

STRENGTHS • Strong foundation of experience with seaweed culture (37 million MT grown in 2022) • Low capital investment • Environmental benefits include carbon sequestration, positive biodiversity impact, and buffer against ocean acidification) • Some species contain long-chain n-3 fatty acids	WEAKNESSES • High moisture content increases drying cost • Low protein and lipid content in most species • High content of indigestible carbohydrates • Potentially harmful levels of heavy metals accumulated from the environment can be passed on to the fish
OPPORTUNITIES • Utilization of the byproducts from the industrial production of hydrocolloids • Utilization of bromophenols in seaweeds to impart a sea-like flavor to other products • Fermentation/silage treatment to increase protein levels and improve digestibility • A large variety of seaweed species to select from genetic selection to improve nutrient composition and performance	THREATS • Competes with high-value seaweed markets for direct human consumption

1 The remaining 20 percent is used in a range of other applications, including fertilizers, biofuels, cosmetics, and pharmaceuticals.

2 Scope 1 emissions are direct GHG emissions from sources owned or controlled by an organization. In the context of macroalgae production, this typically includes emissions from on-site fuel combustion during processes like mechanical drying, especially in regions where natural sunlight and ambient heat are not adequate for passive drying.

Single-cell protein

Single-cell protein (SCP) is protein products developed using bacteria or fungi (yeasts). It has been used for human consumption throughout history to convert wheat to leavened bread, milk to cheese, and grapes to wine. Microalgae such as spirulina have also been a part of the human diet for centuries (Matassa et al., 2016).

Bacterial SCP

Production of bacterial SCP has been part of commercial food production since the 1960s, but with limited success in the past. In recent years, SCP research and development have regained momentum as the need for feed protein has re-emerged. Bacterial SCP are now being produced by several companies using new strains and processes. Calysta, Unibio, KnipBio, and StringBio have begun production with methanotrophic bacteria, and promising feeding trial data are accumulating for salmon, trout, and shrimp (Jones et al., 2020).

The following is a summary of three feeding trials with SCP sponsored by String Bio Pvt Ltd in Bangalore, India from *Methylococcus capsulatus* grown on methane. Founded by the industrial biotechnologist Ezhil Subbian in 2013, String Bio uses biotechnology to solve the problem of sustainable animal feed production by using methane as a raw material.

Marit et al. (2023) fed four types of this SCP to *L. vannamei*. Results indicated similar growth, nutrient digestibility, and utilization as fishmeal, along with higher phosphorus availability. Second, Felix et al. (2023) tested different inclusion levels of the same SCP in *L. vannamei* and found the optimum level to be 20 percent. He measured protein digestibility of 90 percent and also reported enhanced immune function of shrimp fed on an SCP diet. Third, Rajesh et al. (2022) tested this SCP in diets for rainbow trout and found the optimum level of fishmeal replacement at 12.5 percent inclusion (25 percent fishmeal replacement).

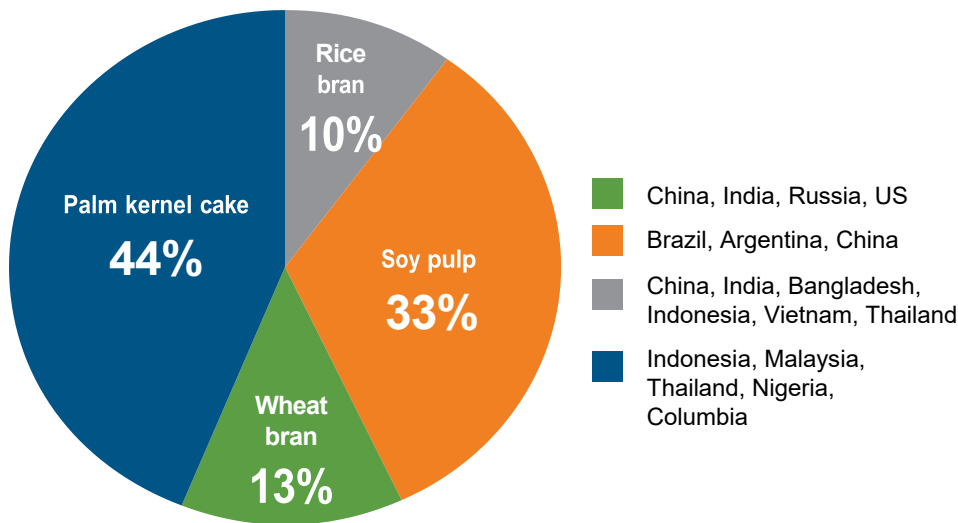
Current SCP production is estimated to be 30,000 t/year (Hatch, 2024). Plants have been built or are being built in China, Europe, India, Norway, Saudi Arabia, and the United States. The LCA impacts of these projects—land occupation, water consumption, and global warming potential—are highly variable. For example, GWP ranges from 4.03 to 29.9 kg CO₂ eq/kg of product, depending largely on the feedstock used and source of energy for drying (for example, coal or natural gas). This technology has the potential to scale up to produce significant volumes in a projected price range of \$700–3,300/t, but it involves high upfront capital investment (\$80–330 million for a 100,000 t/year plant), together with uncertain technology, biology, and development time (Hatch, 2024).

SCP transformation of agricultural waste

A more fit-for-purpose SCP approach for the target countries—Bangladesh, Ecuador, Senegal, Sri Lanka, Tanzania, and Vietnam—in this report would involve transforming discarded agro-industrial wastes into fermented, protein-rich byproducts for direct use in feeds or as a nutritionally enhanced substrate for the production of insect protein (Sun et al., 2024).

Annually, the cultivation and processing of crops, fruits, and livestock produce millions of metric tons of agricultural waste (Kari et al., 2023). In major producer countries, this includes approximately 60 million metric tons of wheat bran (13 percent of total production), 150 million metric tons of soy pulp (33 percent of total production), 45 million metric tons of rice bran (10 percent of total production), and 200 million metric tons of palm kernel cake (44 percent of total production) a year. These wastes arise from various agricultural activities at different stages of production. Figure 3 presents the estimated output of crop waste in 2020 for four agricultural products in 13 countries.

FIGURE 3: Estimated agricultural waste production as a percentage of total production for four crops in 2020



Source: Cai, et al. (2021)

Yafetto, Odamtten and Wiafe-Kwagyan (2023) reviewed how solid-state fermentation fits within the global and Ghanaian context as a relatively simple, circular-economy strategy to avoid pollution and valorize byproducts by increasing nutrient levels and reducing antinutritional factors. They stressed that help is needed from government and development partners to augment this work. Sun et al. (2024) described appropriate bioreactors, microorganisms, and techniques to synergistically combine high-moisture fruit and vegetable waste with dry, recalcitrant agricultural byproducts to produce high-value animal feed through solid-state fermentation.

Microbial biomass (biofloc)

Bioflocs are particles of suspended organic material formed in intensive aquaculture systems due to high feeding rates and little or no water exchange. The particles consist of assemblages of bacteria, algae, uneaten feed, fecal waste, protozoans, and rotifers, which constitute the detrital food chain. Biomass forms when particles of organic matter are kept suspended in the water column, where they become a substrate for heterotrophic bacteria. They remain aerobic and nontoxic and can help purify the water by recycling nitrogen and reducing ammonia levels.

The use of suspended microbial biomass directly within aquaculture production systems emerged in the 1970s and 1980s with small-scale shrimp and tilapia production (Serfling, 2000; Raza, Zheng, and Yang, 2024). By the 2000s, commercial use had begun (Hargreaves, 2013).

Bioflocs typically consist of 27–32 percent crude protein, a favorable amino acid profile, and growth-promoting compounds including chelated minerals, enzymes, and other micronutrients. They can be maintained directly within culture systems, but large inputs of energy may be required to keep the organic particles suspended and to maintain the dissolved oxygen levels that are appropriate for the target organism.

Alternatively, biofloc can be produced in separate aquaculture treatment ponds. This has the advantage of improving water quality by removing ammonia, but with reduced energy requirements. In this scenario, culture organisms are unable to graze directly on the floc particles, but the floc can be harvested, dried, and incorporated into feeds as biofloc meal to replace or supplement protein ingredients like fishmeal or soybean meal (Gokulnath et al., 2022).

A dry microbial biomass product marketed as Novacq™ (CSIRO Canberra, Australia) has shown improved growth of black tiger shrimp when included as 10 percent of the diet (Arnold et al., 2016). Ekasari et al. (2019) recommend 20 percent inclusion of biofloc meal in African catfish diets to spur growth and enhance health status. Prabu et al. (2018) found that 20 percent inclusion of biofloc meal yields the best growth and survival of GIFT tilapia.

Microbial biomass directly from floc treatment ponds (without drying) can be used as a fresh food supplement, harnessing the capability of heterotrophic bacteria to recycle ammonia nitrogen back into protein. Low-value substrates such as rice bran or other agricultural byproducts could be added to biofloc waste treatment ponds where they would become substrates for carbon-limited heterotrophic bacteria. This floc material could be transferred to production ponds as a feed supplement. While this seems promising as a means of avoiding the excessive energy required for in-situ biofloc systems, and for dewatering and drying biofloc meal, it requires further testing before it can be recommended for commercial application.

Fungal (yeast) protein

Mycoprotein is a form of SCP produced from yeast or fungus, often from agricultural byproducts such as distiller's or brewer's meals. Mycoprotein can also be produced from agricultural or forestry byproducts. Protein levels range from 30 to 60 percent. Enifer, a Finnish startup founded in 2020, has commercialized a mycoprotein production process that was originally developed by the Finnish forest industry and implemented commercially for over a decade. Enifer has two sites that have a combined production capacity of 10,000 t of mycoprotein, marketed as Pekilo for pig and poultry feeds. The process can be applied to recycle carbon-rich liquid side streams such as sugars, acetic acid, formic acid, and methanol (Byrne, 2021). Likely industrial sources are ethanol plants and large breweries.

Although Enifer's production is currently limited, the biotech startup is now testing Pekilo®Aqua, a fungal protein with up to 65 percent crude protein for use in aquafeeds. In a promising recent study of shrimp aquaculture using Pekilo®Aqua at an inclusion level of 30 percent, shrimp growth and survival improved without having to increase their feed intake and feed conversion ratio (FCR). The 30 percent Pekilo®Aqua completely replaced 24 percent inclusion of fishmeal (AquaBioTech, 2024).

Microalgae

Microalgae are cultivated in controlled fermentation tanks primarily as a source of the essential long chain n3 fatty acids, EPA and DHA. Despite various efforts to produce algal biomass in photobioreactors or outdoor systems as a cost-effective source of biofuel, no such alternatives have been developed, aside from spirulina, which tolerates high pH levels to the exclusion of its predators (Malcata, 2011).

TABLE 13: SWOT analysis: Single-cell protein

STRENGTHS • Inherently efficient because it works low on the trophic chain • In many cases, SCP can produce amino acids de novo from inorganic nitrogen and carbon sources • Is not a source of direct human nutrition, so SCP offers the market a noncompeting nutrient • Nutritional composition of some SCP is similar to fishmeal: 70 percent protein, 10 percent lipid	WEAKNESSES • Significant content of non-protein nitrogen due to high nucleotide content • Some types of microalgae have high levels of indigestible carbohydrates (alginates) • Given the capital intensity of this product and lack of example companies with environmental footprints • Comparable to traditional ingredients, these are not yet high-quality options for the target countries
OPPORTUNITIES • Genetic modification to improve protein yields and essential amino acid balance, or to add nutrients like n-3 fatty acids or carotenoids (Glencross et al., 2024a) • Presence of bioactive compounds such as immunostimulants, digestive enhancers • Inclusion of value-adding steps such as fermentation and autolysis to improve nutritional value	THREATS • Cost and scalability

Key takeaways

- Sustainable sourcing of aquafeed ingredients is critical if environmental impacts such as deforestation, overfishing, and greenhouse gas emissions are to be mitigated
- Aquafeed ingredients can be categorized into three types: traditional, alternative, and novel. Each type has distinct sustainability and nutritional profiles

Traditional feed ingredients

- **Marine ingredients (for example, fishmeal, fish oil)**
 - High nutritional value but limited supply; reliance on forage fisheries raises sustainability concerns.
 - Overfishing risks and competition with local food security (for example, West Africa).

- **Agricultural byproducts (for example, soybean meal, wheat gluten)**

- Widely used but linked to deforestation (for example, soy production in the Amazon).
- Lower marine biodiversity impact compared to fishmeal but high water and land use.

- **PAPs (for example, poultry meal, blood meal)**

- Cost-effective and rich in amino acids but face regulatory and consumer acceptance barriers (for example, religious restrictions, “yuck factor”).
- Lower environmental footprint due to byproduct utilization.

Alternative feed ingredients

- **High-Protein Fermentation Products (for example, corn fermented protein, fermented soybean meal)**

- Upcycled from ethanol or brewing byproducts to improve protein content and reduce antinutritional factors.
- Competitive pricing but limited inclusion levels in some species (for example, shrimp).

- **Potential for local production**

- Cassava or sugarcane byproducts in Vietnam, Ecuador, and Tanzania could be leveraged.

Novel feed ingredients

- **Seaweed derivatives**

- Low protein content and high drying costs but offer environmental benefits (carbon sequestration, habitat creation).
- Best suited as functional additives (2–10 percent inclusion) or for herbivorous species.

- **SCP (for example, bacterial, fungal proteins)**

- High production costs and energy-intensive but promising for amino acid profiles and immune benefits.
- Potential to transform agricultural waste into protein-rich feed.

- **Microbial Biomass (Biofloc)**

- Recycles nitrogen, improves water quality, and can replace fishmeal (up to 20% inclusion).
- Energy-intensive for in-situ systems but viable as harvested/dried meal.

- **Microalgae (for example, spirulina)**

- Rich in omega-3s but costly to produce at scale; limited to niche applications.

4

INSECT MEAL AS AQUAFEED

Overview

Raising insects as food both for human consumption and for fish and livestock is not a novel idea, but in the last decade, there has been a renewed interest in producing insect meal by upcycling otherwise underutilized, low-value agricultural byproducts and organic waste. This would help address the fourfold challenge of food insecurity, waste, GHG emissions, and overreliance on fishmeal and fish oil, which is leading to the overfishing of already fully exploited wild stocks.

Fed aquaculture systems face the pressing problem of dependence on natural systems that produce finite feed stocks that are approaching or have surpassed their production capacity. There is therefore an urgent need to look beyond traditional sources of feed. Inherent limitations discussed in appendix 3 demonstrate the need to explore new kinds of aquafeed such as insect meal. Aimed at countries where investors are interested in supporting ecologically sustainable aquaculture, appendix 3 also discusses the potential of including insect meal in aquafeed. The range of considerations include production volumes, costs, regulatory constraints, and technology readiness, together with nutrient composition, palatability, and digestibility, as well as societal and environmental constraints (Glencross et al., 2024b).

Key takeaways

1. **Price competition with fishmeal** can be a major hurdle for small and medium-size insect meal companies. Most initially prefer to sell to higher-priced end markets such as pet food stores, before turning their attention to producing aquafeed.
2. Although several insect species are viable as aquafeed, the most promising is black soldier fly larvae because of its desirable nutritional profile, digestibility, sustainability, disease resistance, and ease of farming.
3. Scaling up emerging insect farming enterprises requires identifying and accessing major sources of suitable substrate from agricultural or food-processing waste streams. Assuming a substrate-to-larvae bioconversion ratio of 4:1, it will require about 40,000 MT of substrate to produce 10,000 MT of insect larvae (200 billion larvae)¹ a year—a substantial quantity.
4. The insect meal industry has high potential to provide livelihood and employment opportunities for women and youth. In rural areas, household or small community-owned insect-rearing operations could provide women with self-employment opportunities, or directly employ youth and women.
5. Insect meal production can have positive climate and environmental impacts: Where feedstock would have been considered a waste, avoiding the release of methane by using the waste to feed insects could have a net positive GHG emissions impact. Using organic waste materials could also result in a net positive impact on land use.

A Deep Dive into the Insect Meal Industry

Production volumes and costs

Estimates of the global production of insect meal vary between 10,000 and 20,000 t a year (Hatch, 2024). Production volumes are expected to increase as large-scale, vertically integrated, and highly automated commercial facilities in the Global North begin to come online. Capital investment per ton of protein output is estimated to be \$2,333 to \$4,500 for facilities producing between 10,000 and 100,000 tons of protein per year.

As of 2021, insect meal prices ranged from \$3,900 to \$6,200/t (de Jong and Nikolik, 2021). Production costs currently are approximately \$1/kg for live larvae, \$3/kg for dried larvae, and \$4/kg for defatted insect meal (Hatch, 2024). In the Global North where products compete with fishmeal and soybean meal, this is too expensive for mainstream use in aquafeeds.

Insect meal in the Global South is significantly cheaper per unit weight than in the Global North. But this does not take into account the higher-quality nutritional composition of the final product in the Global North, which is partly driven by the processing requirements of buyers there.

Production in the Global South employs smaller, more manual, lower-investment systems that use local food waste as raw material. In this context, decentralized models, where local farmers both collect food waste and raise insects, can be effective. Additionally, simple on-farm systems that allow farmers to directly feed live insects to fish offer a practical, low-tech solution. Significantly cheaper feedstock and labor costs, and minimal heating requirements, further reduce the production costs (Munthali et al., 2023).

