Aquafeed Innovation: Investment Opportunities for Responsible Aquaculture

UpSwell Whitepaper

SeaAhead BLUETECH INNOVATION

New England Aquarium

Protecting the blue planet

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EXECUTIVE SUMMARY

Aquaculture, the farming of aquatic organisms, is one of the hottest growth areas in the blue economy, with a global market size expected to reach near $300 billion in the coming decade. Aquaculture is predicted to account for close to two thirds of global food fish production by 2030, as catches from wild capture fisheries continue to level off and demand for seafood increases.

Aquafeed, the feed given to fish and invertebrates in aquaculture, is a major component of that overall market size, valued at over $70 billion and rising. Over 70% of global animal aquaculture production uses aquafeed, including farmed shrimp and salmon, which dominate the US market. However, aquafeed has been in the crosshairs as it is responsible for making up the single largest cost associated with farming, acts as the main contributor to aquaculture's greenhouse gas emissions (e.g., CO_2), and creates a market bottleneck as the production of traditional ingredients, such as fishmeal and fish oil (largely sourced from wild fisheries and fish processing byproducts) has plateaued, while demand has continued to rise. In recognition of these concerns, and in addition to other sustainability concerns, over 90% of major retailers in the US and Europe have introduced responsible seafood sourcing commitments, and are seeking more responsible sourcing of feed ingredients and efficient use of marine feed ingredients.

This confluence of issues has created opportunities where innovation can help the aquaculture industry maintain its present growth, while also increasing the overall environmental performance and sustainability of the space. It should come as no surprise that entrepreneurs and investors have become curious and active in this space, searching for reliable information to inform prudent investments. This paper has been developed as a response to that need, with the goal of providing an overview of aquafeed innovation, which will allow investors a better understanding of the market and the opportunities therein.

Research supporting this paper included detailed analysis of the aquafeed market, extensive literature reviews of peer-reviewed science, and interviews with over a dozen experts in the aquafeed industry, including feed companies, novel feed ingredient producers, aquaculture innovation centers, academics, and farmers. This paper will examine findings from this effort and focus on four key areas: 1) responsible feed ingredients that serve as alternatives to traditional aquafeed marine ingredients, 2) functional feed ingredients (FFIs) that boost farming efficiency, 3) enabling technologies (ET) that increase feed efficiency and reduce environmental waste, and 4) forward-looking opportunities where new startups could address some of the most persistent challenges in global aquaculture.

1. In the responsible feed ingredient space, there are a wide variety of new options and a huge demand for novel sources of protein. Aquafeed mills will likely use a number of sources to produce the necessary nutritional and economic requirements of the desired feed formulation, which need to be nutritionally equivalent to current ingredients, with consistent quality, compatible with the existing production infrastructure, and produced at scale in quantities large enough to meet production batch requirements.

2. FFIs are a fast-growing component within the aquafeed market. They are typically more focused on achieving specific performance attributes and can include ingredients that improve aquatic animal health or disease resistance, enhance growth rates, or that benefit final product quality, such as by eliminating off flavors. FFIs command a relatively higher price point, however they face skepticism and need to validate their claims in order to gain acceptance and market traction. They also face challenges regarding scale and compatibility with existing infrastructure.

3. Enabling technologies are one of the fastest ways to improve the efficiency of feed use in

The global shrimp farming industry is a major consumer of aquafeed.

aquaculture. Automated feeding, monitoring, enhanced feed formulation intelligence, and other hardware and software solutions can improve feed efficiency of existing farms quickly and with shorter regulatory approval and scale up cycles than novel and FFIs. Both land-based Recirculating Aquaculture Systems (RAS) and offshore aquaculture will greatly benefit from the development of enabling technologies. While gaining scale and market adoption can be challenging in fractured markets with mainly smaller farms, enabling technologies show a high level of promise, and some of the largest bluetech deals today are in this space.

4. There are several novel, forward-looking opportunities where new startups could address some of the largest and most persistent challenges in global aquaculture, including technologies embedded in feed that mitigate disease or parasites, and make land-based RAS more efficient. Innovations in these areas that can make meaningful impacts on any of these issues could be of interest to aquaculture investors.

Food security, the environment, and positive economic outcomes increasingly rely on new methods and technologies that promote and maintain responsible aquaculture. Innovations related to aquaculture feed that can mitigate negative impacts, increase efficiencies, and promote high-quality aquaculture end-products will create win-win opportunities for investors and a sustainable future.

INTRODUCTION

The aquaculture industry is projected to continue rapid growth into the foreseeable future, with aquafeed as its cornerstone. However, the industry will struggle to maintain current growth rates without additional sources of responsible feed ingredients. Incumbents are fully aware of this situation, and there has been significant investment and activity in the aquafeed space. There is also evidence that aquafeed plays can command high valuations. For example, eFishery, an Indonesian startup providing smart-feeding systems for the Indonesian farmed shrimp industry, recently raised a $200MM Series D at a unicorn valuation.[1] Strategic players are also active in this space, with Cargill investing in single-celled protein company Calysta[2] and DSM and Evonik collaborating on the algal oil play, Veramaris.

High growth potential in aquaculture, coupled with increased scrutiny on sustainability and constraints on traditional sources of raw material, is creating a market ripe for innovative aquafeed startups. The potential for attractive returns will depend on how effective and scalable their new products and technologies can be in four key focus areas:

1. Responsible feed ingredients that serve as alternatives to traditional aquafeed marine ingredients.

2. Functional feed ingredients (FFIs) that boost aquatic animal health, growth rate, disease-resistance or that improve the quality of the final product.

3. Enabling technologies (ET) that increase feed efficiency and reduce environmental waste.

4. Forward-looking opportunities where new startups could address some of the most persistent challenges in global aquaculture.

> "There is strong and growing acceptance of alternative ingredients… driven by a need to diversify nutrient sources beyond soya and anchovy to reduce supply chain risks."
>
> *— Ian Carr, Senior Director, Global Business Development, Veramaris*

The goal of this paper is to provide entrepreneurs and investors with an overview of aquafeed innovation and help them better understand the market and the opportunities therein. Research supporting this paper included detailed analysis of the aquafeed market, extensive literature reviews of peer-reviewed science, and interviews with over a dozen experts in the aquafeed industry, including feed companies, novel feed ingredient producers, aquaculture innovation centers, academics, and farmers. While many companies are referenced and listed in this report because of this research effort, this should not be considered an endorsement, promotion, or specific recommendation to invest.

FOCUS AREA 1

Responsible feed ingredients

Wild fisheries used for fishmeal and fish oil have reached their maximum possible production.

1. Key context: Fishmeal and fish oil are nutritionally ideal for many aquatic species, but their stagnant supply, and correspondingly high price, are driving the demand for alternatives.

Fishmeal and fish oil are considered the ideal feed ingredients for aquaculture, as they contain the essential nutrients, in the right amounts, that many farmed aquatic species need for effective growth and health, while also being easily digestible and highly palatable.[3] Fish oils are also a critical source of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) long-chain fatty acids. The US Food and Drug Administration (FDA) recognizes that "supportive but not conclusive research shows that consumption of EPA and DHA omega-3 fatty acids may reduce the risk of coronary heart disease."[4] Driven by these benefits, the aquafeed industry currently uses around 73% and 86% of the globe's total annual production of fish oil and fishmeal, respectively.[6] Most of the remaining fish oil is consumed by humans, while the majority of fishmeal not used by aquaculture is used to feed pigs and chickens.[5] Global production of these marine ingredients, which consistently ranges from around 5.5-6 million metric tons per year, is produced from a combination of commercial fishery harvests[6] and increasingly from byproducts of fish processing.[7] Although there is some limited capacity to increase

> "For aquaculture to grow, it needs more feed and feed ingredients. There is a place for every ingredient, your competitor is not fishmeal—they have nothing more to sell—and it's not another novel ingredient company. It's volume that's needed."
>
> *— Erik-Jan Lock, PhD, Research Director, Norwegian Food Research Institute*

A quick word on Soy in Aquafeed

Soy is currently one of the go-to alternatives for fishmeal protein in the global aquaculture industry, which consumed around 6% [over 20 million metric tons (WAP, 2023)] of global soy production in 2021 (Moren, 2021). Soy can be used in many forms, including meal, oil, protein concentrate (Jackson, 2021) and has been used to offset significant amounts, or even completely replace, fishmeal in aquafeeds, depending on the species being farmed (Cremer, 2011). In 2015, over 30 million metric tons of freshwater fish were farmed using plant-based—primarily soy—diets (Cremer, 2015). However, challenges exist with the use of plant-based proteins, including soy. In particular, antinutritional factors (e.g., high carbohydrate, phytates and saponins) that limit inclusion rates in feeds, especially for more carnivorous fish species (e.g., intestinal inflammation in salmonids) (Boorman et al., 2021). Additional concerns exist—in particular, deforestation in the Amazon Basin for soy farming, but alternative sources are available at scale, such as from U.S. production (while noting much of this is genetically modified (US FDA, 2022), which may not be suitable in all markets) (Jackson, 2021). Work is also underway to address the antinutritional factors of soy in salmonid feeds, such as fermented soy meal (Chen, 2023) or mixing with functional feed ingredients. Soybean oil is also used in aquafeeds but does not contain DHA or EPA (Cremer, 2015). In summary, soy, like fishmeal, is a critical source of protein in the aquafeed ingredient basket but there remains a critical need and opportunity for more options.

References cited:

Boorman, M., Forster, I., Vederas, J.C., Groman, D.B. & Jones, S.R.M. (2021). Soybean meal-induced enteritis in Atlantic salmon (Salmo salar) and Chinook salmon (Oncorhynchus tshawytscha) but not in pink salmon (O. gorbuscha). Aquaculture 483: 238-243

Chen, L. (2023). Fermentation opens up fresh prospects for soy and distillers grains in aquafeeds. Accessed 8-17-23. Available at: https://thefishsite.com/articles/fermentation-opens-up-fresh-prospects-for-soy-and-distillers-grains-in-aquafeeds-houdek-prairie-aquatech

Cremer, M. (2011). Soy products and aquaculture are a winning combination. Accessed 8-17-23. Available at: https://spo.nmfs.noaa.gov/sites/default/files/tm124.pdf

Cremer, M. (2015). Innovations in Soy for Aquaculture. Accessed 8-17-23. Available at: https://www.globalseafood.org/wp-content/uploads/2015/04/goal11-cremer.pdf

FDA (2022). GMO Crops, Animal Food, and Beyond. Accessed 8-17-23. Available at: https://www.fda.gov/food/agricultural-biotechnology/gmo-crops-animal-food-and-beyond#:~:text=Most%20soy%20grown%20in%20the,and%20proteins)%20in%20processed%20foods.