¹ A kilogram of medium-sized black soldier fly larvae (1/4–5/8 inches) is approximately 20,000 larvae.

As a result, in some countries, insect meal is already priced comparably to fishmeal. For example, in East Africa the market price of dried black soldier fly larvae is \$1,100 to \$1,400/t (Tanga et al., 2021) compared to \$6,000 in Europe and North America (Hatch, 2024). And in countries like Kenya, Uganda and Tanzania, BSFL can sell at half the price of soybean meal (World Bank, 2023).

Rabobank estimates that prices for European insect meal will fall by \$1,120/t when global volumes surpass 200,000 t/year, and drop into the range of \$1,700–\$2832/t when production reaches the maturity phase of 500,000 t/year. If this is reached, aquafeeds are likely to become the dominant market (200,000 t/year), followed by pet food, poultry layers, poultry broilers, and piglets (de Jong and Nikolic, 2021).

Basics of insect production

To select the right insects for cultivation and processing into feed ingredients, they must possess several important characteristics: abundance, appropriate size when grown, low levels of cannibalism when massed, handling safety, high reproductive potential, high nutritional value, and good feed conversion ratio (Caparros Megido et al., 2024). In addition to these, practical considerations for industrial-scale insect rearing must be addressed:

1. **Possibility of automated large-scale rearing:** Holometabolous insects (with four very distinct life stages) like flies and ants are easier to cultivate using automatic rearing technologies than hemimetabolous (three-life-stage) insects like crickets, which already look like adults when they are immature, because from egg to larva to pupa holometabolous insects can be reared in stacked trays (Kok and van Huis, 2021).
2. **Availability of consistent, low-cost substrates:** Insects are attractive in the animal feed space because they can upgrade food waste and other substrates that are either unsuitable as feed ingredients or have low nutritional value (Pinotti et al., 2019). But the ability to obtain low-cost substrates that are consistent in quality, composition, and quantity can be a challenge, particularly when trying to ensure that the feedstock is both environmentally sustainable and available at the scale needed for large-scale insect production.

Insects reared to produce feed ingredients consist mainly of mealworms and flies (Diptera) such as the black soldier fly and the house fly (van Huis et al., 2020). In the European Union, seven insect species are permitted: BSF, common housefly, yellow mealworm, lesser mealworm, house cricket, banded cricket, and field cricket. Among the insect species suitable for large-scale farming, the BSF, the house fly, and the yellow mealworm—all of them holometabolous—show the highest promise. In Africa, a wider range of suitable insects are available for farming based on the availability of substrate and the long history of insect farming (Verner et al., 2021). A notable example is the (holometabolous) African palm weevil (*Rhynchophorus phoenicis*), a species currently farmed in West Africa.

BSF has the greatest advantage because of its superior nutritional profile and digestibility, ease of farming, and disease resistance. BSF lays eggs readily on various materials such as wood and even cardboard. Larvae grow rapidly on a variety of substrates, including manure, and 5-day-old larvae can be harvested in 8 or 9 days. Favorable rearing conditions include an adequate supply of substrate, being raised within certain density parameters, and being reared within a certain temperature range (Eggink et al., 2022).

The yellow mealworm is also promising because of its ease of mass-rearing, excellent nutritional characteristics, and adaptability to a variety of substrates (Grau, Vilcinskis, and Joop, 2017). There is also a small but lucrative market for larvae as food for pets and exotic birds. According to Grau et al. (2017) there is a much larger knowledge base on growing mealworms than on other insects, and this helps support efforts to commercialize mealworm production at an industrial level. But in mass culture, they are susceptible to disease if the rearing conditions are not well managed.

Feedstock

Insect larvae require feedstock substrates. There is a wide range of substrates including agricultural byproducts, byproducts of food production, restaurant, or market food waste, and even animal manure. Ideally, the substrates would be locally sourced, high-volume, low-cost or no-cost materials that support rapid growth. The right choice depends on the context (Verner et al., 2021).

Substrates vary by region. Western countries use rejected or out-of-date commercial animal feed, oilseed and grain byproducts, and allowable foods from production surpluses, misshapen products, food that is past its expiration date, and other products that were produced in compliance with food legislation and have already been approved as dietary energy sources in animal nutrition (Luciano et al., 2020; Pinotti et al., 2019, Pinotti and Ottoboni, 2021).

In African and Asian countries, many materials not allowed in North America or Europe are used as substrates. Often these products are composted, heat-treated, or inoculated with lactobacillus to reduce or eliminate pathogens and to extend storage life by lowering their pH. The substrates include vegetable and fruit market discards, meals from seasonally available grains and legumes such as maize, sorghum and soybeans, and indigenous vegetables such as collard greens, jute mallow, amaranth leaves, black nightshade, cowpea leaves, and spider plants.

Composted poultry litter and livestock manure are also used as substrates in some regions. During the dry season, insect producers substitute forage leaves—from cassava, banana, sweet potato, tomato, pawpaw, and moringa, among others—for vegetables (Münke-Svendsen et al., 2017), although there is competition over these leaves because they are used in other farming activities and as human food.

Legal requirements

Legal requirements play a major role in the type of feedstock an insect producer can use. Whether a company can use manure or post-consumer waste as feedstock varies globally, with cost and volume implications. EU regulations limit the substrates that can be used to grow insects to feed materials of animal origin (for example, fishmeal, blood products from nonruminants, hydrolyzed proteins or gelatin and collagen from nonruminants, eggs, dietary products). Materials of animal origin that are designated “non-feed grade” cannot be used. This includes manure, discarded foods containing meat or fish, and restaurant or catering establishment waste) (Gassco et al., 2020).

Material handling issues

Insect larvae are high in lipid content. Their consistency makes whole insect products difficult to handle in bulk. To use in feed on an industrial scale, insect larvae must therefore be defatted to produce a dry meal that can be handled by conventional transportation systems and in feed production facilities. A second solution, called co-drying, is to dry the larvae with conventional dry meals, such as wheat or corn bran, to make handling and storage easier.

The biological safety of both the insect larvae and humans is another concern with substrate selection. Substrates must be free of dangerous levels of toxic chemicals such as pesticides, persistent organic pollutants, and heavy metals, and free of contamination by human bacterial pathogens such as *E. coli*. The conditions under which the substrate mixture is stored before use—for instance, anaerobic conditions in the bottom layers of a tank or storage tote—can favor the growth of spoilage or pathogenic bacteria. Inoculating batches of substrate with lactobacillus cultures helps to prevent the growth of spoilage bacteria and reduces the pH of the mixture, extending substrate shelf life (Pinotti and Otoconia, 2021).

Cost and competition

A typical substrate-to-larvae bioconversion ratio is 4:1. An insect farm, such as Entobel, that aims to produce 10,000 MT of insect larvae a year will therefore require about 40,000 MT of substrate (van Huis, 2022). Some 20–25 percent of insect larvae weight is dry matter. So to produce insect meal, the yield from 1 MT of larvae will be in the range of 250–250 kg after water and fat are removed. The precise yield will depend on how much fat is removed, but every kg of dry insect meal needs about 12 times its weight in substrate. Substrate price is therefore a critical influence on the profitability of insect meal production. A small difference in price can make a significant economic impact. For this reason, scaling up an insect farming enterprise in an emerging aquaculture market requires accessing major sources of suitable but cost-effective substrate from agricultural or food-processing waste streams.

Where substrate is used in other farming activities or as human food (Münke-Svendsen et al., 2017), competition can raise prices. Some insect meal companies in the west compete with other circular economy industries such as biofuel for feedstock. Distance and transport infrastructure to supply insect meal facilities with substrate are another cost consideration. Some insect meal companies locate their production near the substrate source.

Volume and year-round consistency and availability

Small insect farms in nascent markets tend to have the flexibility to utilize a variety of different substrate sources, or substrate sources that may vary seasonally in nutritional composition. But using varying substrates as feedstock to rear insects for insect meal production makes it challenging to produce a consistent ingredient for commercial feed at scale. By contrast, large-scale insect farms, or those that supply mature aquafeed markets, normally require substrate sources with relatively consistent composition, and global feed manufacturers require all their ingredients to meet relatively rigorous nutritional standards. Insect farms in mature markets therefore prefer to locate themselves near a business that generates a significant, consistent supply of substrate such as brewery waste (for example, spent grains) or palm oil residue. In nascent or emerging markets, lower-cost insect meal production with more diverse feedstock can still attain acceptable quality levels if different feedstock streams are blended in appropriate ratios to achieve a good balance of nutritional composition and palatability.

Nutritional composition

Protein and amino acids

Insect meal is a protein-rich ingredient with a balanced amino acid profile suitable for many warm-water, omnivorous species farmed in subtropical countries, including those discussed in this report. The nutritional profile varies with the insect species, substrate, and feedstock used. The crude protein concentration of insect meal can range from 38 to 70 percent (Singh et al., 2023; Hatch, 2024). Aquaculture enterprises tend to prefer insect meal protein to plant-based alternatives because it includes high concentrations of essential amino acids such as methionine and lysine (Nogales-Mérida, 2018).

Fatty acid profile

Insect meal can contain a relatively high proportion of lipids and have been tested as a fish oil substitute in aquafeeds, with promising results (reviewed by Hossain et al, 2023). In black soldier fly larvae, the lipids mainly consist of medium-

chain saturated fatty acids, lauric acid being the dominant one. Improved fat removal efficiency can further increase insect meal protein levels.

TABLE 14. Comparing the nutritional profiles of black soldier fly larvae meal and fishmeal

	Black soldier fly larvae meal	Fishmeal
Protein (%)	55	67
Lysine (%)	5.0	5.1
Methionine (%)	1.6	1.96
Price (\$/MT)	2,920	1,562
Cost per MT of protein (\$)	6,000	2,331
GHG (kg CO2 eq/MT of product)	3,030 (EU)	1,070 (Peru)

Sources: GFLI (2022); NRC (2011); Feedstuffs (2024); Tanga et al. (2021); Singh et al. (2023)

Impacts on production: feed conversion ratio, biomass production, and growth rate

The protein, carbohydrate, and fat/oil levels in substrates affect larval growth, bioconversion ratios,² and the protein and fat levels of larvae (table 15). High protein levels in substrate yield high protein levels in larvae. On the other hand, high carbohydrate levels in substrates result in high fat levels in larvae. The table 16 presents the efficiency of BSFL biomass in processing various types of organic waste.

A recent study of the effects of different moisture content levels in substrate (40, 50, 60, 70 and 80 percent) indicates that increasing substrate moisture content reduces larval wet weight and body size, but on the other hand, shortens their development time (Dzepe et al., 2020). When high-moisture substrates are used, they must therefore be mixed with drier substrates to lower the moisture content for optimum larval growth performance.

² The relevant bioconversion ratio in this case is the amount of substrate consumed divided by larval weight gain.

TABLE 15. Major fatty acids in black soldier fly biomass after feeding on several types of substrate

Substrate	Life stage	Lauric acid (C12:0)	Myristic acid (C14:0)	Palmitic acid (C16:0)	Oleic acid (C18:1n9)
Bread	Larvae	51.8	9.5	12.7	12.0
Brewery byproduct	Larvae	32.4	6.7	20.4	9.2
Brewer's spent grain	Larvae	21.2	4.5	17.0	12.0
Chicken feed	Prepupa	57.4	7.3	9.7	7.5
Chicken feed	Larvae	32.2	4.7	9.1	20.0
Digestate	Prepupa	43.7	6.9	10.1	7.9
Ensiled mussels	Larvae	13.4	5.8	21.9	14.0
Fish (rainbow trout)	Larvae	28.6	6.1	12.6	25.1
Food waste	Larvae	39.9	6.7	16.3	19.1
Fresh mussels	Larvae	52.1	8.0	11.9	10.3
Fruit waste	Larvae	57.4- 76.13	8.46- 9.6	6.98- 13.1	4.97- 9.3
Horse manure	Larvae	28.1	6.7	22	22.9
Industrial waste 80% + organic waste 20%	Larvae	46.72	11.13	12.12	15.98
Mitigation mussels	Larvae	7.5	3.4	13.5	20.7
Mixed feed	Larvae	37.6	6.6	10.8	15.7
Palm decanter	Larvae	48.06	2.90	25.48	16.06
Palm kernel meal	Larvae	40.54	15.57	14.55	17.48
Rapeseed cake	Larvae	10.0	2.0	5.8	46.8
Raw coconut endosperm waste	Larvae	55	12	6	4
Restaurant waste	Prepupa	58	7.1	10.3	8.0
Rotten mussels	Larvae	32.3	10.1	19.8	12.9
Sewage sludge	Larvae	58.32	6.90	16.49	13.16
Vegetable waste	Prepupa	61	9.5	9.5	5.7
Vegetable and fruit waste (7:3)	Larvae	52.1	10.4	13.9	8.5
Wheat bran	Prepupa	41.96	7.05	12.59	11.19
Wheat bran and quail manure (40%)	Prepupa	40.5	6.28	11.91	12.51
Winery byproduct	Larvae	34.7	9.6	13.1	12.5

Source: Suryati et al. (2023)

TABLE 16. Efficiency of BSF larval biomass in processing different kinds of organic waste

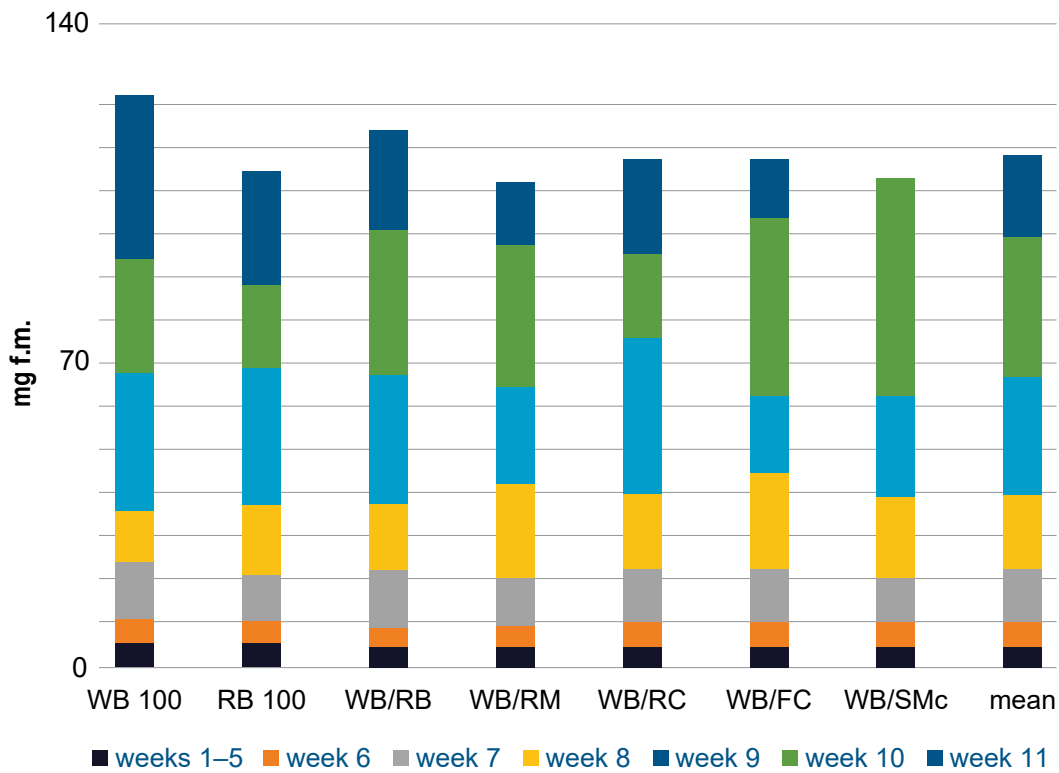
Substrate	Larval biomass (DW)	Waste reduction (%DW)	Biomass conversion ratio (%DM)	Survival rate (%)	WRI (g/d)	ECD
Abattoir waste	248 ± 3 mg	46.3 ± 2.9	15.2 ± 1.6	101.5 ± 2.8	—	—
Abattoir waste– fruit and vegetable	252 ± 13	61.1 ± 10.7	14.2 ± 1.9	96.3 ± 5.2	—	—
Bread	137 ± 7 mg	—	24.1 ± 3.3	69.8 ± 9.8	—	—
Brewery by-product	11.32 ± 0.86 g (total)	42.5 ± 8.41	—	—	5.3 ± 1.05	0.14 ± 0.034
Digested sludge	70 ± 5 mg	13.2 ± 0.8	0.2 ± 0.0	39.0 ± 4.4	—	—
Dog food	252 ± 6 mg	60.5 ± 1.5	13.4 ± 0.9	89.3 ± 6.6	—	—
Ensiled mussels	25 mg	—	<0.1	11.0 ± 4.5	—	—
Fish	89 ± 18 mg	—	3.2 ± 0.1	18.4 ± 2.6	—	—
Food waste	212 ± 4 mg	55.3 ± 4.1	13.9 ± 0.3	87.2 ± 0.5	—	—
Food waste	191 ± 19 mg	—	18.9 ± 2.4	89.1 ± 6.0	—	—
Fresh mussels	235 ± 15 mg	—	0.8 ± 0.1	89.3 ± 6.8	—	—
Fruit waste	10.92 ± 2.06 g (total)	70.8 ± 8.39	—	—	3.2 ± 0.41	0.05 ± 0.011
Fruits and vegetable	218 ± 4 mg	46.7 ± 3.1	4.1 ± 0.2	90.7 ± 5.6	—	—
Human feces	245 ± 5 mg	47.7 ± 1.1	11.3 ± 0.3	91.8 ± 4.5	—	—
Poultry feed	251 ± 6 mg	84.8 ± 3.6	12.8 ± 0.7	93.0 ± 2.9	—	—
Poultry manure	164 ± 14 mg	60.0 ± 2.3	7.1 ± 0.6	92.7 ± 3.3	—	—
Primary sludge	137 ± 5 mg	63.3 ± 1.9	2.3 ± 0.1	81.0 ± 1.5	—	—
Rotten mussels	106 ± 29 mg	—	0.2 ± 0.0	55.1 ± 11.2	—	—
Undigested sludge	145 ± 5 mg	49.2 ± 3.7	2.2 ± 0.2	76.2 ± 7.1	—	—
Vegetable and fruit waste (7:3)	10.42 ± 0.65 g (total)	65.2 ± 5.54	—	—	3.2 ± 0.26	0.07 ± 0.009
Winery by-product	9.90 ± 0.79 g (total)	53.0 ± 5.28	—	—	2.4 ± 0.32	0.06 ± 0.002

Source: Suryati et al. (2023)

Note: DW = dry weight, DM = dry matter, ECD = efficiency of conversion of digested food, WRI = waste reduction index

Combining substrate types also appears to boost larval growth compared to using a single type. In several trials, after four weeks of feeding mealworms on different combinations of substrates, the larvae on average gained 40–46 percent more weight feeding on a combination of wheat bran and fresh carrots, oranges, or red cabbage than on wheat bran alone (Liu et al., 2020). Combinations of agricultural byproducts were also found to significantly increase mealworm growth (figure 4) and positively affect larval proximate composition (Bordiean et al., 2022a, b).