Moren, M. (2021). When will we eliminate soy from salmon feeds? Accessed 8-17-23. Available at: https://thefishsite.com/articles/when-will-we-eliminate-soy-from-salmon-feeds

Jackson, L. (2021). Soy helped build aquaculture into a global force. How far can it take it? Accessed 8-17-23. Available at: https://www.globalseafood.org/advocate/soy-helped-build-aquaculture-into-a-global-force-how-far-can-it-take-it/

production from byproducts, the vast majority of the wild fishery sources have reached their maximum possible production, meaning global production from these marine ingredients is unlikely to grow substantially in the future.[7] Fisheries for feed ingredients may generally be well managed at the stock level, but may be associated with critical environmental issues, including overfishing; illegal, unreported, and unregulated (IUU) fishing; and negative ecosystem impacts associated with outcompeting marine predators, such as seabirds and marine mammals.[6]

These risks and production limitations are increasingly being addressed by certification standards that seek to control sourcing, inclusion rates in feeds, and/or limit overall efficiency of marine ingredient use. The vast majority of retailers in the US and Europe have responsible seafood sourcing commitments[8] and prefer, if not require, product from certified sources.

Limited supply and growing demand for marine ingredients from the aquaculture industry continues to drive up the price for fishmeal and fish oil. When combined with sustainability pressures, the result has been a decrease of inclusion rates in aquafeeds with a concentration of use in hatchery (young fish) or finishing feeds designed to improve the quality and/or omega-3 fatty acid profile of fish prior to harvest.[3,6] This has also raised questions on whether the limited availability of marine ingredients could stagnate the future growth of the aquaculture industry, with one study estimating that the aquaculture industry may face a shortage of fishmeal ranging from between 0.4 million metric tons to as high as 1.32 million metric tons by 2050.[9] These factors create a favorable environment for alternatives.[10]

2. Status of solutions

2.1 Microalgae are the most promising alternative to fish oil, but are early in their journey to extensive use

Algal sources of aquafeed ingredients are often divided by the type of algae used. Macroalgae include large seaweeds such as kelp, whereas microalgae are unicellular microorganisms and can be used as a source of algal oils including DHA and EPA[11], the two main omega-3 fatty acids that are missing in plant-based alternative feeds.[12] Both are photosynthetic, can be grown in saltwater, and do not need arable land to grow. Macroalgae is commonly farmed on nearshore submerged farms, while microalgae can be grown in land-based systems, including tanks and photobioreactors.[13] Certain types of microalgae can also be grown in bioreactors without light and carbon dioxide, instead using carbon from alternative sources, such as waste sugar cane and corn.[14,15] These are termed "heterotrophic microalgae" and are considered the most productive systems, have the lowest costs, and are a leading strategy for producing fish oil alternatives at scale;[13] however, using heterotrophic microalgae currently costs twice as much as fish oil. Production needs to expand to ensure that economies of scale bring costs down to compete with marine and plant-based alternatives.[16] The use of microalgae in aquafeed is being pursued

"The need for innovation is desperate… we are at the end of our tether for marine oils (EPA and DHA)."

— Björgolfur Hávardsson, Innovation Manager, NCE Seafood Innovation

DHA and EPA in fish oils are desirable but globally limited, creating opportunities for novel sources, such as algal oils.

by well-established companies, including Corbion, Veramaris, and Archer Daniels Midland (ADM)[17], with the first two companies using heterotrophic microalgae to produce EPA and DHA.[18] Microalgae can produce high levels of these fatty acids, and production practices are relatively simple and well-known.[19] Several key benefits of microalgae as an aquafeed ingredient have been reported, including ideal levels of lipids and other nutrients for fish,[13] as well as the potential for significant reductions in persistent organic pollutants in the final product relative to wild sourced ingredients.[20] However, production challenges have also been reported, including bioreactor production efficiency and microalgae broodstock development.[13] Feed producers understand that microalgae have the potential to supplement fish oil at scale. However, as microalgae are harder to scale than terrestrial plant-based alternatives, additional investment is needed to achieve its potential. Although outside the scope of this paper, it should be noted that plant-based alternatives are also available, for example, Nuseed created Aquaterra® oil from canola enhanced with microalgae genetics. Aquaterra contains seven omega-3 fatty acids, including DHA and EPA, and is produced using existing canola production infrastructure.[21]

2.2 Insects show potential as a responsible fishmeal alternative at scale

Insects are a promising candidate for aquafeed as they are protein rich and often a natural food source for many fish species.[22] A review of insect ingredients used in aquafeeds published in 2022 identified multiple species in various stages of production and investigation, as well as the potential for additional species in the future.[22] The best candidates for aquafeeds include crickets, mealworms, and the larvae of several fly species, including the black soldier fly (*Hermetia illucens*). Of these insect species, the report identified black soldier fly larvae as the most similar to fishmeal, and cited a large number of studies where partial or even complete replacement of fishmeal resulted in no significant negative effects on animal growth or health.[22] Black soldier fly larvae production may also have environmental advantages, as it is estimated to only use about 25% of the arable land and freshwater that soy protein concentrate does per kilogram of production.[23]

> "Feed mills can cost hundreds of millions of dollars to build and may be space limited, they can't simply add new silos and tanks…new ingredients must fit into the current system."
>
> *— Björgolfur Hávardsson, Innovation Manager, NCE Seafood Innovation*

One thing to note from the background research into this paper: many different stakeholders stated that there is room in the market for multiple winners in the responsible ingredient space, so long as they were able to provide a consistent product, at scale, at a competitive price point.

A key benefit of insect farming is its ability to be part of a circular economy and convert waste products from food systems into usable protein.[24] Insects can utilize various biowastes as feed, and early tests have even suggested that waxworm larvae fed plastics may provide similar nutritional value as other insect meals.[25]

Insects, including black soldier fly larvae, offer potential new sources of protein for aquafeeds.

Several insect meals have regulatory approval in the US, Canada, and the EU for use in aquafeeds, including black soldier fly.[26] Some consumers may prefer insect-fed animals and conversations with industry participants validated that statement, noting that certain salmonids were advertised as being fed a more natural diet, including insects, to differentiate the product.[27] With regulatory approvals in place, Rabobank predicted that the insect protein industry could produce 500K metric tons/year by 2030, with 200K metric tons destined for aquafeed.[28] The black soldier fly larvae market is expected to grow by 30.5% CAGR 2022-2032 and be worth nearly $4B in a decade.[29]

That being said, insect meal production faces a number of key challenges, including insufficient levels of omega-3 fatty acids to supplement fish oils, insufficient production to meet commercial feed mill demands for protein, competition for feedstock with other users, inconsistent nutritional quality of meals, and limited research of insect-based diets and potential antinutritional effects.[30] Insect farming for protein production and aquafeed ingredient purposes can be an intensive process, with the insects raised in a strictly controlled indoor environment.[22] While this results in predictable year-round production, the process is complicated and uses a significant amount of energy. An additional concern is whether the food waste used to feed insects would be better utilized by being fed directly to animals. Insect feed should ideally come from sources with no other practical use, and due to efficiency losses during digestion, feeding insects to fish may be less efficient than simply feeding a terrestrial animal the waste product directly.

Many alternative feed ingredient innovators have sought to ease into the challenges of scaling and finding markets with high willingness to pay by focusing on serving the pet food market, which has higher margins than aquafeed.[31] Some who have initially focused on aquafeed, such as France's Ÿnsect, have similarly pivoted into pet feed as well.[32]

2.3 Single-cell proteins have an attractive promise of utilizing chemical feedstocks to reach scale, following a biotech business model, but are still in early days

A variety of organisms are being investigated for their potential as single-cell proteins (SCP) for use in aquafeeds, including microalgae (discussed earlier in this report), yeast, and bacteria.[9] Many SCP production plants are joint ventures between a biotech startup and a conventional feed company, which is beneficial as firms focused on biotech innovation are typically less capable of scaling up production facilities on their own. A key advantage of SCP production is the ability to use bioreactors incorporating waste streams from other industries as feedstocks, including alcohol and brewery byproducts, methane, or CO_2.[33] Feedstock sourcing is critical to both economic viability and practicality in terms of availability and consistency of supply, ease of use in the production system, and regulatory approval.[9]

> "Cargill has a 25-point matrix to evaluate the performance and sustainability of novel ingredients… and are focused on those that are the best fit for formulation and have the best path towards commercial scale."
>
> *— Taylor Voorhees, Sustainability Leader, Cargill Aqua Nutrition*

General challenges in SCP production include high costs of production, low overall production volumes compared to industry needs, and the requirements associated with processing raw SCP into useable protein.[33] Significant increases in the scale of production and decreases in cost are required before SCPs can emerge as a mainstream aquafeed ingredient. However, fermented ingredients (as many SCP ingredients are) may also offer gut health benefits not found in other ingredients, which could allow SCPs to command price premiums relative to crude protein.[34]

Bacteria have the highest protein content of the single-cell organisms, ranging from 50-80%, and can also produce additional nutrients such as amino acids and vitamins.[35] Research studies have shown that growth performance of certain marine fish species could be negatively impacted at high inclusion rates of bacterial SCPs compared to control diets, but that these high rates also showed significant improvements in survival rates.[35] A different study suggested that bacterial proteins may also have palatability challenges.[9] Despite these hurdles, several promising partnerships using bacterial proteins currently exist.

Yeasts generally have lower protein content than bacteria (30-50%) but can also produce additional vitamins and nutrients.[35] Yeasts can also utilize a wide range of feeds, including agricultural and forestry byproducts, which fit into circular economies. Challenges associated with yeast in aquafeed include digestibility (versus fishmeal-based control diets), reduced pellet quality and lipid retention in feeds containing yeast, and the potential for increased uric acid in the kidneys of fish, which may cap inclusion rates for yeast in feed.[35] The commercial use of yeast as an aquafeed ingredient was pursued in 2011 by Verlasso, a joint venture of DuPont and AquaChile, using a genetically modified yeast to produce EPA fatty acids and reduce fish oil in the formulation.[36] However, the product faced challenges in certain markets due to the use of GMOs, and chains like Whole Foods Market declined to carry it.[37] In 2019, the salmon company announced a reformulation of its feed to use fishery byproducts and algae.[38]

Single-cell organisms, including bacteria, are another potential source of protein for the aquafeed ingredient basket.