FIGURE 4. Weekly weight gain of yellow mealworm larvae fed differing diets, wet weight basis



Source: Bordiean et al. (2022a,b)

Note: WB = wheat bran, RB =rye bran, WB/RB = wheat bran/rye bran, WB/RM = wheat bran/rapeseed meal, WB/RC = wheat bran/rapeseed cake, WB/FC = wheat bran/flax cake, WB/SMc =wheat bran/Silybum cake

Manure as a feedstock

A recent study has noted that feeding insects with aquaculture solid waste (for example, uneaten feed, feces, and an assemblage of organic matter and microorganisms) can improve their larval growth and waste bioconversion efficiency while reducing the risk of eutrophication and related GHG emissions (Rossi et al., 2023). The circularity of the use of waste from fish as feedstock for insects is attractive from first principles, but some countries and regions, such as the EU, do not allow manure to be used as a substrate for insect meal because of potential health concerns.

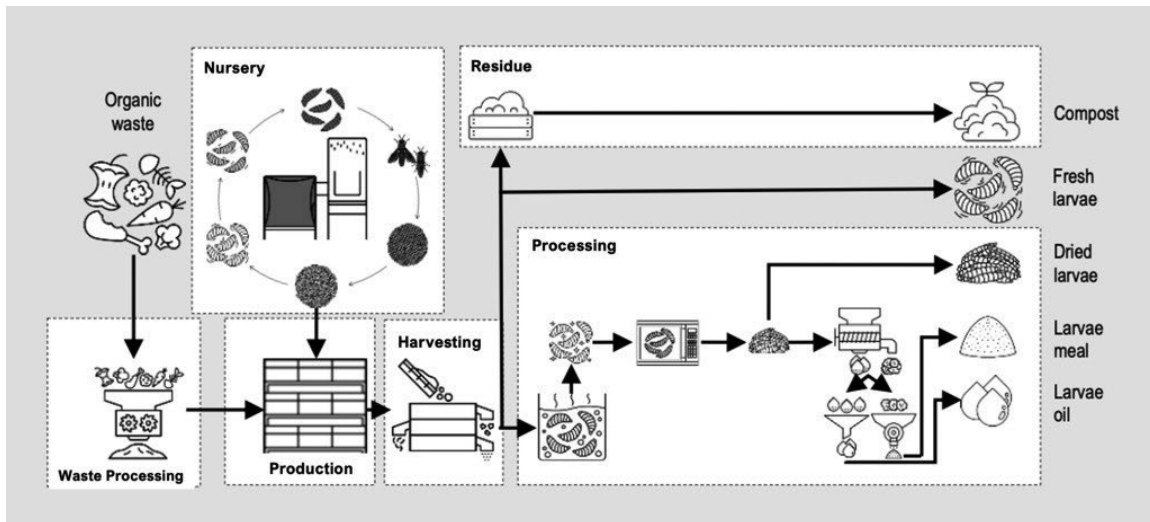
Nutritional value of frass

Frass has been shown to have value as a feed ingredient for aquaculture species. For channel catfish, including frass as 10–30 percent of the diet increased palatability (Aksoy et al., 2020). For Pacific white shrimp, dietary inclusion levels less than 20 percent improved immune function without impacting growth (Yildirim-Aksoy et al., 2022). For hybrid tilapia, inclusion levels of 30 percent improved growth and bacterial pathogen resistance (Yildirim-Aksoy et al., 2020).

Production steps

Insect proteins are produced by growing selected insect larvae under controlled conditions following well-defined steps (Figure 5) (van Huis, 2020; Grau et al, 2022). Feedstock is collected and transported to an insect production facility and introduced to the insect production system. Insects are harvested and processed into the final product, which can include dried larvae, insect meal, larvae oil, or fresh larvae. Residue from insect production can be used as compost or further processed into feed ingredients.

FIGURE 5. Producing black soldier fly oil and meal



Source: Grau et al. (2022)

Waste processing

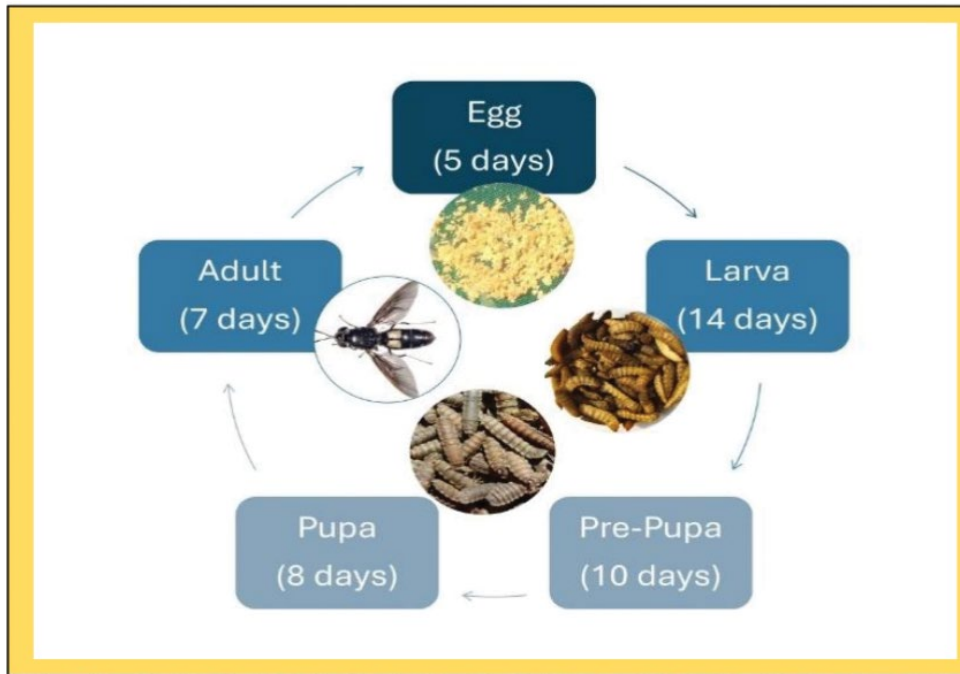
Waste streams are ground, blended and, where appropriate, treated through a fermentation process to supply a consistent nutrient supply and moisture level.

Nurseries manage the metamorphosis of the black soldier fly from egg laying to egg collection to hatching, and then the rearing of neonates until they are 5-day-old larvae (5-DOL) (figure 6).

- **Egg laying:** Female adult black soldier flies are induced to produce eggs by placing them in a netted enclosure containing a pungent attractant like chicken manure, fish offal, or decomposing matter, together with “eggies,” a moistened, porous substrate such as an inexpensive paper carton into which they insert their eggs (Fabo, 2023). While eggies vary, the cheapest are small strips of cardboard box, or two adjacent boards of wood with crevices into which the flies can lay their eggs (Fabo, 2023).
- **Egg collection and hatching:** After the eggs are laid, producers transfer the eggies to sit above a hatching container. This hatching “shower” allows eggs to fall from the eggies into the container below, which is filled with feedstock (Huber, 2023). It is particularly important that the new hatchlings be given the highest-quality feedstock the enterprise can afford because this is the most crucial stage for larval development (Fabo, 2023).

- **Larvae rearing:** Within about 4 days, the eggs hatch into larvae that start to feed immediately, eating twice their body mass per day. After the larvae are 5 days old, the producers separate them from the substrate and the frass (a mix of shed exoskeletons, larvae excreta, and uneaten substrate) that has developed, then transfer them to a new rearing container with new feed (Huber, 2023). Producers must be careful to monitor the moisture content of the containers to maximize larval growth (Fabo, 2023). During this stage, the trays must be monitored closely and dead larvae removed immediately.

FIGURE 6. Black soldier fly life cycle



Source: INCiTiS-FOOD (n.d.)

Production

Lighting, temperature and humidity conditions are important production parameters. (Most larvae are photophobic (light-averse) and will burrow if their surroundings are not sufficiently darkened.) For mealworm production, air temperature should be kept around 25–30°C and humidity around 50–75 percent. For BSF production, temperature should be maintained at 27°C with 60–70 percent humidity. A constant photoperiod of 14:10 (light–dark) is optimum. Maintaining these conditions in tropical regions does not require energy expenditure to heat or cool larvae-rearing areas, in contrast to insect farming in temperate climates. If insect farming is conducted in closed rooms, provision for air circulation to remove CO₂ produced by insect larvae must be made. Energy is necessary to move air in and out of insect larvae rearing areas.

Harvesting

Once larvae turn beige in color, they are the correct maturity and size for harvesting (Fabo, 2023). Producers remove the larvae by manually sieving to let small frass particles fall, or using an automatic sifting machine, which mechanically

separates the larvae from the frass using a mesh (Fabo, 2023). The producers may then rinse the larvae to remove any remaining particles. As indicated in figure 5, harvesting generates three products: 1) live larvae for processing, 2) live larvae for direct use as feed, and 3) frass for compost or, as noted earlier, as a feed ingredient.

Processing

The larvae are then killed and sterilized to ensure they are not disease vectors that could contaminate feeds. This is often done by blanching (immersing in boiling water for a short period) to reduce bacterial loads on their surface and to deactivate endogenous proteolytic enzymes in the larvae. This prevents autolysis (self-digestion).

If larvae are going to be fed fresh to poultry or fish within a day or so, no further processing is undertaken. But if they are to be preserved for later sale, they need to be dried. Methods vary with the scale of production and range from sun-drying to baking, microwaving, or other forms of thermal drying. If dried insect meal is the primary product, a lipid extraction step may be added before drying. The consistency of ground, whole larvae is similar to that of peanut butter, making it unsuitable for use in conventional feed manufacturing equipment. But larvae can be co-dried with other materials such as byproducts of wheat flour production, resulting in a product suitable for normal handling and storage. Lipids can be removed from the larvae by mechanical pressing or solvent extraction, followed by drying, grinding and, for some high-value products, removal of chitin from their exoskeletons.

Oh et al. (2024) evaluated four lipid extraction methods—alkali extraction, enzyme treatment, salt-assisted, and screw press—and found that each delivered products with specific properties that could be tailored to maximize health benefits such as antioxidant capacity, bioactive compounds, and antihyperglycemic properties. These extracted products are potentially important value additions. Further research is planned on fermentation treatment of insect meal and its impact on health benefits.

Packaging and storage

Packaging and storage of final products complete the process. Sanitation is important in any animal farming system, and insects are no exception. After harvest, rearing trays must be cleaned and disinfected before being used in the next cycle. Frass must be removed and disposed of, preferably by composting to produce soil amendments.³

After processing, dried insects are susceptible to lipid oxidation, the severity of which depends on the species and the lipid content. Such oxidation lowers the value of insect meal and can affect the health of fish consuming feeds that contain oxidized meal (Hurtado-Ribeira et al., 2023). Lipid removal reduces, but does not eliminate, the threat of lipid oxidation. Oxidation can be prevented by adding antioxidants to dry insect meal, by vacuum-packing, or by modified atmosphere packaging. Such steps are unlikely on smaller-scale farms, but it is essential on industrial-scale farms that aim to produce stable insect meal with consistent proximate composition.

Production models

There are various insect meal production models, ranging from centralized or decentralized production arrangements, and from batch processing to continuous production. Let us take batch versus continuous first.

³ Soil amendments, like mulch, compost, biochar, wood ash, lime, and manure, improve the structure of the soil and enhance its physical properties, like texture, water retention, aeration, drainage, and pH.

Batch versus continuous production

The batch system involves rearing batches of larvae in containers and is labor-intensive because the batches must be fed and checked daily. But the benefits include lower capital costs and the lower risk of system-wide larval die-offs that, in a continuous system, would require the entire system to be emptied, cleaned, disinfected, and repopulated. If an individual container in the batch system experiences a die-off, it is unlikely to affect the entire farm's production. Another advantage is that each container typically contains larvae of similar age and size. This minimizes cannibalism, which can occur, for example, on mealworm farms.

Continuous systems, with their automated feeding and monitoring, increased production intensity, higher efficiency, and lower labor costs, are better suited for industrialized mass-rearing of larvae. But it requires more sophisticated technology. For example, all inputs, such as eggs and substrates, must be carefully synchronized to supply the right amount of substrate to the larvae to avoid feed spoilage.

Facilities in North America and Europe are highly automated with expensive machinery. For example, insect producer Innovafeed has a vertical farm model that is nearly entirely automated, with automated egg collection, optimized heating, ventilation, and air conditioning, and a sophisticated low-temperature processing machine. On the other hand, in tropical locations, simple and more labor-intensive commercial-scale projects are often leveraged and can have relatively low upfront costs.

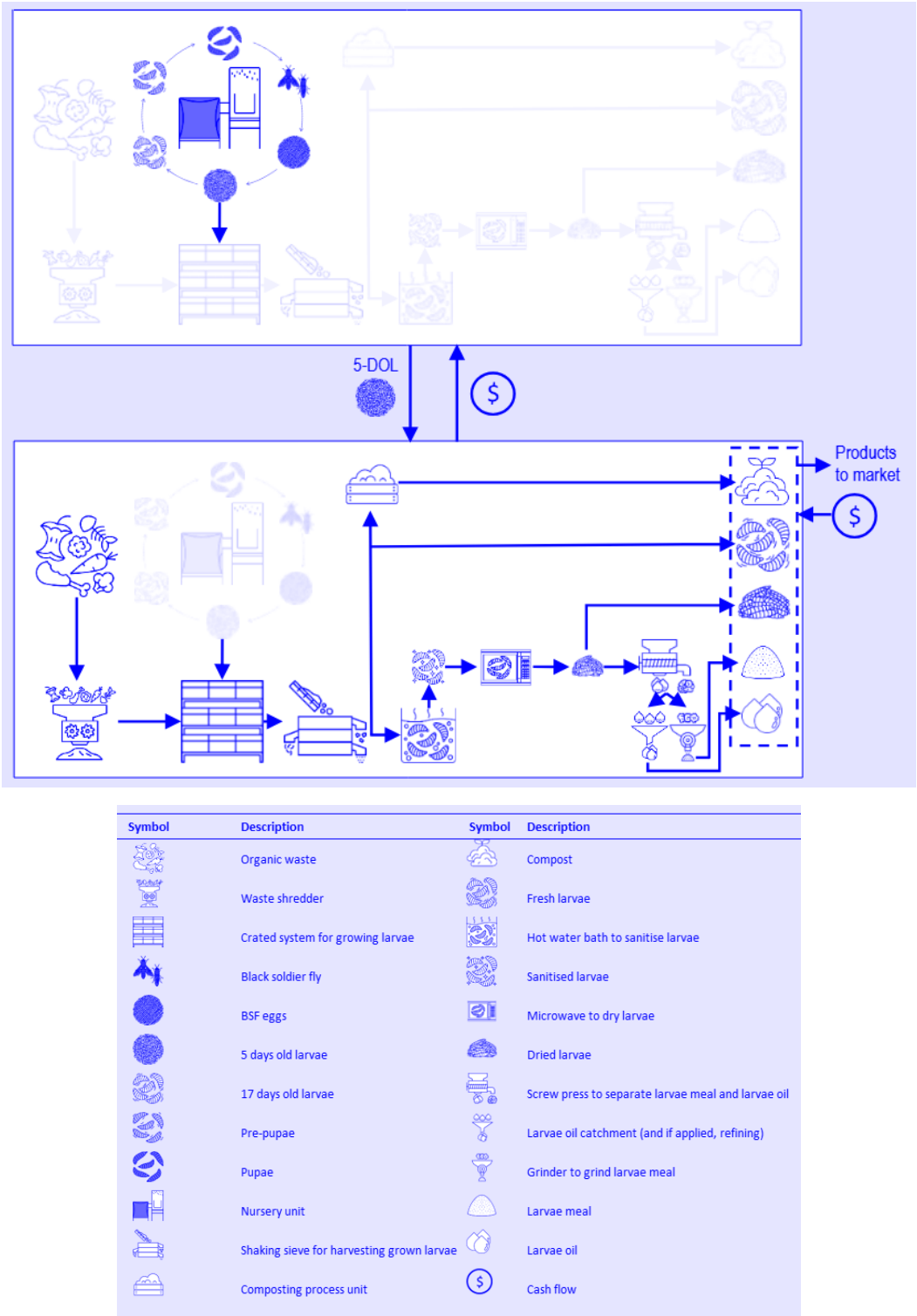
Centralized versus decentralized production

On the centralized to decentralized continuum, production facilities can range from large-scale, fully centralized, integrated systems with all the processes controlled under one roof, to completely decentralized production models in nascent aquaculture sectors where low-capital, small-scale farmers engage in various stages—such as feed production, larvae rearing, growing insects to maturity, or processing them into meal—to in-between hybrid models that contain both centralized and decentralized elements. One widely employed hybrid model is the hub-and-spoke production model, a semi-decentralized system of BSFL farming where a central processing facility (the hub) oversees critical operations such as egg production, quality control, and the processing of harvested larvae into market-ready products. The hub supplies satellite rearing units (the spokes) with starter materials like eggs or young larvae, while the spokes—often community-based farms—focus on cost-effective biomass growth, feeding the larvae organic waste streams, and returning mature larvae to the hub for final processing. This division of labor optimizes scale and efficiency, the hub ensures consistency and compliance, and the spokes minimize transport costs and leverage local waste resources.

Centralization offers the advantages of efficiency, standardization, aggregation, and scale but tends to be more capital-intensive, while more decentralized models can create inclusive business opportunities for lower-income households and communities but tend to be less efficient, smaller in scale, and potentially more variable in quality and consistency from facility to facility and from season to season. A hub-and-spoke model strikes a middle ground—benefiting from centralized processing and quality control at the hub while enabling localized production and reduced transport costs through spokes—although it requires sound logistical coordination and may still face scalability constraints as compared to fully centralized systems.

Figure 7 below shows a decentralized production unit (lower part-figure) that buy 5-day-old larvae from a central integrator's nursery (upper part-figure), grows them for 12 additional days, then sells the 17-day-old larvae back to the integrator's processing facility (Grau et al., 2022).

FIGURE 7. A central nursery (above) that supplies 5-day-old BSF larvae to one of many decentralized waste treatment/ post-processing units (below) that grow and sell them as larvae products



Source: Grau et al. (2022)
 Note: The black soldier fly larvae products sold are fresh larvae, dried larvae, larvae meal and oil

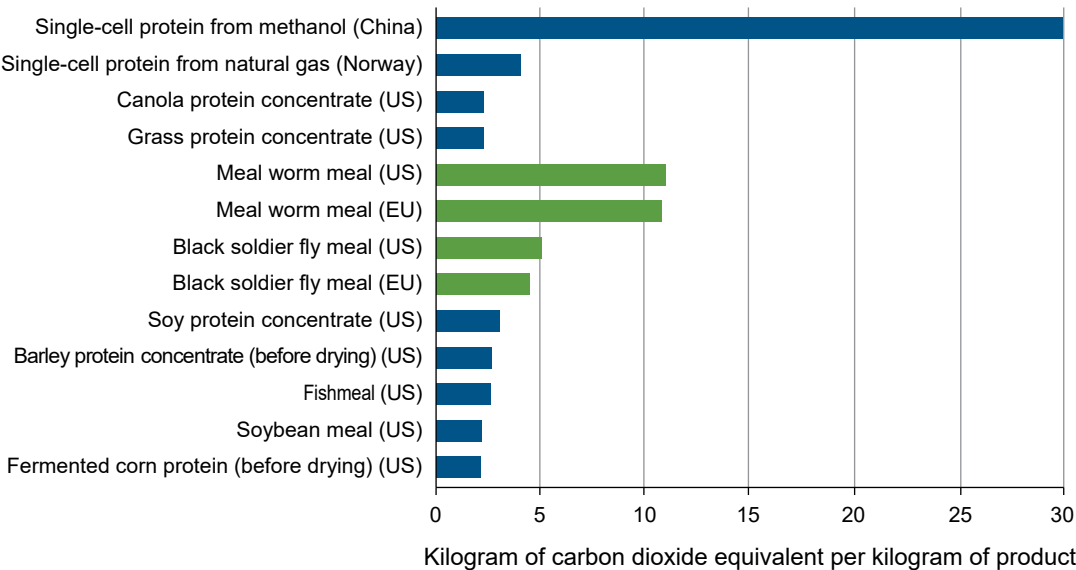
Grau et al. (2022) modeled the financial viability of centralized and decentralized BSF operations in Indonesia. The centralized plant scenario achieved higher net present value (NPV), mainly through achieving economies of scale in managing all steps. The decentralized operation also generated a positive, albeit lower, NPV—cash inflows, in other words, were greater than costs—but it also provided other benefits such as generating new jobs within the community and lowering transport costs by locating closer to waste facilities. Local government can coordinate and facilitate decentralized BSF production facilities by operating a central nursery and providing the young larvae at low or now cost to improve the financial viability of the processing plants treating the waste (Grau et al., 2022).

Environmental impact

Greenhouse gas emissions

Table 8 compares the global warming potential of insect meals with that of various aquafeed protein ingredients. The GHG emissions of insect meal vary based on the feedstock used, species grown, climate system requirements (for example, heating and air conditioning), and processing method. The proximity of insect meal facilities to the source of feedstock and to end-market buyers can also affect Scope 3 emissions—indirect emissions that occur in the value chain, such as those from the transportation of raw materials and finished products.

FIGURE 8. Global warming potential* of insect meals compared to that of various aquafeed protein ingredients

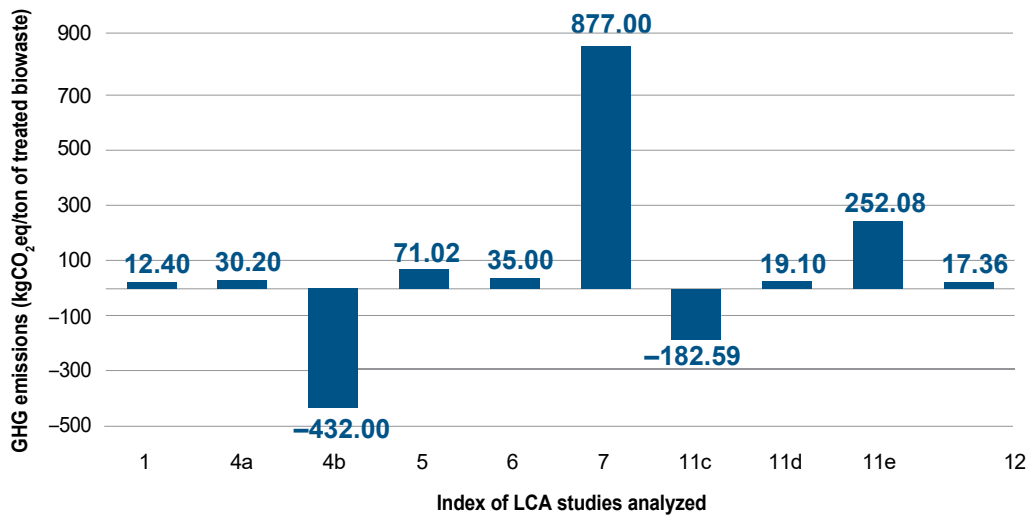


Note: *The global warming potential includes land use change

Choice of feedstock has the largest effect on emissions from insect meal, contributing 75–90 percent of total emissions (figure 9) (Galán-Díaz et. al., 2024). Emission estimates for intensive production models in northern-hemisphere countries range between 3.0 and 6.0 kg CO₂eq per kg of dried insect meal, significantly higher than the roughly 1 kg CO₂eq emitted during the production of 1 kg of fishmeal on average (GFLI, 2022; Bava et al., 2019). But in cases where feedstock would otherwise be considered a waste stream, the GHG emissions profile can actually have a

net positive impact of up to -6.42 kg CO₂e/kg of insect meal by avoiding the associated release of methane from the decomposition of waste (Smetana et al., 2023).

FIGURE 9. Emissions from biowaste treatment using BSFL production



Source: Boakye-Yiadom et. al. (2022)

Note: The figure shows global warming potential results as reported in a comprehensive review of 10 life cycle assessment studies on biowaste treatment using BSFL:

1 compares different biowaste treatment technologies.

4a is without avoided products (e.g., no nitrogen in the fertilizer).

4b is with avoided products.

5 compares different food waste treatment strategies.

6 compares emissions from biowaste treatment and composting with BSFL.

7 attributes different emissions to different stages of BSFL production and identifies the outcome of different production and consumption choices.

11c uses brewery grains as the substrate.

11d uses expired food as the substrate.

11e uses potato peels as the substrate.

12 describes the environmental impact of a BSFL bioconversion plant.

Because of the significant contribution of feedstock to the emissions associated with production, BSFL producers should avoid selecting substrate those that would otherwise be used for human consumption or for direct inclusion in feed. Sources must be consistent and plentiful to meet the long-term quality and nutritional consistency requirements of BSFL and insect meal buyers. Indeed, to secure long-term feedstock supplies, some insect meal companies have paid for agricultural byproducts that would otherwise be free, as competition for these side streams can be a challenge.

Energy, land, and water use

The upstream, direct production, processing, and downstream stages of the insect meal sector all use energy, land area and water at each step. There are more efficient/sustainable and less efficient/sustainable ways of using each of these resources—for example, renewable energy versus a coal-powered grid; or water recirculation versus reliance on a primary water body source; or using previously converted land versus converting new habitat for facilities or crops. This creates opportunities all along the supply chain to enhance the sustainability of final insect products by avoiding, reducing, or mitigating negative environmental impacts.

Energy use

Insect production facilities in tropical countries require less energy for climate control (for example, heating and air conditioning) than those in northern countries. The most energy-efficient use of insects is pond-side production and direct feeding of live larvae, an approach that may offer great value in nascent and emerging aquafeed industries where feed is still produced on farms. Fresh or live insect larvae can be fed directly to fish because insects are a major part of the diet of many fish species. In trials in tilapia ponds in Uganda, researchers have found that live black soldier fly larvae can substitute for 66 percent of compound feed, with no negative sequences. Such small-scale supplementary production recycles local wastes and obviates the costs of devitalizing, drying, and defatting incurred in producing insect meal (Richard Newton, personal communication, University of Stirling, UK, August 21, 2024; video of field trial: <https://www.susaquastirling.net/blog/2022/12/5/supporting-insect-larvae-production-in-uganda>). Direct feeding of insect larvae is also set to be tested in Ecuador by the shrimp production company Lukmar.

As far as is known, there is to date no publicly available comprehensive life cycle assessment of tropical insect meal production at scale. Nonetheless, *several companies in the Global South are claiming significant carbon offsets from the production of black soldier flies*. For example, Regen Organics, based in Kenya, claims that each of its facilities can be expected to offset 50,000 MT of CO₂ equivalent per year by diverting agricultural waste from landfills and thereby avoiding methane emissions (Regen, 2024).

A comprehensive review of LCA studies conducted on BSFL production in 2022 indicated a range of 15–174 megajoules (MJ) required to produce a kilogram of insect protein (Boakye-Yiadom et. al., 2022). This range covers studies conducted at facilities using different feedstock materials and energy sources, with some studies including the drying stage within the system boundary, and others not. Of note, the high end of the range, 174 MJ/kg protein, results from the use of food-grade material as feedstock, and the drying stage is not included in the system boundary of that study. The drying process is often associated with increased energy use in northern countries.

Land and water use

Land use for insect production occurs upstream, in production and processing of insects, and potentially in downstream supply chain areas such as storage prior to dispersal to buyers. The type of feedstock used significantly affects the land use for insect production, assuming the system boundary for assessment is the direct source of feedstock (that is, food-grade materials, feed-grade materials, organic material not useable for food or agricultural feed, and organic waste material). Food-grade materials are among the drivers of the conversion of land for production of crops for human consumption, and as such, using these as feedstock for insects significantly downgrades the direct benefit for human consumption, as well as the economic value of the product, resulting in a higher land use impact value.

Conversely, using feedstock that is considered a waste (for example, organic matter not suitable for human or livestock consumption) can result in a net positive land use value, as these materials increase in value, and are upcycled, increasing their useable yield. A comprehensive review of LCA studies conducted on BSFL production indicated a range of 0.0–67 square meters of arable land for the production of 1 kg of insect protein. The lower bound of the range results from the use of nonfood or feed-grade organic material as feedstock, while the higher bound reflects the use of food-grade materials. The use of organic waste materials such as brewery grains, potato peel, or expired food can result in a net positive impact on land use (-477.2, -1.16, and -0.61 m² per ton of feedstock, respectively) (Boakye-Yiadom et. al., 2022).

Applying the system boundary to water use, LCA studies have generally considered freshwater consumption during insect rearing and processing to be of lower significance. This is because relatively little freshwater is needed during these stages compared to the substantial amounts required to produce feedstock materials, such as those needed in crop agriculture.

Ingredient sustainability

Although agricultural byproducts may, from first principles, be considered more sustainable than the use of the primary product as a feedstock, insect product producers should be aware of the farming methods and strategies used to grow primary products that are creating the byproducts they are using as feedstock. For example, the land and water use section of this report cites LCAs that have boundaries set one step upstream of the insect production and processing stage, specifically focusing on the types of feedstock used. But if the farms exploit land, water, and energy in ways that degrade ecosystems (for example, through deforestation), then the use of byproducts from this production indirectly becomes associated with unsustainable farming practices.

Appendix 3 provides an overview of the current state of the insect meal industry, highlighting key players, production models, and case studies. The major insect meal producers, such as Innovafeed, Ynsect, and Protix, are primarily based in the mature aquaculture markets of Europe and North America, having raised significant capital (over \$1 billion collectively) to build large-scale, capital-intensive facilities. In the tropics countries like Vietnam, Kenya, and India, the companies are typically smaller and have varying production scales—from small on-farm setups to industrial-scale operations.

Three case studies (discussed in appendix 3) illustrate three different production models:

1. **ProNuvo**, in Costa Rica: A centralized, industrial-scale producer that uses banana byproducts, choosing labor over automation to reduce costs, create jobs, and harness the country's comparative advantage in the ready availability of a large, relatively low-income workforce.
2. **Rural Aquaculture Development**, in Uganda: A hub-and-spoke model that supplies smallholder farmers with live BSFL, keeping feed costs low and promoting circularity.
3. **Regen Organics**, in Kenya: A hybrid, in-between model that combines centralized hatchery operations with decentralized, community-based larval rearing, leveraging diverse organic waste streams from the surrounding city of Nairobi, and generating employment.

Appendix 3 also examines the workforce impact of insect farming, noting that it frequently creates large numbers of jobs, particularly for women and youth, with employment opportunities scaling with production size and but somewhat diminishing as automation levels increase. Market projections for Tanzania and Ecuador suggest significant growth potential in both, although challenges like feedstock consistency, complicated regulatory frameworks, and high production costs remain. Finally, the factors that facilitate or impede the transition from the nascent to the mature industry stage are discussed, emphasizing the need for appropriate infrastructure, financing, coordination, consumer demand, policy direction, and technical knowledge to scale operations sustainably.

5

SUMMARY AND CONCLUSIONS

A century ago, there were 2 billion people on earth. Today, that number has more than quadrupled, to 8.2 billion. As the global population approaches 9.7 billion by 2050, ensuring sustainable access to nutritious protein sources has become, and will increasingly become, one of the human community's defining challenges. A vital part of the solution is aquaculture. With wild capture fisheries on the verge of their ecological limits, aquaculture production has already surpassed that of capture fisheries and is projected to double by mid-century.

This growth in aquaculture production is unsustainable without significant advancements in the feed given to farmed fish and other aquatic animals. Aquafeed is the single largest operating cost in aquaculture, and its formulation and production profoundly affect the sector's environmental impact, economic viability, and nutritional outcomes. How the aquafeed industry evolves is therefore pivotal to achieving sustainable global food security.

Yet influenced by local and national market dynamics, climate conditions, and the fish, plant, and insect species native to that area, the aquafeed industry varies widely from region to region in growth rate, maturity stage, degree of supply chain integration, infrastructure readiness, and available financing. What works superbly well in one national industry may not necessarily work in another. Understanding these industry-to-industry variations is crucial for designing context-specific development and investment strategies.