3. Challenges to adoption: Mimicking complex nutritional profiles of forage fish, integrating with existing production methodology, charting a pathway to industrial production volumes, collecting the right data, and regulatory approvals

The main challenge to adoption is matching the 40 essential nutrients found in a near optimal balance for fish growth in marine ingredients like fishmeal and fish oil.[3] Plant proteins (unless modified) lack the essential nutrients found in wild fish, such as taurine,[39] and exclusive use of vegetarian diets for more carnivorous fish species (e.g., Atlantic salmon) could increase risk of disease due to changes in gut health.[10] Novel ingredients must also find a clear pathway to scale into the range of thousands of tons annually, while maintaining quality and consistency across batches. One of the largest aquaculture companies in the world produces two million tons of aquaculture feed annually, and while it actively searches for new ingredients, potential for scale is an immediate filter for alternative ingredient candidates.[40] Furthermore, achieving scale requires integration with existing infrastructure.

> "Feed mills are producing 30 metric tons of feed each hour and cannot fail on quality. If ingredients cannot consistently provide the quantity or quality, that's a real issue."
>
> *— Tor Andreas Samuelson, PhD, Senior Scientist, Norwegian Food Research Institute*

A quick word on F3 — Future of Fish Feed

F3 describes itself as "a collaborative effort between NGOs, researchers, and private partnerships to accelerate and support the scaling of innovative, substitute aquaculture feed ingredients such as bacterial meals, plant-based proteins, algae, and yeast to replace wild-caught fish." (F3, 2023). As noted, F3's goals are to replace, rather than supplement, wild-caught fish harvested for marine ingredients, due to the concerns over the aquaculture industry competing with other marine life or potential direct human consumption of these resources. F3 uses three approaches to catalyze innovation for fish-free feeds, including a series of competitions ("Challenges") that include a cash prize, research trials of novel feed ingredients, and supporting the Feed Innovation Network (FIN, a platform to share and collaborate on feed innovation). Past F3 Challenges have included the Fish-Free Feed Challenge, the Fish Oil Challenge, the F3 Challenge – Carnivore Edition (focused on more marine ingredient dependent species, such as Atlantic salmon). In 2023, F3 launched the Krill Replacement Challenge. Previous winners include Veramaris (an algal oil producer), which won the Fish Oil Challenge in 2019.

References cited: F3 (2023). F3 – Future of Fish Feed. Accessed 8-21-23. Available at: https://f3fin.org/about/

One key theme identified during interviews with industry players was the need for novel ingredients to work seamlessly within existing production lines. This means integration with storage facilities and silos, and having similar moisture and temperature requirements, similar particle sizes, and similar pellet manufacturing properties as current ingredients in order to function within the modern-day extruders that are ubiquitous within the aquafeed industry.

Another challenge is that, because R&D and trials are expensive, startups can waste capital without generating suitable data for the feed companies if they do not have an appropriate and representative trial design. Data analytics company Wittaya is working to address this issue by using predictive intelligence to virtually evaluate ingredient mixes and provide more focused recommendations for trials, similar to discovery services offered in life science-focused biotech. This stage of development is crucial, as collecting actionable trial data is the first step to independent validation of efficacy and deployment of products at higher inclusion rates.

Finally, carbon footprints and ease of traceability (which is particularly hard for raw ingredients and those from byproducts and waste sources) can be additional critical considerations. These features, along with other factors, have been utilized by large aquafeed producers when evaluating novel ingredients.[34]

4. Startup activity and fundraising rounds in the alternative feeds market

The alternative feed market is robust with many startups active in this space. This is no surprise given the total addressable market size. The following are a number of recent fundraising rounds in alternative feeds:

- NovoNutrients, a California-based biotech firm that produces single-cell proteins from fermented fossil fuels and captured CO_2, raised a $4.7MM seed round in 2021.[41]
- Calysta built a production plant for FeedKind in the US (2018-2020) with Cargill to produce

200K metric tons/year.[42] Calysta also raised a $39MM Series D in 2021 to build a factory in Asia. The raise was led by BP Ventures (British Petroleum), which invested previously and is looking for sustainable uses for its gas infrastructure.[43] Calysta previously raised a $3mm Series A in 2013, a $10MM Series B in 2015, and a $30MM Series C in 2016.[44, 45, 46]