Roughly speaking, every aquafeed industry the world over is currently in one of three stages of maturation—**nascent**, **emerging**, or **mature**—although a closer look would reveal that parts of an industry may be at one stage while other parts are already transitioning to the stage beyond. Each of the three stages has distinctive structural and functional features, and brings its own set of challenges and investment considerations. The next paragraphs discuss each of the three.

Mature-stage markets: Efficiency meets innovation challenges

In established aquafeed-producing nations such as Ecuador and Vietnam, centralized production systems dominated by large corporations, supported by vertically integrated supply chains, enable the efficient, large-scale production of high-quality feed, bolstered by robust infrastructure, good logistics, and a sound institutional framework. This combination of production elements yields substantial economic benefits, boosts growth, and positions these countries as global aquaculture leaders. But such success has come at an environmental and social cost. Intensive aquaculture in areas like Vietnam's Mekong Delta contribute to water pollution, eutrophication, and the loss of biodiversity.

Additionally, mature markets, with their emphasis on consistency, quality, high volume, low risk, reliable availability, and expansion, tend to depend heavily on what they regard as familiar, tried-and-tested, conventional feed ingredients—in particular fishmeal and soybean meal. Yet because of overfishing and deforestation-linked GHG emissions, both fishmeal and soybean meal exert substantial ecological pressure on the global environment.

To help the food industry achieve long-term sustainability, the large corporations that lead mature markets must shift away from efficiency-driven models and toward innovation-led approaches. They need to invest in researching and developing alternative proteins (such as insect meal, algae, microbial proteins), deploy digital feeding systems to minimize waste and enhance nutrient delivery, and adopt circular-economy principles such as nutrient recycling and waste valorization. Although these enterprises possess the institutional capacity and resources to lead this transformation, timely and decisive action is essential. For that, there needs to be a more rapid shift in corporate culture and a reevaluation of goals and incentives.

Emerging-stage markets: Scaling up with strategic investment

In emerging-stage aquafeed markets, such as Bangladesh and Kenya, aquaculture is growing rapidly, driven by rising domestic demand, improved farming practices, and increasing export opportunities. These markets are in transition. From their beginnings as traditional, low-input, informal or semi-formal, decentralized systems, they have grown into more intensive, commercially oriented production sectors that are centralized but still lack the fully integrated production/supply chains that enable true economies of scale. Their technological infrastructure is beginning to advance in sophistication, marked by the emergence of commercial feed mills that bring enhanced feed quality and consistency.

But with the cost of feed accounting for 50 to 70 percent of total fish farm expenses, robust profitability remains a challenge. It highlights the need for cost-effective, nutritionally balanced feeds made from locally available ingredients and processed using modern technologies that can achieve volume and lower marginal cost.

One such solution is extrusion technology, which, although relatively capital-intensive, provides enhanced levels of precision and control across a range of manufacturing parameters—from cooking intensity and product density to oil content, size, and form—that bring major benefits almost immediately. These include greater pellet durability (which reduces waste), improved digestibility for better fish growth, reduced microbial contamination, and greater versatility in accepting a wide range of liquid, dry, or fibrous ingredients.

But to unlock the full potential of emerging-stage markets, strategic partnerships—public–private collaborations, joint ventures, foreign investment, and value chain integration—are essential. So are the utilization of already existing infrastructure from related sectors like livestock to minimize cost and risk, and the inclusion of transport and logistics actors to lower entry barriers and catalyze sector-wide development.

Nascent-stage markets: Breaking the feed investment deadlock

In nascent aquafeed markets, such as Senegal, aquaculture is just starting out and still in its infancy. Rapid growth and takeoff are hindered by the market’s decentralized architecture and by the absence of domestic feed producers. This constraint tends to perpetuate a self-reinforcing cycle: the aquaculture sector cannot expand without affordable, high-quality feed, yet the low volumes of fish production do not yet make it commercially attractive to invest in building a feed mill. Each side, in essence, is waiting for the other to make the first move.

To disrupt this stalemate and catalyze sector growth, targeted interventions are required from both government and the international development community. These might include establishing foundational infrastructure like hatcheries to ensure a consistent supply of fry and fingerlings, developing processing and cold-chain facilities to maintain product quality and market value, and implementing clear, business-friendly regulations to attract private investment, including catalytic capital. In parallel, alternative approaches to jumpstart local feed production can and should be explored, such as supporting domestic ingredient suppliers—like fishmeal factories and meat-rendering operations—and encouraging the production of insect-based proteins, particularly from black soldier fly larvae.

The larvae of the black soldier fly, a large, non-pestiferous, wasp-like fly with a ravenous appetite and excellent biowaste management and recycling potential (Chineme et al., 2023), is especially promising for these markets because it can be reared on locally sourced agricultural waste, converting low-value biomass into nutrient-rich, sustainable feed ingredients with minimal technological requirements. However, to scale this solution, challenges must be addressed, including securing a consistent and adequate supply of organic waste, bringing production costs down to compete with conventional feed inputs, and navigating market dynamics that currently favor higher-margin sectors such as premium pet food. Overcoming these obstacles will be key to unlocking the potential of aquaculture in emerging economies and positioning it as a viable contributor to food security and rural development.

The future of aquafeed: Navigating environmental tradeoffs and advancing circular solutions in aquaculture

The environmental impact of aquafeed ingredients has emerged as one of modern aquaculture’s most pressing challenges, demanding innovation, creativity, and systemic reform. Marine-based ingredients like fishmeal, though rich in essential nutrients and relatively efficient in terms of land use, are increasingly criticized for contributing to overfishing and threatening marine biodiversity. Ensuring the sustainability of these inputs requires rigorous traceability and sourcing from certified, well-managed fisheries to prevent irreversible damage to ocean ecosystems.

Simultaneously, the heavy reliance on plant-based ingredients—particularly soy—also raises significant environmental concerns. Soy cultivation generates high GHG emissions, competes with local communities for water and arable land, and is a major driver of deforestation in biodiverse regions like the Amazon.

In response, researchers and industry stakeholders are actively exploring a suite of alternative aquafeed ingredients that have lower environmental footprints. These include agricultural byproducts such as maize husks and distillers grains, processed animal proteins (PAPs) sourced from waste from animal-rendering processing plants, and novel protein sources like single-cell organisms, fermented microbial biomass, and algal oils. These options show promise for reducing land and water use, lowering emissions, and promoting the circular economy.

However, integrating these alternatives into mainstream aquafeed production requires a comprehensive assessment to avoid unintended tradeoffs—such as single-crop farming that reduces biodiversity encouraging the overproduction of industrial waste (on the confidence that someone will buy it), and disrupting local food systems. Ultimately, achieving environmentally responsible aquafeed formulation calls for a balanced approach among several competing factors, goals, and interests—one that considers ecological integrity, economic feasibility, and the long-term resilience of aquatic food systems.

A strategic vision for sustainable, inclusive aquafeed development

To ensure the aquafeed sector evolves in a way that supports global food security while minimizing its environmental impact, its development must be strategically aligned with the real-world contexts of different market segments—nascent, emerging, or mature—while pursuing the overarching goals of sustainability, low impact, climate resilience, and socioeconomic inclusivity.

In nascent markets, such as many in Sub-Saharan Africa, the priority must be the development of foundational infrastructure—hatcheries, feed mills, and cold chains—coupled with targeted investments to build local capacity and improve the access of smallholder farmers and small- and medium-size enterprises (SMEs) to finance because they are often excluded from mainstream value chains.

In emerging markets, where aquaculture production is accelerating, the emphasis should be on adopting advanced feed technologies such as extrusion, which enhances feed efficiency and reduces environmental waste, and creating public–private partnerships to drive down costs and improve feed quality.

Mature markets, which already operate at industrial scale, need to take a strategic longer-term view and lead the way in R&D, focusing on alternative ingredients such as insect meal, algae, and single-cell proteins, while integrating digital tools and circular-economy practices to optimize feed use and minimize ecological footprints.

At the global level, cross-border collaboration is paramount. It is needed to harmonize and streamline regulatory frameworks for the new wave of novel feed ingredients, to facilitate the transfer of scientific and technical knowledge and best practices to the Global South, and to promote robust, transparent certification systems for environmentally safe, sustainable sourcing. An integrated, differentiated, and cooperative approach will be vital to ensuring that the aquafeed sector not only meets demand but does so in a way that supports inclusive development, climate action, and long-term ecosystem health.

Recommendations for a resilient aquafeed future

The aquafeed sector is at a critical crossroads—either seize the opportunity to proactively reshape global food systems toward sustainable protein sources by addressing the growing demand for it, or fail to act and passively allow market forces, business trends, and corporate interests to determine the future by default.

As aquaculture continues to expand, this sector must take on the dual interrelated challenges of rapid growth and significant environmental and social impacts that need to be mitigated. To navigate this crossroads, the industry, working with governments and the development community, will need to take firm steps/courageous steps to balance economic growth with ecological sustainability and social responsibility.

In this context, the aquafeed industry must embrace innovative technologies and sustainable practices that will ensure long-term viability. A key opportunity is the integration of alternative protein sources, such as insect meal, algae, and other nontraditional inputs, into the aquafeed industry. These alternatives not only reduce reliance on conventional fishmeal, which is straining marine ecosystems, but also promise to reduce the sector's environmental footprint. Additionally, adopting circular economy models that focus on waste reduction, resource efficiency, and closed-loop systems will significantly enhance the sustainability of aquafeed production.

Additionally, the industry must prioritize social equity and inclusivity by adopting policies that support smallholder farmers, local communities, and other diverse stakeholders. By creating an ecosystem that nurtures collaboration and offers equitable opportunities, the aquafeed sector can help build resilient food systems. This shift should include improving SMEs' access to resources and technologies, empowering local communities, and ensuring that the benefits of growth are shared across the value chain.

Besides focusing on productivity gains, the aquafeed sector must construct and employ a comprehensive framework that takes into account ecosystem health, the improvement of rural livelihoods, and the strengthening of long-term food security. By aligning the sector's goals with environmental and social objectives, the industry can help meet global nutritional needs while contributing to the planet's health.

The decisions made in the coming years will be central to determining whether the aquafeed industry becomes a catalyst for positive environmental change and sustainable development or exacerbates existing challenges. This is a moment for the aquafeed sector—nascent and emerging, but perhaps especially the mature—to revisit its approach, redefine it if need be, and ensure that it is operating in ways that support a resilient, equitable global food system. By acting now to prioritize innovation and social responsibility, the industry can be a driving force for good.

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APPENDICES

Appendix 1: Summary Figures

TABLE S1: Suitability of five alternative protein sources for commercial development

	Suitability as feed for carp, tilapia, catfish, and shrimp	Necessary inputs	Potential for scaling in the Global South	Risks and challenges
Insect meal	Expensive, palatable, high-protein, functional benefits	Low-cost organic byproducts, decentralized production options	High —Insects thrive in the tropics and can consume diverse feedstocks	Relatively high cost of production, varying quality depending on feedstock
Agricultural byproducts	Primary ingredients for all animal feeds	Nearby agricultural production and/or processing with available byproducts	Med to high —The staple crops of the focus countries are generally suitable for inclusion in aquafeeds	Competition with other agriculture sectors, often driven by imports
Processed animal proteins	Inexpensive, high-protein, local PAPs may require upgraded processing	Meat-processing facilities with rendering capabilities	Med to high —Already in most compound feeds, but depends on the size of the meat industry	Some countries lack large, centralized rendering facilities. Varying raw material quality
Single-cell protein	High protein, but some products require cell wall disruption	Microbial fermentation substrates (e.g., algae, yeast, bacteria), sugars, or waste carbon sources	Med to high —Can be low-tech fermentation of ingredients and insect substrates	The high-tech approach requires high volumes; the low-tech approach requires field verification
Seaweed	Suitable for feeds after fermentation or directly as partial feedstock for insects	Posts, rope, U nails, raffia, wire, and labor	Medium —Evaluate insect-based and fermentation-based feedstocks	Competition with other uses such as human consumption; the high cost of drying

TABLE S2: Opportunities for developing alternative protein feeds in selected countries

	Maturity level of the aquaculture industry	Availability of raw material inputs	Are there associated industries?	Workforce considerations	Potential for scaling up ingredients
Vietnam	Mature; very strong and diverse	High volume of raw materials	Yes, pigs, poultry and fishmeal	Diverse and high levels of aquaculture expertise	High
Ecuador	Mature; strong shrimp industry	High volume of raw materials	Yes, pigs, poultry and fishmeal	High level of shrimp and tilapia farming expertise	High
Tanzania	Emerging; fast-growing tilapia and catfish	Raw materials exist but not yet at scale	Yes, in limited form	Interest from women and youth; growing aquaculture awareness	Med to high
Sri Lanka	Emerging; fast-growing shrimp industry	Supplies present but development is needed	Yes, poultry	Interest from women and youth; existing shrimp aquaculture history	Med to high
Senegal	Nascent; small but growing tilapia and catfish industry	Supplies present but development is needed	Yes, fish meal and poultry	Expertise with capture fisheries and poultry	Medium

Appendix 2: The Nutrient Requirements of Target Species

Priority species: *Tilapia, catfish, and shrimp*

Target countries: *Tanzania, Senegal, Sri Lanka, Vietnam, and Ecuador*

Tilapia and catfish

Tilapia and catfish at the post-juvenile stage are omnivorous fish species capable of utilizing relatively large percentages of cooked starch as an energy source, in contrast to carnivorous species like salmonids, sea bass, and grouper. Nonetheless, fry and fingerling tilapia and catfish grow best when they are fed high-protein, low-carbohydrate feeds, similar to starter feeds for salmonids. Their digestive systems develop as the fish grow, as does their capacity to utilize carbohydrates. Feeds used in commercial tilapia production follow the recommendations for fish at various life stages shown in table S3 below.

TABLE S3: Recommended percentages of proteins, lipids, and carbohydrates in tilapia feed

Production Stage	Weight range (g)	Proteins (%)	Lipids (%)	Carbohydrates (%)
Fry	<1.0	40–45	10	10
Fingerling	1–10	35–40	12	10
Juvenile	10–25	32–35	15	15–25
Post-juvenile	25–200	30–32	15	25–35
Adult/Grow-out	>200	28–30	15	35–40

Source: FAO (n.d.-c); NRC (2011)

Note: Other dietary components, such as water, fiber, ash, minerals, and other non-nutritive compounds, contribute to the total mass but are not included in these macronutrient percentage breakdowns.

Several farmed fish species are commonly referred to as “catfish,” including channel catfish (*Ictalurus punctatus*), North African catfish (*Clarias gariepinus*) and striped catfish (*Pangaslanodon hypophthalmus*). All are freshwater species and share many characteristics, including being opportunistic predators that consume a range of prey such as other fish, amphibians, reptiles, birds, and insects. They also consume aquatic plant material. At all growth stages, high-protein feeds (about 40 percent) support the highest growth rates (table S4).

TABLE S4: Recommended percentages of proteins, lipids, and carbohydrates for channel, North African, and striped catfish to achieve the highest growth rates

Production Stage	Weight range (g)	Proteins (%)	Lipids (%)	Carbohydrates (%)
Larvae stage	<0.5	55	9	21
Nursery stage	0.5–10	50	9–11	21
Grow-out stage	10–1000	40–42	11–17	26–32

Source: FAO (n.d.-c.)

Note: Other dietary components, such as water, fiber, ash, minerals, and other non-nutritive compounds, contribute to the total mass but are not included in these macronutrient percentage breakdowns.

Lower levels of feed protein are used in the commercial production of channel catfish because protein utilization is higher at these lower levels (28–35 percent), and the economic feed conversion ratio (eFCR) is lower. For North African catfish and striped catfish, protein levels in commercial feed are in the 38–43 percent range. It is important to note that the optimum dietary protein level for grow-out catfish feeds varies with several factors, including the source and quality of the protein ingredients, the energy level in feeds, feeding level, and the availability of natural feed in rearing ponds. Economic considerations partly dictate protein levels in commercial feed formulations because the optimal economic feed conversion ratio are typically reached with feed protein levels that are lower than those that support maximum growth.¹

Essential nutrient requirements

With a few exceptions, the optimal levels of essential and non-essential amino acids in feeds for tilapia and catfish are not precisely known, but current estimates appear to be sufficient to support rapid fish growth at all stages of production (tables S5 and S6). Starch is the storage form of energy in terrestrial plant seeds, nuts, berries and tubers, and is also least expensive energy source for animal and fish feeds. Crude fiber has limited energy value for fish; excess levels dilute the energy content of feeds and increase feces production, reducing water quality in ponds. Crude fiber should not exceed 10 percent of the feed, and even lower levels are recommended in feeds for fry and fingerling tilapia.

The nutritional benefits and doses of vitamins and essential minerals have been researched, and some tentative nutritional requirements have been established for some fish species. Vitamin and mineral premixes are typically included in tilapia and catfish feeds, although practical feed formulations for tilapia and catfish can supply enough levels of these nutrients to support optimum fish growth if some natural food is also present in the ponds.

¹ An analogy from transportation is that a car engine does not attain its highest fuel efficiency when attempting to achieve maximum acceleration or maximum vehicle speed. Attaining maximum acceleration (analogous to maximum fish growth rate) or maximum speed (analogous to maximum fish size) is usually not fuel-efficient.

TABLE S5: Estimated essential amino acid requirements of Nile tilapia (percentage of diet) at three production stages

Amino acid	Fry/fingerling	Juvenile/post-juvenile	Adult/grow-out
Arginine	2.4	1.8	1.6
Histidine	1.1	0.84	0.77
Leucine	1.8	1.3	1.2
Isoleucine	1.9	1.5	1.3
Lysine	2.6	2.0	1.8
Methionine	1.3	1.0	0.9
Phenylalanine	1.6	1.2	1.1
Threonine	2.0	1.5	1.4
Tryptophan	0.05	0.04	0.03
Valine	1.6	1.2	1.1

Source: Furuya et al. (2023); Nguyen, Salem, and Davis (2022)

TABLE S6: Essential amino acid requirements of channel, North African, and striped catfish (percentage of protein) during the grow-out stage

Amino acid	Channel catfish	North African catfish	Striped catfish
Arginine	4.3		
Histidine	1.5	1.4	
Leucine	3.5	4.9	
Isoleucine	2.6	4.5	
Lysine	5.1	4.5	5.35
Methionine + cystine	2.3	3.2	2.67
Phenylalanine	5.0	4.6	
Threonine	2.0	2.04	
Tryptophan	0.5	2.6	
Valine	3.0	2.1	

Source: Pantazis (1999)

Feed formulations for catfish at the fry/fingerling stage differ from the formulation for the grow-out stage. Grow-out feeds, which account for more than 95 percent of the total feed used during a production cycle, are formulated to maximize the economic feed conversion ratio (eFCR)—that is, the unit cost of feed fed divided by the unit value of the harvested yield.

Grow-out feeds for catfish contain little or no fishmeal; protein is provided by soybean meal and processed land animal proteins. In Southeast Asia and Africa, energy is supplied by high-starch ingredients such as broken rich and maize. These ingredients constitute about 40 percent of the feed, protein ingredients constitute 45 percent, and the remaining 15 percent is comprised of vitamin/mineral pre-mixes, lipids, and supplements.

Shrimp

Two species of shrimp account for most global farmed shrimp production: whiteleg shrimp (*Litopenaeus vannamei*) and giant (or black) tiger prawn (*Penaeus monodon*). Whiteleg shrimp represents more than 80 percent of global shrimp production, while giant tiger prawn represents less than 10 percent. The two species have similar nutritional requirements; both require 10 essential amino acids and behave like omnivorous fish species in that they can utilize cooked (gelatinized) starch as a dietary energy source. Like farmed omnivorous fish species such as tilapia and catfish, high levels of dietary lipids reduce growth.

If shrimp are reared in semi-intensive systems, ponds are typically fertilized in advance of stocking to stimulate a plankton bloom that serves as a supplemental food source during the first few weeks. In intensive ponds, high-quality starter feeds are offered that contain all essential dietary constituents to support the rapid growth of healthy shrimp. When juvenile shrimp reach about 1 gram in weight, they can accept pelleted grow-out feed.

Shrimp are not typically surface feeders. Rather, they search for feed at the bottom of ponds, locating feed through their sense of smell. Thus, it is important that pelleted feeds are water-stable and that feed pellets contain ingredients that release attractant compounds. Marine ingredients, especially invertebrate meals such as squid meal or krill meal, are particularly effective attractants. Insect meal may also function as a shrimp attractant, but further research is required.

In addition to protein (amino acids) and dietary energy sources (lipids and carbohydrates), shrimp require vitamins, minerals, and essential fatty acids. Practical feeds contain vitamin/mineral premixes that ensure that feed micronutrient levels exceed required levels.

Typical ingredients

A major emphasis of research on shrimp feeds is the substitution of marine proteins such as fishmeal with vegetable ingredients and rendered animal proteins. A survey of practical feed formulations used by commercial shrimp feed manufacturers indicates that, besides fishmeal and fish oil (or sometimes squid oil), the feeds typically contain soybean meal, poultry byproduct meal, wheat, lecithin, pellet binders, attractants such as crab meal, squid liver meal, krill meal or fish solubles, and vitamin/mineral premixes (Center for Responsible Seafood, 2023). Some feed producers employ other additives, such as probiotics, toxin absorbers (clay), or immunostimulants.

TABLE S7: Recommended percentages of proteins and lipids in shrimp feeds

Production stage	Weight range (g)	Protein (%)	Lipid (%)	Carbohydrate (%)	Cholesterol (%)
Post-larvae stage	>0.1–0.2	35–40	6–8	<25	0.15–0.25
Juvenile/ grow-out stage	1–40	30–35	6–8	25–30	0.1–0.2

Source: FAO (n.d.-b); NRC (2011)

TABLE S8: Estimated essential amino acid requirements of Tiger shrimp (percentage of diet) at two production stages

Amino acid	Post-larvae (PL)	Juvenile/grow-out
Arginine	unknown	2.2
Histidine	0.8	0.8
Leucine	1.7	2.1
Isoleucine	1.0	1.3
Lysine	unknown	2.0
Methionine	0.9	0.9–1.0
Phenylalanine	1.4	1.5
Threonine	1.4	1.4
Tryptophan	0.2	0.3
Valine	1.35	1.5

Source: FAO (n.d.-b)

TABLE S9: Inclusion rates of key ingredients from eight commercial manufacturers of shrimp feed in Asia and the Americas

	Feed manufacturer							
	1	2	3	4	5	6	7	8
Fishmeal and marine products	24%	5%	26%	22%	14%	16–22%	7–22%	21%
Soybean meal	25%	46%	35%	40%	30%	0%	25–40%	32%
Wheat products	33%	30%	30%	17%	39%	30–33%	25–40%	20%
Rice (e.g., byproducts)	8%	0%	0%	4%	0%	0%	0%	7%
Processed animal proteins (e.g., poultry meal)	2%	11%	10%	12%	10%	0%	5–15%	0%

Source: The Center for Responsible Seafood (2023)

Appendix 3: Market Potential and Production Models of the Insect Meal Industry: Insights from Case Studies and Emerging Trends

Industry status and case studies

The current state of the industry

Several insect meal companies have been able to obtain significant funding. Collectively, the largest companies have raised hundreds of millions of dollars in recent funding rounds, including from corporate feed companies. For example, in its Series D fundraising round in 2023, to expand capacity, insect producer Innovafeed raised \$250 million, with feed producers ADM and Cargill each investing in the round (Crunchbase, 2024). Similarly, Protix raised \$60 million from the protein-focused food company Tyson Foods.

The largest insect meal companies are primarily based in Europe and North America. They are capital-intensive facilities that process approximately 10,000 to over 100,000 metric tons of raw materials annually to produce insect-based products, with a capex intensity of about \$200 million per 20,000 metric tons of capacity (Ynsect, 2024). They include Innovafeed (based in France), Ynsect (France), and Protix (the Netherlands). The three biggest producers have collectively raised over \$1 billion in capital to fund capacity growth. Additional facilities are expected to be built in the US and Europe, but with no current announced plans to expand to the Global South.

Numerous other companies have established insect meal production facilities in tropical climates, including the target countries of this report. They include Entobel in Vietnam, Nutrition Technologies and Entofood in Malaysia, Arthro Biotech in India, Pronuvo in Costa Rica, a joint venture of Lukmar and Mutatec in Ecuador (in pilot phase), Limuru, the Bug Picture, Regen Organics and the Insectary in Kenya, Rural Aquaculture Development in Uganda, and Chanzi and BioBuu in Tanzania (Tanga and Kababu, 2023). This list, not exhaustive, shows the global breadth of companies beginning to operate in the sector, with companies ranging from small on-farm businesses to industrial-scale enterprises. Entobel in Vietnam has a current capacity of roughly 10,000 MT a year (Entobel, 2024). It is currently raising Series C funding to expand capacity in Vietnam, Malaysia, and Indonesia, and notes that the availability and consistency of feedstocks is crucial to its success (Entobel, 2023).

Loopworm, an Indian-based insect meal company, described how it developed rapidly in just three years (company product manager, personal communication, July 17, 2024). Founded in 2019 by two recent graduates of the Indian Institute of Technology, the agritech and biotech company produces insect meal and oil from silkworm larvae for feed manufacturers. In 2022 Loopworm raised \$3.4 million in seed funding. As of early 2025, it produces 6,000 MT of insect meal a year, and aims to produce 300,000 MT a year by 2030.

The production facility is in Bangalore, the home of India's beer-brewing industry, providing large quantities of brewer's spent grains as feedstock for the larvae. Bakery waste is also readily available. Loopworm's products have found markets in the pet food and aquaculture (shrimp) industries. In the future, the company will seek opportunities to export dry meal to Southeast Asia and Europe if regulatory frameworks are developed.

TABLE S10: A selection of insect meal companies

Company	Species	Headquarters	Production facilities	Current end market	Funding
Ynsect	Mealworm	France	FR, NL, US	Poultry, pigs, aquaculture, pet food	\$625 million
Loopworm	Silkworm pupae meal	India	India	Poultry, pet food, aquaculture,	\$3.4 million
Innovafeed	BSFL	France	FR, US	Poultry, pigs, aquaculture, pet food	\$450 million
Protix	BSFL	Netherlands	NL, US	Poultry, pigs, aquaculture, pet food	\$227 million
Entobel	BSFL	Singapore	Vietnam	Aquaculture, livestock	\$33 million
Regen Organics	BSFL	Kenya	Kenya	Poultry	<i>TBD</i>
Mutatec	BSFL	France	FR, Ecuador	<i>n/a</i>	<i>TBD</i>
ProNuvo	BSFL	Costa Rica	Costa Rica	Poultry, pet food	\$2 million
F4F	BSFL	Chile	Chile	Pet food	\$4 million
Chanzi	BSFL	Tanzania	Tanzania	Poultry	<i>n/a</i>
RAD	BSFL	Uganda	Uganda	Aquaculture	<i>n/a</i>

Sources: Company websites; Crunchbase (2024); Business Wire

Production model case studies

Table S11 summarizes case studies of three companies—ProNuvo, RAD, and Regen Organics. The table compares various features of their production models—including feedstock, production method, environmental, social and governance (ESG) characteristics, success factors and challenges, and future plans.

TABLE S11: Three insect meal producers: Comparing the centralized, decentralized, and combination production models

	Integrated model	Hub-and-spoke model	Combination model
Company	ProNuvo	RAD	Regen Organics
Location	Costa Rica	Uganda	Kenya
Production model	Centralized, industrial-scale insect meal production, leveraging a mix of automation and manual labor	Centralized hatchery that sells to small-scale decentralized aquaculture farmers for direct use as feed in their ponds	Centralized hatchery that Regen uses not only for its own industrial-scale insect meal production but also to sell wholesale to small-scale, decentralized insect producers, often paired with land animal protein production

	Integrated model	Hub-and-spoke model	Combination model
Type of feedstock	Fruit byproducts from large-volume commercial sources	Pre-consumer waste from low-volume distributed sources; agricultural waste	Pre- and post-consumer waste from low-volume distributed sources; agricultural waste
Main takeaways	Effective model when there is a clear and sizable mature end market, as it allows for economies of scale The specific country context should be taken into account when considering automation vs. manual processes (e.g., labor costs, energy infrastructure, access to capital for upfront costs)	Effective model for smallholder farmers facing high costs of commercial feed Proves that direct insect use in feed is possible and can reduce both costs and the environmental footprint of insect-based ingredients	Decoupling breeding (separating larval rearing from adult colony maintenance) reduces barrier to entry for small-scale producers Shows that post-consumer waste can be used successfully as feedstock Organic waste collection infrastructure is crucial to ensuring the availability of enough feedstock

Case Study 1: ProNuvo (Costa Rica)

Overview: Founded in 2018, ProNuvo is a Costa Rican-based company that produces black soldier fly larvae on an industrial scale. ProNuvo has centralized commercial operations that cover the full production cycle including breeding, hatching, rearing, and processing. Its end products are whole dried insects, defatted insect meal, insect oil, and frass. Today, ProNuvo primarily sells to the pet food market, which can pay higher prices, but the company plans to expand into aquaculture, including feed for shrimp, tilapia, and *Pangasius* species, once it reaches greater economies of scale.

Feedstock: ProNuvo's feedstock is primarily banana peels, a high-volume agricultural byproduct in Costa Rica, purchased from local banana puree producers. ProNuvo selected this feedstock because of its high availability, consolidated procurement, inexpensive cost, strong nutritional profile, and less fibrous composition. ProNuvo's facility is located near banana puree producers, reducing transport costs and associated emissions. Using one reliably available feedstock also ensures a consistent, high-quality BSFL end-product for use in aquafeed.

Production: ProNuvo has taken advantage of its strategic location in Costa Rica, a hot, humid climate to which black soldier flies are native. ProNuvo manages its own onsite hatchery. Once hatched, the eggs are transferred to larvae-rearing stations where banana peels are fed to the larvae, which consume twice their own weight per day. The stations use little energy, leveraging the natural light, humidity, and temperature of the tropical climate. Extractor and injector technology that supply air flow throughout the stations account for most of the energy used.

FIGURE S1: Centralized, integrated, industrial-scale insect meal production



Source: Russo (2024)

When the larvae are fully grown (in roughly 15 days), they are dried in large ovens fueled by natural gas. Part the product is sold directly as whole dried larvae; the rest is further processed in a defatting compressor. ProNuvo also sells the frass the larvae produce as fertilizer, further strengthening the circularity of the production process.

At each step, ProNuvo has selected less capital-intensive production processes, leveraging local labor rather than expensive automation. For example, employees manually shovel and carry materials such as feedstock, larvae, and frass. The advantages of this more labor-intensive production approach include lower cost (in certain countries), lower energy usage, job creation potential, and more rapid scaleup without the need to raise as much capital upfront as fully automated facilities. Simpler technology with a higher labor component can also be advantageous in a country with unstable electricity supply (though this does not apply to Costa Rica).

By contrast, many companies in the Global North have production facilities that are nearly entirely automated. Production capacity tends to be higher, as are upfront costs and energy usage.

ESG considerations: ProNuvo's feedstock is an otherwise underutilized product—fruit and vegetable byproducts such as banana peels. These byproducts have limited commercial value and may otherwise be buried in landfills, releasing methane via anaerobic digestion. By converting these carbon sources into food, ProNuvo is promoting the circular economy and upcycling organic waste. Its location and factory processes also enable lower energy consumption than its European or American counterparts. The social benefits of ProNuvo's model include the creation of more than 140 well-paying jobs in an otherwise low-income area of Costa Rica. ProNuvo is planning to, but has not yet, conducted an LCA.

Success factors: Several success factors have enabled ProNuvo to grow. Two in particular stand out: its tropical location, which reduces energy needs, and its long-term agreements with reliable high-volume suppliers of cheap, nutritious organic byproducts.

Challenges: ProNuvo's plans to sell to aquafeed companies faces similar challenges as other insect meal companies: First, insect meal still costs quite a bit more than fishmeal. Increasing scale will be critical to becoming price-competitive. Scaling up is also critical for reaching the volumes needed by large aquaculture feed mills in more mature markets, for example, Ecuadorian shrimp producers. Second, large companies in mature aquafeed markets expect to conduct extensive in-house testing before certifying and approving a feed source. To scale up, ProNuvo is expanding into other countries in the region, such as Ecuador, and standing up additional capacity, targeting pet foods and other premium markets, and building relationships to enter the aquafeed market. The target countries of this report are likely to face similar challenges when they are ready to develop into more mature insect meal markets.

Future: In 2024 ProNuvo secured a \$2 million investment from International Finance Corporation (IFC) to complete the construction of a 4,000 MT per year insect feed plant in Guápiles, Costa Rica (Feed Strategy, 2024).

Case Study 2: Rural Aquaculture Development Program, Uganda

Overview: Founded in 2020 in Uganda, the Rural Aquaculture Development (RAD) program, initiated by Tim Messeder and Pauson Mpabukire, is a fish farm hub-and-spoke model that empowers smallholder farmers by providing them with access to innovative aquaculture technologies and services, including black soldier fly larvae for direct use as feed. The program sells its own tilapia and also provides aquaculture producers with fingerlings for rearing, live BSFL for use as feed, frass, and catfish (The Fish Site, 2023a). RAD manages the full production cycle of its cultured fish, including breeding, hatching, rearing, and processing.

Feedstock: RAD's feedstock primarily consists of mulched organic waste sourced from local markets and green manure from a local slaughterhouse. It employs individuals to collect organic waste from these surrounding urban areas (Alando, 2023).

Production: The initial RAD hub manages its own four-pond tilapia hatchery and three-pond production section. RAD both sells its fingerlings to smallholder farmers and keeps a portion for its own production. It also has its own black soldier fly production unit to rear larvae, which includes a fly hatchery. To feed its fish, RAD uses both live BSFL and commercial feed. RAD uses roughly one-third BSFL (Alando, 2023). Email correspondence with an involved scientist indicates that RAD has successfully substituted two-thirds of compound feed for live BSFL. The use of BSFL is less expensive than compound feed, and using live larvae instead of insect meal further reduces costs since grinding and defatting equipment are not needed. After harvesting its product, RAD sells its fish through a network of sellers (Alando, 2023).