- Entocycle, a UK-based startup providing tech/services for insect farming, raised a $5MM Series A in Febuary 2023 from investors including Lowercarbon Capital.[47]
- Ittinsect (Italy), an insect and agri-waste protein producer, raised a $670K pre-seed in Febuary 2023.[48]
- Brilliant Planet (UK) is growing algae in a desert without freshwater. They raised a $12MM Series A in 2022 (Toyota Ventures, Union Square Ventures, Hatch, others).[49]
- Nasekomo (Bulgaria) turns food waste into insect feed and raised a $4.5MM seed round in 2019 (Morningside Hill, New Vision 3).[50]
- Symbiobe (Japan) is using photosynthesis to make biopolymers for multiple markets, including feed. They raised a $2.1MM seed round in 2022 with Beyond Next Ventures and others.[51]
- Nutrition Technologies (Singapore) produces insect protein and raised $20MM in 2022 to expand production, R&D, and enter new markets. They recently signed an MOU worth $100MM with Sumitomo Corporation to sell into the Japanese pet food and aquafeed markets.[52]
- Russia-based Biovolf raised $140K angel investment for their bioreactor innovation to produce alternative aquaculture feed.[53]
- InnovaFeed, Paris-based producer of insect feed, raised a $250MM Series D round in September 2022. It currently produces 15,000 tons of insect protein annually, the most of any insect protein play, and has plans to expand its production plant by 2024.[54, 55] They have raised over $450MM in total funding to date.[56]
- Aquanzo is a Scottish company that has raised roughly $440K to domesticate and farm zooplankton as a feed ingredient for fish and shrimp. Aquanzo has raised a total of £1.2MM including some grant financing to date.[57]
- AgroNutris is a French biotech company that produces feed from dehydrated and defatted black soldier fly larvae. They raised a $58MM Series C in 2021, and have recently partnered with feed producer BioMar to produce their Ultra'in insect protein.[32]
- Ÿnsect, a French insect feed producer, recently raised 160MM euro and has raised over $600MM to date.[58] However, they have announced a pivot away from aquafeeds to seek higher margins in pet food. This pivot also precipitated closing down a production plant and cutting a number of jobs.[32]
- Finnish startup Volare landed an $830K seed round in 2021, and is producing an insect feed for garden birds in a partnership with pet food producer Lemmikki Insect. Volare also announced in January a new production facility that will allow it to produce 5,000 tons of protein and lipids annually.[32]
- Dutch company Protix creates insect meal and lipid oils from black soldier flies, and raised $57MM in 2022 to fund an international expansion of operations.[59] Protix previously raised $50mm in a 2017 round led by Aqua-Spark and Rabobank.[60]
- NuSeed, a subsidiary of agriculture seed innovator NuFarm, has launched Aquaterra®, claiming it is the first land-based source of Omega-3 fatty acids.
- EniferBio, a Finnish startup, is creating a fungi-based protein alternative to soy using waste streams as a feed stock. They raised €11 million in April of 2023.[31]

FOCUS AREA 2

Functional feed ingredients

Feed usually represents the highest cost item to the farmer, who is often highly motivated to achieve efficiency gains.

1. Key context: Feed ingredients that provide nutrition and enhance growth rates or disease resistance are highly desirable and promote sustainability.

Functional feed ingredients (FFI) are broadly defined as feed ingredients that provide superior performance compared with those using conventional feed ingredients and includes specialty/high-tech ingredients typically aimed at promoting improved growth, health, and survival.[61] In addition to supplementing globally limited supplies of fishmeal and fish oil, FFIs can play a key role in addressing some of the most pressing challenges to the aquaculture industry, including mitigating disease and maximizing utilization of existing resources.[62] FFIs are different from veterinary drugs, such as antibiotics to treat disease, and probiotics (live bacteria that provide health benefits when consumed), although some FFIs may have probiotic characteristics.

> "Reducing omega-3 oils in fish feeds reduces omega-3 content in fillets, therefore reducing the health benefits of eating seafood…fish oil alternatives support fish health, human health, and ocean health."
>
> *— Katrina Benedicto, Sustainability Director, Nuseed Nutritional*

Disease and parasites are leading challenges for the aquaculture industry. According to one expert, microbial disease costs the global aquaculture industry an estimated $6 billion each year.[63] One bacterial disease called hepatopancreatic necrosis disease (AHPND, also known as Early Mortality Syndrome), caused a 40% decline in global shrimp aquaculture production.[64] In Thailand alone, AHPND caused losses of $11.5 billion and cost over 100,000 jobs during the six year period from 2010 to 2016.[65] Sea lice, a parasite that infects both farmed and wild fish and causes trauma that can be fatal, are estimated to cost the salmon farming industry between $400 to $600MM each year, and result in extensive regulatory requirements to control outbreaks as lice have become resistant to chemical treatments.[66] Farms can amplify lice populations, which can then spread to threatened wild salmon populations. This is one of the key factors driving a transition from net pen salmon farms in British Columbia to land-based farms.[67]

In addition to economic impact, diseases and parasites can also influence the industry's reputation and social license to operate. FFIs that reduce the risk or impact of disease and parasitic outbreaks may also have benefits on other issues impacting aquaculture sustainability, including:

- Reducing mortality
- Improving the Feed Conversion Ratio (FCR, the ratio of the amount of feed used to produce a given weight of farmed fish) and efficiency of ingredients used in the aquafeeds
- Decreasing time to market and the Fish In: Fish Out ratio (FIFO, a measure of the amount of whole wild fish used to produce a given weight of farmed fish)
- Reducing the need for, and use of, antibiotics and preventing the potential spread of antibiotic-resistant bacteria, through reduced incidence of disease
- Reducing susceptibility to disease for fish being fed less fishmeal and fish oil
- Enhancing the flavor, texture, or other qualities of the finished product