The RAD hub supports about 50 surrounding “cluster” farmers, who manage one or two ponds each (The Fish Site, 2023). RAD provides an array of supportive services to help local smallholder farmers, including its hatchery, black soldier fly production, fish seller network, and free advisory services. In its hatchery, RAD sells fingerlings to local farmers, who can then rear these fish, and RAD also provides live larvae to these farmers to help feed their fish for optimal growth (Alando, 2023).

RAD’s fish seller network includes ice machines and vehicles to keep fish fresh and transport them to markets. The company sells its own tilapia while also purchasing fish from smallholder farmers, distributing through its own cold chain. Additionally, RAD provides training and advisory services to help community members start or improve their fish farms.

ESG considerations: RAD promotes environmental sustainability by using agricultural byproducts that would otherwise go to waste. This reduces methane emissions from decomposing organic matter and promotes a circular economy. The direct use of BSFL in fishponds, rather than further processing them into insect meal, also reduces the emissions impact of the feed ingredient. Finally, the program has provided more than 200 people with jobs (Alando, 2023). It is unknown whether RAD has conducted an LCA for their insect production.

Success factors and challenges: Success factors include the program’s strategic location, access to abundant, low-cost feedstocks, and partnerships with local suppliers and distributors. Government support and favorable regulations have also facilitated its growth. But challenges remain, such as scaling operations to meet increasing demand, accessing larger markets, and the high cost of commercial feed—which strains small-scale farmers’ budgets and reduces profit margins.

Future: RAD’s goal is to replicate its hub-and-spoke model by setting up new hubs in other African regions and onboarding more farmers (The Fish Site, 2023). ThinkAqua, a UK-based nonprofit, will support this expansion into eastern and southern Africa (The Fish Site, 2023).

Case Study 3: Regen Organics, Kenya

Overview: Founded in 2014 in Nairobi, Kenya, Regen Organics (formerly Sanergy) produces black soldier fly larvae (BSFL) on an industrial scale and sells insect meal to feed and pet food producers. It also distributes fly eggs wholesale to other insect meal producers. Regen Organics’ products include whole BSFL, BSFL meal, eggs to other insect farms, fertilizer from thermophilic co-composting, biofuel briquettes from frass, and carbon credits.

Feedstock: Regen Organics uses a variety of organic waste sources as feedstock, including pre-consumer waste such as from vegetable markets and avocado skin, post-consumer waste from central kitchens, and even managed sanitation waste. Given Kenya’s challenged waste management system, Regen Organics has developed a network of waste collection vehicles under its own brand name, Citifresh, to gather and transport waste to its facility. To build reputation, Citifresh treats its waste suppliers as “customers” of its collection services.

In the center of Nairobi, Regen's logistics hub sorts incoming waste to remove and recycle plastics and other non-organic wastes, before sending on the remainder to its main facility south of the city. Given the wide diversity of its feedstock sources, some highly seasonal, Regen Organics has developed a quality-control process to balance the feedstock's nutritional profile by adjusting the inclusion rates of different sources to create in a range of "recipes" to ensure a consistent, high-quality end product regardless of what comes in. This nutrient balancing process allows the company to achieve a minimum of 40 percent crude protein content of BSFL.

Production: Regen Organics is an end-to-end producer of BSFL, beginning with its large hatchery. The facility's location in a naturally warm and humid climate supports optimal conditions for BSFL growth, leading to better yields without the need for expensive climate control, and facilitating higher egg production rates at lower energy costs than facilities in colder climates. After breeding the flies to lay eggs, Regen keeps some of the eggs for its own production of BSFL and sells the rest wholesale to other BSFL producers, exporting some abroad, for example, to farmers in Tanzania.

These downstream insect farmers are often livestock and poultry producers that use insect meal to upcycle their on-farm agricultural waste such as manure. But the eggs could also be sold to aquaculture farms for feeding live insects to fish like tilapia. In all these cases, Regen's centralized hatchery lowers the barriers to entry for its wholesale customers by reducing the costs, equipment needed, and level of expertise required for these downstream producers.

The breeding and hatching steps of the rearing process are the most technically challenging to optimize, so having this step centralized can be an invaluable benefit to the market. Centralized hatcheries can selectively breed flies to enhance larvae size, egg count, and other key attributes, which would not be possible in smaller or less sophisticated facilities.

For its own production of BSFL, Regen Organics rears its hatched larvae on a carefully balanced feedstock made from processing 60,000 tons of diverse organic waste annually. After the larvae are full-grown, they are devitalized, dried in large ovens powered in part by solar and renewable energy (for example, biogas from organic waste), and either sold whole or ground to be sold as insect meal.

ESG considerations: Regen Organics' feedstock is sourced from diverse organic wastes, most of which would end up in landfills or left untreated and would release methane. Regen Organics' 5-year environmental goals include offsetting 50,000 tons of carbon and methane emissions in CO₂eq, and safely removing 1 million tons of organic waste annually. The company's use of post-consumer waste and sanitation waste also upcycles otherwise low-value resources.

The collection and productive use of this waste also reduces the risk of disease from undermanaged sanitation waste. Besides providing more than 200 direct jobs on its site, Regen Organics' egg sales support numerous smaller producers.

Finally, the organic fertilizer produced from the remaining frass is a valuable input for smallholder farmers. The company's five-year goals include supporting over 250,000 farmers to improve their livelihoods through regenerative agriculture and creating 10,000 new green jobs. Regen Organics has conducted an LCA of their insect meal business.

Success factors and challenges: One success factor is Regen's location in Kenya, which has ample underutilized organic waste and a favorable regulatory framework for post-consumer waste use and overall insect meal production. A second factor is Regen's decision to build its own network of waste collection vehicles. While a significant investment, it unlocked a low-cost and reliable source of organic substrate. A third factor is the support it received from nonprofit research organizations like the Nairobi-based International Centre of Insect Physiology and Ecology (ICIPE), which conducts research and training on insect rearing. Fourth, Regen benefited from equipment and expertise from the mushroom industry. Regen was able to retrofit mushroom industry equipment in its facilities, and use production processes similar to those used for mushrooms.

Fifth, in addition to the primary product, the BSF production process generates byproducts such as frass and residual fats that can be sold for additional revenue without requiring extra inputs. So far, the most significant are sales of carbon credits resulting from the collection and repurposing of the organic waste and sales of organic fertilizers to farmers.

Future: Regen Organics expansion plans, including building a second facility in Kenya, working regionally, and expanding into Southern Africa and Asia.

Market and employment potential in selected countries

Insect meal has significant growth potential in this report's countries of focus. Several already have insect meal companies. To understand the market's potential, aquafeed demand was modeled for two focus countries, Tanzania and Ecuador, as examples of emerging and mature aquafeed markets. Aquafeed demand, and the capacity of ingredients to meet this demand, were projected based on tilapia and catfish production in Tanzania and shrimp production in Ecuador. (For additional information, please see the partner Excel model of this report.)

Workforce considerations

The number of employees at an insect farm varies with its scale and degree of mechanization/automation. A small household or community insect farm may require 1–15 part-time workers producing 1–5 MT of insect meal a year (5–20 kg/day). At this scale, worker specialization is not required; any worker can do any production task.

Larger-scale commercial enterprises have more distinct production steps that require more specialized knowledge and often more employees, depending on the level of automation. Kenyan companies Regen Organics and Ecodudu estimate that production systems with lower levels of automation require 815 hours of labor to produce 1 metric ton of black soldier fly larvae (Abro et al., 2020). Assuming a roughly 50-hour work week, this implies that every 3 metric tons of insect meal produced has the potential to add one direct, full-time job to the industry. Assuming that labor scales linearly with production, an operation producing 1,000 MT annually could require more than 300 full-time employees.

For highly automated facilities, the number of workers needed per unit of output can be far fewer. For example, in Vietnam, Entobel's roughly 150 full-time employees produce 10,000 MT of insect meal a year (Entobel, 2023), implying that one employee can produce more than 50 MT a year (versus 3 MT per employee in Kenya).

Youth and female employment

The gender distribution in insect rearing varies by region, but all around the world, women express strong interest in insect farming. For example, in East Africa, women composed over 70 percent of people hired by BSF farming enterprises (Tanga et al., 2021). Of the 23 staff who were employed by Tanzania-based insect meal company, Chanzi, at its first site, 90 percent were youth and 50 percent women (FINCA, 2024).

In rural areas, household or small community-owned insect-rearing operations can provide women with self-employment opportunities, or provide youth and women with direct employment. This is a particularly viable entry point for women, who have historically not been given equitable opportunities for employment or business ownership.

Given the sector's limited capital, land, and water requirements in small-scale production, barriers to entry for women are relatively low. Small-scale household insect-farming enterprises can be integrated into existing agricultural operations, allowing women to work from home and enabling flexible work schedules. Household insect-farming can either create an additional revenue stream for smallholder farmers who decide to sell the larvae/insects, or be used as feed for animals being raised by the household or community.

Youth and women also have the opportunity to work at larger commercial facilities. In this case, employees can gain valuable skills in a structured business environment, including agriculture, business management, and sustainability practices. These are transferable skills that enhance overall employability.

Some countries have allocated funds to support women-owned and youth-owned small businesses. For example, Tanzania has a decentralized system in which municipal councils allocate 10 percent of revenue to support women and youth in small- and medium-size enterprises (Lukanga, 2022).

Market potential in selected countries

Aquaculture growth estimates for Tanzania and Ecuador vary in the literature, but the growth rate and corresponding feed demand are generally expected to be in the low single digits (FAO, 2024b). In both Tanzania and Ecuador, insect meal is a promising feed ingredient—its inclusion in feeds could incrementally expand the supply of aquafeed and serve as a protein-rich and palatable alternative to traditional ingredients.

Two primary insect production models were explored: the centralized production model and the hub-and-spoke model. The centralized model depicts end-to-end insect meal production in a facility that includes a hatchery, rearing station, and processing equipment. Based on market participant interviews, it was modeled using a facility construction cost of \$12 million and a 3-year ramp-up period to reach full production capacity, at which point the facility will produce 4,000 MT per year.

The hub-and-spoke model depicts a centralized hatchery that sells 5-day old larvae to a network of smaller operations to rear on local organic waste materials for later use in aquafeed or other applications. Regen Organics and the Rural Aquaculture Development program use models similar to this, with both companies maintaining their own insect-rearing stations at centralized facilities. This model depicts construction of a hub facility and 200 small “spoke” farms, each producing 15 MT of insect meal a year after a 5-year ramp-up period. Initial construction is estimated to cost \$7.5 million.

Employment potential in selected countries

The insect meal industry in Tanzania and Ecuador offers meaningful employment opportunities.

In the model, it is estimated that, by 2035, an insect meal industry in Tanzania built around two large hubs, producing 6,000 MT of meal a year, could provide about 2,000 direct jobs. Those jobs would earn about \$2.3 million in wages, based on the typical wages in the industry and accounting for Tanzanian income levels (Abro et al., 2020; World Bank national accounts data, 2024).

In Ecuador, building four centralized insect meal facilities, equivalent to 16,000 MT per year, would create roughly 800 direct jobs (ITA, 2022), fewer than in Tanzania because centralized facilities require fewer employees with more automation based on operational models drawn from existing companies. Using wages typical for similar agricultural work in Ecuador, the 800 employees would earn about \$5.1 million a year.

Key elements of insect meal industry development

Hub-and-spoke model

One approach employed in many countries to facilitate the expansion of insect meal production is the hub-and-spoke model, where an emerging-stage insect meal business—the “hub”—contracts with several local producers—the “spokes”—to grow larvae that it supplies them with. The emerging business offers technical support and handles post-harvest larvae processing (blanching, lipid extraction, drying, packaging) and marketing the final products.

Both the hub and the spokes will, in turn, require access to reliable suppliers of substrate to maintain their feedstocks. Given the dispersed distribution of the hub-and-spoke model, good transportation infrastructure is paramount, as is dependable energy sources to power the hub facility’s hatchery and processing operations.

As discussed in the prior sections on the decentralized, emerging, and mature stages of development, the growth of an aquaculture industry is typically influenced by several factors: the availability of affordable accessible funding; adequate infrastructure and equipment; a skilled and well-trained workforce; reliable and good-quality inputs of feedstock and breeding populations; strong and steady market demand; and a supportive regulatory framework. Many of those factors earlier discussed apply equally to the development of an insect meal sector. This section therefore focuses only on aspects unique to that industry.

Evolving from the nascent toward the emerging stage

Developing and running an insect meal sector at a nascent, decentralized stage requires minimal investment in equipment and facility construction. Small-scale household or community production requires little more than feedstock, trays or racks with screens or nets, and a source of insect eggs or neonate larvae. Expanding production in a nascent insect-farming business can be accomplished simply by scaling up the insect-growing system and the harvesting/processing system. Additionally, the regulatory environment is unlikely to have much of an influence in a decentralized nascent sector if offtake occurs where the insect production take place, or if markets remain local.

Until a nascent sector begins to evolve into the emerging stage, where insect and aquafeed producers start demanding a consistent supply of insects or larvae—which requires establishing a consistent breeding population and a consistent feedstock stream—a sector comprised of small, decentralized systems can therefore expand with minimal requirements in inputs, equipment, and workforce, and few or no regulatory constraints. In West Africa’s nascent-stage insect meal sectors, for example, the lack of consistent, reliable, suitable sources of feed for larvae (substrates) can be a limiting factor that constrains expansion into the emerging stage (Tanga et al., 2021).

In East Africa, by contrast, the constraint is primarily that of knowledge. There is high interest in insect farming but a general lack of knowledge and knowledge-delivery systems such as training or production manuals for nascent enterprises. The knowledge constraint is not limited to East Africa, however. Surveys show that African farmers are willing to farm insects yet lack knowledge on how to go about it—for example, understanding the production cycle and what humans and animals would gain from it.² Additionally, few organizations or institutions are able to convey this knowledge, and there are few to no formal training opportunities or producer groups that might facilitate informal peer-to-peer learning (Tanga et al., 2021). Similarly, the regulatory sector in Africa provides little guidance on insect production methods or the maintenance of safe hygienic conditions. Industry development has therefore been a challenge.

² For example, there is a lack of understanding of the insect production cycle and the nutritional gains it can bring to humans and animals.

In turn, the lack of regulatory guidance and minimal technical knowledge of the insect-farming sector significantly limits access to finance, and for many farmers with limited purchasing power, there are very real cost constraints especially on expanding operations to produce the reliably consistent volumes that are needed for transformation into an emerging-stage sector (Tanga et al., 2021). But even at the purely nascent stage, surveys show that many low-income, smallholder farmers would like to expand their insect production—or even just begin—but they are not able to because of a lack of finance to defray the startup costs or the cost of inputs (eggs, feedstock, hardware), or because of access barriers. This, in short, underscores the systemic financing gap that affects both sides of the agricultural value chain and reinforces the need for holistic interventions that address all significant structural constraints nearly simultaneously.

For example, in Madagascar, several interviewed farmers said they had to travel more than 50 kilometers just to buy insect eggs. But Tanga et al. (2021) have observed that when farmers in Kenya had greater access to finance, many of these input and scaling constraints disappeared. As nascent insect production sectors attempt to expand, whether by scaling up decentralized systems, or striving to meet the demands of emerging-stage aquaculture, the transition to centralized production eventually becomes necessary to ensure consistent supply, quality control, economies of scale, and operational efficiency.

But this shift does not happen abruptly. It is driven, or impeded, by market pressures, the pace of technological adoption, the rate of investment in infrastructure, the presence or absence of parallel developments in related sectors that have backward or forward linkages with the insect meal sector, and the entrepreneurial orientation and energy of actors in the sector. For example, when small-scale producers or early-stage enterprises begin to grow and supply larger buyers such as aquafeed manufacturers, revenues rise but they also face increasing demands for standardized meal compositions, reliable supplies of larval feedstock, more rigorous hygiene standards, and traceable processing methods.

To meet these requirements, the producers have to start incorporating specialized breeding systems, mechanized harvesting, and controlled-environment rearing facilities—the core features of centralized production. This evolution toward centralization often passes through intermediate steps such as cooperative farming models or semi-centralized processing hubs, before fully transitioning into large-scale, industrial operations.

The following section explores how insect production systems adapt as they move from nascent toward emerging-stage centralized production.

Moving toward emerging-stage centralized production

Once an aquaculture sector begins to expand and produce at scale, buyers start demanding higher levels of consistency and guaranteed quality from egg, insect, and insect meal producers. In turn, the producers begin to require staff with specialized knowledge to undertake various functions, such as maintaining a breeding colony of adult insects to produce a constant supply of eggs. Scaling up typically requires centralized production of inputs rather than smallholder farmers producing small, on-farm quantities. To operate the automated systems employed in larger-scale, centralized production, the staff also may need to be trained.