> "Industry cannot continue to feed in the way they have fed for the last 15 years…the future of the aquafeed market is these functional feed plays."
>
> *— Timothy Bouley, MD, CEO & Founder, BioFeyn*

FFIs can achieve these goals in different ways, including improving the immune response in fish, reducing stress that may make the animal more susceptible to disease, or inhibiting the growth of pathogenic microorganisms. Because they are feed-based, FFIs can also be supplied to aquatic animals more easily than injections. FFIs that promote general health, growth rate, or disease resistance can demonstrate an attractive cost/benefit profile compared to other ingredients and improve their market demand. Additionally, the ability for an ingredient to do more than one thing (e.g., deliver protein while enhancing gut health) could be particularly advantageous in aquafeeds where the pellet is already 'space limited,' such as in Atlantic salmon feeds.[40] FFIs may also benefit local ecosystems, due to improved digestibility leading to less nutrients in farm wastes,[lv] while RAS systems may also benefit from reduced costs associated with life support systems (e.g., electricity to pump and water treatment).

2. Status of solutions

The FFI market is seeing a variety of technology transfers from terrestrial animal production, as well as human health, and biotech companies are entering the market either horizontally from the terrestrial animal space or by targeting aquaculture from the beginning. Products are often targeted towards very specific end uses, such as nutrient uptake, digestibility, or species-specific applications. Many are focused on increasing the performance of alternative feeds in animal digestion or mitigating the side effects of alternative feeds. Several examples of FFI are currently in varying stages of development and targeting specific applications. One example, KnipBio, has demonstrated efficacy in reducing off flavors in RAS-raised salmonids,[68] while also improving growth rate and other performance metrics in juvenile fish[69] at relatively low inclusion rates (5%). This is a good example of how FFIs can have a significant impact on farm performance with small changes to feed formulation. Additionally, there are other FFI ingredient plays that have demonstrated exciting performance

“The minimum batch size at the commercial feed manufacturing level is often several tons of feed…this is massive scale for any test or pilot of functional feed ingredients.”

— Larry Feinberg, PhD, CEO & Co-Founder, KnipBio

attributes in research that are not yet publicly available, making this space one with a high degree of innovation and investment opportunity.

2.1 Fish health enhancement

Many FFIs are targeting applications that reduce stress, promote gut health, or reduce antibiotic use to help ameliorate the fact that fish fed less fishmeal and fish oil can be more susceptible to disease.[70] Additionally, there are some ingredients that have broad similarities to other FFIs but are used as oral vaccine delivery platforms. The use of vaccination in aquaculture is a very broad topic, much of which is beyond the scope of this paper. However, the delivery of vaccines may be an opportunity for FFIs, particularly those that can encapsulate vaccines or mitigate attractability or palatability reductions when vaccines are used in or on feed. Vaccines in aquaculture can be applied in three ways: immersion, injection, and oral delivery. Immersion and injection can be labor-intensive and stressful for the animals, while oral delivery is potentially an easier and less stressful option.[71] Oral vaccines seek to integrate vaccine delivery into everyday feed activities by adding a specific coating to formulated feed, encapsulating vaccines in polymers, or by bio-encapsulating them in live feeds like brine shrimp and other aquatic invertebrates. However, few oral vaccines are approved for use to date and they may generate a lower immune response when compared with injected vaccines, as antigens tend to break down as they are digested.[72] Vaccination may not be a viable option for certain situations. For example, farmed shrimp do not have an immune system that can be “trained” through vaccination[73] and important

Functional Feed Ingredients need to be made at scale to meet the needs of commercial feed mills.

farmed-salmon diseases, such as Salmon Rickettsial Syndrome (SRS) in Chile, have not been successfully controlled through vaccination.[74]

3. Challenges for adoption

Interviews with experts in the aquafeed industry expressed mixed feelings towards FFIs. Certain products had very clear applications and functional outcomes, such as KnipBio’s application to combat off-flavor producing compounds in RAS systems, which RAS farmers cited as a clear product-market fit.[75] However, FFIs claiming more general probiotic (e.g., immune system boosting) functions were generally perceived as needing more proof of efficacy to gain traction.

The need for a consistent product is also a key consideration for an FFI, and there have been issues around limited production infrastructure for small batch sizes. Many FFI innovators have partnered with larger industry players to access higher capacity production facilities without needing to spend the capital themselves. However, FFIs face a different and logistically simpler scaling challenge when compared with fishmeal and fish oil alternatives, as inclusion rates (the amount of a given ingredient used in the feed, usually as a percentage of the whole pellet) are much lower: typically, 1-10% compared to 40-50% for crude protein supplements.

Nonetheless, scaling still remains a challenge, as there is little production infrastructure in between small R&D batches and industrial-scale production. Finally, access to capital was consistently cited as a major constraint for FFIs. Traditional aquaculture investors may not appreciate the nature of FFI business models, which often mimic that of a biotech play, requiring big investment and R&D upfront before a commercial product is developed and revenues are generated. Likewise, biotech investors may not understand the aquaculture market and be hesitant to invest.