In contrast to the small-scale, labor-intensive operations that characterize the nascent stage, where larvae are harvested manually or semi-manually—and often inconsistently—the centralized production systems of the emerging stage introduce a more scalable, more mechanized approach in which the larvae are harvested by mechanical sifting using a simple shaker-screen system that automatically separates the larvae from the frass, and then sorts the frass particles by size. Shaker screens are simple to operate and maintain and relatively inexpensive but they support higher throughput and more standardized outputs—a key step toward commercial scalability.

An emerging-sector insect-rearing business, may also deploy systems that clean trays and then automatically add substrate and larvae. These can be relatively simple conveyor systems where the trays first pass through a washing

and disinfection station, and then are loaded with a precise amount of substrate from overhead tubs operated manually using a simple dosing system. The right number of larvae (determined by weight) are then loaded into the trays and the trays loaded onto racks. When fully loaded, the racks are wheeled into rearing rooms where environmental parameters are controlled and adjusted, if needed.

From emerging-stage toward mature-stage production

At the mature stage, insect farming is not merely the linear expansion of an emerging-stage insect-farming sector but rather the industrialization of insect farming, with all the complexity and logistics associated with any contemporary manufacturing supply and production chain. Although mature businesses do incorporate many elements of an emerging-stage business, those elements—such as pilot-scale rearing systems, species-specific breeding protocols, and basic feedstock trials—are primarily technical in nature, involving scientific, engineering, or procedural innovations rather than scaled logistical or commercial operations. In contrast, mature-stage production encompasses system-level upgrades such as industrial-scale automation, supply chain integration, product standardization, and regulatory compliance infrastructure. The actual production components of a mature, high-productivity, insect farm are typically designed and constructed *de novo* with efficiency as the goal and guiding principle. One of the prime objectives is to reduce production costs so that its final products are commercially competitive with standard protein feed ingredients, especially fishmeal. Increased mechanization, automation, integration, and centralization help achieve this goal, but the upfront capital costs of a mature-stage insect-farming enterprise are substantial and may not be achievable everywhere. In many economic contexts, a nascent or decentralized-stage industry, or a centralized but not fully integrated emerging-market industry, is in the short or medium term, the more realistic goal.

Key Takeaways

1. The insect meal industry has **excellent potential for growth both in Tanzania and in Ecuador**; it could contribute up to about 2,000 direct jobs in Tanzania and about 800 in Ecuador.
2. Investment **opportunities in women-owned and/or -led aquafeed companies** and farms are ample.
 - a. Some country governments have allocated funds to support women- and youth-owned small businesses. These models could be expanded through additional investment.
2. In rural areas, household or small community-owned insect-rearing operations can provide **women with opportunities for self-employment**, or provide direct employment to both youth and women.
3. Opportunities in Africa
 - a. In **West Africa, investment is needed** in reliable and suitable sources of feed for larvae (substrates).
 - b. In **East Africa, there is high interest in insect farming but a general lack of knowledge**, training or guidance, such as standard production manuals for decentralized production enterprises.
 - c. Regen Organics is **planning to expand in Kenya and southern Africa**.
4. Climate and environmental impacts
 - a. Where **feedstock would be considered waste**, the GHG emissions profile can have a **net positive impact** by avoiding the release of methane.
 - b. There **may be significant carbon offsets from the production of black soldier flies** in the Global South, though this has yet to be authenticated.
 - c. The use of organic waste materials can result in a net positive land use impact on the environment.

Appendix 4: Selected Countries with Emerging-Stage Aquaculture

Sri Lanka

Aquaculture industry. Sri Lanka’s aquaculture industry produces about 59,000 MT annually, as of 2022. Production is focused on three species: tilapia (about 26,410 MT in 2022), carp (about 19,393 MT in 2022), and shrimp (about 13,277 MT in 2022). The FAO began reporting Sri Lanka’s tilapia production in 2008, and between 2008 and 2012 it averaged 1,839 MT a year. Production skyrocketed by a factor of 8 in 2013, reaching 14,889 MT, and has continued surging ever since. Whiteleg shrimp production began just in 2020 (2,640 MT) but by 2022 had quintupled (FAO, 2024a).

The explosive growth is due to improved efficiency and methods. Until recently, Sri Lankan hatcheries primarily relied on broodstock from wild-caught black tiger shrimp (*Penaeus monodon*), but these were often infected with white spot syndrome virus, with substantial mortality rates. Now, specific-pathogen-free (SPF) stocks are available, and hatcheries are improving their protocols to produce healthy post-larvae. SPF Pacific white shrimp (*Litopenaeus vannamei*) have also been introduced, led by Taprobane Seafoods. While black tiger shrimp offers the advantage of fast growth to large sizes at low pond population densities, Pacific white shrimp offers the advantage of higher population densities and increased yields, albeit with smaller sizes (Briggs, 2004).

Aquafeed. Sri Lanka currently lacks any significant production of aquafeed, relying instead on feed from India and Vietnam (Chandrasekera, 2024). Sri Lanka’s lack of domestic feed production creates challenges for its shrimp industry as imported feed costs have continued to rise. Farmers have identified the need for more domestic production of shrimp feed, and Taprobane has announced its intention to develop a domestic feed mill for the shrimp industry (Howell, 2022). Developing an aquafeed line or a dedicated mill would reduce costs and improve the competitiveness of the Sri Lankan aquaculture industry.

Ingredients. Although it does not currently produce aquafeed domestically, Sri Lanka produces feed ingredients such as broken rice, rice polish, rice bran, coconut meal, and sesame meal (Sri Lanka Export Development Board, n.d.). Rice is easily Sri Lanka’s largest crop—more than 3 million MT a year (FAS, 2024b). Coconut meal and sesame meal, coproducts of oil production, are relatively high in protein.

Sri Lankan aquafeed could include processed animal proteins. Poultry is a medium-sized, growing industry in Sri Lanka—10.3 kg are produced per capita—and the byproducts could be used in aquafeed production after rendering (FAO, 2023a). As is often done in other emerging aquaculture markets, Sri Lanka could leverage the technology and expertise of the poultry feed industry to further develop its aquafeed and ingredient markets.

Insect meal production is another possibility. Unused organic and agricultural byproducts—including rice bran, rice straw, coconut byproducts, animal waste, and food waste—are all potential sources of feedstock for insect meal (Papanikou and Mavromichalis, 2023; Manurung et al., 2016).

From an environmental and nutrient efficiency perspective, the direct use of suitable byproducts for consumer foods or animal feeds is preferred over indirect processing methods such as converting them into insect meal, because it typically involves fewer resource inputs. However, this is often not possible due to challenges with collection, treatment, and logistics. Collecting and upcycling this unused material as insect meal can have environmental and social benefits. The United Nations Development Programme (UNDP) has partnered with the Government of Japan to produce and install 2,000 home units of BSF-rearing stations in Sri Lanka (UNDP, 2023). This decentralized approach

resembles a hub-and-spoke model, where individual households act as the “spokes” by processing organic waste and cultivating BSF larvae, contributing to a central “hub” that manages processing, distribution, and quality control.

Tanzania

Aquaculture industry. Tanzania has a history of seaweed production and grew 167,378 MT of *Euclima* and *Kappaphycus* in 2022. Aquaculture production of tilapia increased from about 200 MT in 2010 to about 27,651 MT in 2022. In the same period, African catfish production rose from 1 MT to 1,455 MT, peaking at 3,800 MT in 2018 (FAO, 2024a). The emerging tilapia and catfish sectors have high potential for further growth.

The government has made aquaculture a priority and has implemented new policies and processes for setting up new farms (Gatsby Africa, 2022). Aquaculture production in the country includes both semi-intensive and intensive systems. Earthen pond farming—where fish are raised in ponds constructed from natural soil—accounts for 95 percent of production. Cage systems generate only 5 percent, but are growing, especially in Lake Victoria (LVFO, 2023). Tanzania recently opened Lake Victoria for cage farming, and a satellite study found that there were roughly 46 cages as of 2022 (LAT, 2022). According to the records of the Department of Aquaculture, Tanzania had more than 1170 active cages of different sizes by June 2024.

Tilapia makes up roughly 95 percent of Tanzanian aquaculture production, followed by catfish (FAO, 2024a). Several large shrimp-farming projects have been proposed but none have been initiated because of the concerns of local communities and environmental groups to do with the disruption of traditional fishing livelihoods and potential environmental degradation, such as the destruction of vital mangrove forests and water pollution from chemical runoff (Sadek et al., 2002). The World Bank has undertaken projects in Tanzania to scale up sustainable marine fisheries and improve aquaculture management to help resolve such sustainability issues. With proper siting, design, and management, shrimp farming could be worth reconsidering.

Aquafeed. Feed is currently a limiting factor in Tanzania: many fish farmers report that good-quality commercial feed is either unavailable (domestically produced) or prohibitively expensive (imported) (FAO, 2023b). Roughly 80 percent of fish farmers use on-farm feed (Mmanda et al., 2020) consisting of farmed raw materials such as ground maize bran. More than half of compound commercial feed (57 percent) is imported and significantly more expensive (FAO, 2023b).

Production of domestic aquafeed is modest and has ranged between about 540 and 2,673 MT a year over the past several years (Shoko et al., 2022; FAO, 2023b). Additional investments in feed manufacturing capacity will be crucial to the growth of the aquaculture industry. *Opportunities such as joint ventures between global feed mills and regional seafood producers can help unlock capacity.*

Ingredients. On-farm ingredients are primarily locally obtained (Shoko et al., 2022). Feed ingredients include fish meal, insect meal, plant protein meal, and cereal byproducts (FAO, 2023b). Fish meal comes from Lake Victoria sardines, Nile perch frames and offal, prawn head waste, and freshwater shrimp. Insect meal commonly comes from housefly larvae (maggots) and black soldier fly larvae, although these insect meals are not commercially available for aquafeed production (FAO, 2023b). Plant protein meal ingredients include soybean, cotton seed cake, sunflower seed cake, taro leaf, and moringa leaf (FAO, 2023b; Shoko et al., 2022). Cereal byproducts include coconut waste, maize bran, rice bran, wheat pollard and bran (FAO, 2023b; Shoko et al., 2022).

Tanzania has several crops that could be included in feed, such as maize, the country’s highest-volume crop (ITA, 2022). In 2023–2024, Tanzania produced an average of 6.4 million metric tons of corn per annum (FAS, 2024b). The bran of corn is often included in on-farm feed and may also be included in compound feed produced domestically. Tanzania’s second-most produced crop, rice (2.45 million metric tons annually), is a source of byproduct ingredients in aquafeed such as broken rice, rice bran, and rice bran polish (FAS, 2024b).

Insect meal is a potentially significant market in Tanzania. In East Africa generally, including Tanzania, insect meal is already being included in feed for pigs and poultry, and increasingly for fish. Frass, a byproduct of insect production, is being evaluated as an ingredient in catfish, shrimp, and tilapia diets at inclusion levels of 10–30 percent. Frass is primarily used as a fertilizer to significantly improve farm soil health. Raw materials that could be used as insect feedstocks include fish offal, animal manure, and food waste—for example, at public food markets in Dar es Salaam. While this could be logistically challenging, it could be modeled after Regen Organics’ organic material waste-collection network in Kenya for BSFL production.

Seaweed is in the early stages of being considered for incorporation in aquafeed at high inclusion rates (Mwendwa, Wawire, and Kahenya, 2023). It is the third-largest export in Tanzania’s Zanzibar archipelago and employs more than 25,000 farmers, predominantly women (TNC, 2023). But almost all the farmed seaweed is exported unprocessed to produce carrageenan or agar thickening agents (TNC, 2023). Given the volume of seaweed production and of unprocessed material, its future for use in aquafeed looks positive. The government is promoting the domestic processing of seaweed, which could finally enable domestic aquaculture producers to access the byproducts to use as insect feedstock.

Appendix 5: Terms of Reference—Background Information and Excerpt of Inception Report

Report parameters

Ingredients: The high-level evaluation of target alternative ingredients for their potential impact on sustainability and their suitability in aquafeeds in low- and middle-income countries will focus on insect meal, seaweed, agricultural waste, and animal byproducts.

Species: Where it is necessary or relevant to provide species-specific context or considerations, the analysis will focus on tilapia, shrimp, and catfish because they are the most relevant species for the countries of interest. If data are not readily available for those species, substitute data for salmon or trout may be considered.

Focus countries: Although the report intends to offer examples that will be illuminating for current and future countries of interest, the primary focus will be on examples applicable to Sri Lanka, Senegal, Tanzania, Ecuador, and Vietnam—countries in which the team has experience and which offer aquafeed contexts across the development curve.

The three phases of the report

The report will unfold in three phases:

Phase 1: Fit-for-purpose analysis and high-level evaluation of alternative raw materials

Phase 2: Insect meal deep dive and biofloc/periphyton guidance

Phase 3: Economic and job creation potential in select countries

Phase 1: Fit-for-purpose analysis and high-level evaluation of alternative raw materials

Part A: Fit for purpose: Provide an overview of the development stages of an aquafeed ingredient industry

1. Describe the development stages of a local aquaculture industry, with a focus on the evolution (for example, from nascent to emerging to mature) of the production of aquafeed and individual ingredients.
2. Explain the high-level success factors that enable the emergence of an aquafeed ingredients industry—for example, available feedstock, substrates, and waste streams, an already existing agricultural feed-processing facilities, and an already existing aquaculture industry or export infrastructure.
3. Provide two examples of the development of an aquaculture and aquafeed industry (for instance, freshwater fish in China or shrimp in Ecuador), including the time it took, capital sources and expenditures, and resources required for the country or region to evolve from a nascent, to an emerging, and into a mature aquafeed ingredient industry.

4. Broadly describe the current level of development (for example, nascent, emerging, or mature) of the aquafeed industry in priority countries.

Part B: Conduct a high-level evaluation of target ingredients for their suitability in aquafeed for low- and middle-income countries, specifically, **insect meal, seaweed, agricultural waste, and animal byproducts**.

For each ingredient type, comment on

1. **Its economic value:** Discuss the top ingredient companies, stage of development, the main aquafeed use cases, geographic presence, the presence of and applicability of this ingredient in low- and middle-income tropical countries of interest, its nutritional value, how it compares with traditional ingredients in terms of price and the technology required for its production at increasing levels of sophistication.
2. **Its environmental impact:** Outline the ingredient's current average environmental footprint in terms of GHG emissions and biodiversity impacts (based on the current best-available information and where available); the changes that are needed, or product requirements, to be more sustainable than traditional ingredients in the areas of emissions, biodiversity impact, water use, and so on (for example, feedstock choices).
3. **The aquaculture industry's perspective on it:** Describe how aquafeed companies perceive the ingredient, and describe how the ingredient companies that use this ingredient perceive aquafeed as an end market (versus pet food, for example).
4. **Country-specific examples:** Provide two examples of low- and middle-income countries that developed an aquafeed ingredient industry using this ingredient (for example, insect meal in Vietnam).
5. **Its success factors:** Analyze the core factors required for this ingredient to be successful as a nascent or growing industry in the priority countries.

Phase 2: Insect meal deep dive and biofloc/periphyton guidance

Part A: Building on the initial analysis conducted in phase 1, develop a deeper understanding of the insect meal industry

1. Insect meal production basics: Main insect species used, production guidelines, optimal conditions for production, number of employees required, limiting factors, and suitability of different substrates (seaweed, forest waste, fruit waste, manure, frass, brewery waste, palm oil residue, winery byproducts, vegetable waste), and the carbon footprint of different substrates (if publicly available).
2. Key operational and business performance indicators and relative benchmarks: for example, survival and mortality, and capex/opex per unit of production.
3. Insect meal industry: Top insect meal companies, species used, carbon footprint (where publicly available), geographic focus, end-market focus, funding to date, and other prime areas of difference.
4. Aquafeed industry's perspective: Practitioner perspectives on the current and future use of insect meal in aquafeed, and any important concerns.
5. Country-specific examples: Provide a deep dive into country-specific examples of insect meal from phase 1, and major considerations for focus countries.
6. Success factors: Core considerations for launching an insect meal business in a developing-country context, highlighting one success story and one failure story, with core learnings from both, and their applicability to the report's focus countries.

Part B: Provide high-level guidance for task team leaders on biofloc- and periphyton-based technologies, including some background on their history and core considerations such as energy

Phase 3: Economic and job creation potential in select countries

Gather relevant literature projecting the business case for the future development of insect meal, seaweed, agricultural waste, and animal byproducts. For example, the 2021 Rabobank report on insect meal, *No Longer Crawling: Insect Protein to Come of Age in the 2020s* (de Jong and Nikolik, 2021), is already in hand and the Rabobank authors indicate that their conclusions still seem valid.

1. Use the above literature estimates to confirm countries or regions for scenario modeling with the World Bank.
2. For two countries of interest, model potential future total demand for aquafeed, and therefore the total tonnage of ingredient supply required, employing country-level fish production, TTL-provided data, and a few potential growth rates (for example, low, medium, and high growth based on comparable scenarios in other countries and World Bank input).
3. Leveraging the demand modeling, collated information relevant to each of the countries, and examples from more mature industries, analyze and develop a good grasp of the job creation potential in selected countries (for example, total potential new jobs created in each country of interest).
4. Discuss key considerations for female and youth employment in aquafeed ingredient production, including potential challenges that may hinder or limit female employment.

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