> "The ability for an ingredient to do more than one thing (e.g., deliver protein while enhancing gut health) could be particularly advantageous in aquafeeds where the pellet is already 'space limited,' such as in Atlantic salmon feeds."
>
> *— Taylor Voorhees, Sustainability Leader, Cargill Aqua Nutrition*

4. Startup activity in the functional feeds market

- Ohio-based BiOWiSH Technologies raised a $5MM Series F for their composite biocatalysts and probiotics that increase the attractability and digestibility of various aquaculture feeds.[76]
- Ireland-based MicroSynbiotiX (now owned by Sundew) raised a $1.7MM seed round in 2017 to develop oral vaccines that combat white spot disease in finfish aquaculture.[77]
- BioFeyn (Boston, MA) adapts nano-technologies based on human medicine to deliver nutrients and natural disease preventatives to fish. They raised a $3MM seed round in 2022.
- Organicin (Boston, MA) creates bacteriocin-based functional feeds focused on gut dysbiosis and preventing disease.
- Chile-based IctioBiotic develops oral biotherapeutics for aquaculture.
- Poland-based Proteon Pharmaceuticals produces Bafador, a bacteriophage "cocktail" that helps fish cope with *Aeromonas spp.* and *Pseudomonas spp.* and reduces the need for antibiotics. They closed a $21MM Euro round in 2021 led by Nutreco and Aqua-Spark.[78]
- Keuhnle AgroSystems is a US-based company that has developed a fermentation process for the microalga *Haematococcus pluvialis*, a source of natural astaxanthin, which is used as an antioxidant and pigment for salmon and shrimp. They closed a Series A round in 2022 for an undisclosed amount.[79]
- ViAqua Therapeutics, an Israeli company that is creating RNA-based oral treatments for aquaculture applications, closed a $4.3MM round in summer of 2021 and closed a follow-on round for $8.25MM led by S2G Ventures in 2022.[80]
- Molofeed is a Norwegian startup that has created a line of microencapsulated feeds targeting hatchery applications. They closed an early stage funding round in December 2019.[81]
- KnipBio (Lowell, MA) uses a proprietary fermented leaf bacteria to produce an FFI that addresses off flavor in salmon, while promoting gut health. They raised their last round in February 2022.

FOCUS AREA 3

Enabling technologies

1. Key context: Technologies that enable efficiencies in feed use and increase growth rates can provide economic benefits to a farm, while also reducing impacts of farm waste on the environment and the final product's carbon footprint.

Aquafeed can account for over half of the cost of farming aquatic animals. Feed can also be a major source of nutrient loading into the natural environment, either directly from uneaten feed pellets or indirectly from fish feces and dissolved wastes in urine containing nitrogen and phosphorus.[82] When nutrient loading is excessive, this can lead to eutrophication, which is when over-stimulated algal growth dies and decomposition consumes oxygen in the water. One study estimated that over 60% of the carbon, nitrogen, and phosphorus from the feed given to the Norwegian farmed salmon industry ultimately ended up in the local environment.[83] In addition, uneaten feeds also waste limited feed ingredients, particularly fishmeal or fish oil, and increase the FCR and Fish In: Fish Out ratio of the final product, which could have market implications if a farm is unable to meet the responsible sourcing requirements (e.g., certification) of major buyers (e.g., retailers). Ultimately, there is a clear economic and sustainability incentive to reduce feed inefficiencies and waste, which could create opportunities for enabling technologies (ET), which usually involve hardware or software solutions, rather than feed ingredients.

While still a young field, the sector of precision aquaculture, which includes ET and the Internet of Things (IoT), aims to improve monitoring, control, and automation[84] of the production process and has the potential to save farmers money, increase yields, and reduce waste released to surrounding ecosystems without dramatically altering feed compositions or supply chains. These solutions often take the shape of a piece of hardware backed up by artificial intelligence (AI) or machine learning (ML) that increases accuracy of feeding over time, while also allowing the startups behind the technology to leverage the data to provide deeper insights for farmers. The opportunities offered beyond hardware sales should entice investors, as software-based solutions create potential for scale at a shorter timeframe than hardware or biotech solutions, and often with more attractive margins. Startups in this space span the value chain, from offering pure analytics or hardware to selling combined solutions. Several companies are working towards vertically-integrated plays that offer farmers a holistic farm management platform, such as eFishery and Aquaconnect. The precision aquaculture market was valued at $335MM in 2020 but is expanding rapidly. It is expected to grow at a CAGR of 13.4% through 2028 to an anticipated $934MM.[85]

> "Enabling technologies? The more the better, it's all wonderful!"
>
> *— Neil Sims, Founder & CEO, Ocean Era, Inc.*

2. Status of solutions

2.1 Smart feeders, automated monitoring of animal schooling and feeding behavior, and vertically-integrated farm management platforms

Although there are a range of aquaculture ET innovations, the automated smart feeder, which feeds fish on an optimal schedule over the course of the day, is of particular interest. When used in concert with other hardware and software innovations (e.g., monitoring fish behavior to evaluate when animals are hungry, and when their behavior indicates that they are sated), the automated smart feeder ensures a more even distribution across all the animals in a pond, tank, or pen. Feeder positioning can also be optimized so that all animals receive sufficient feed.

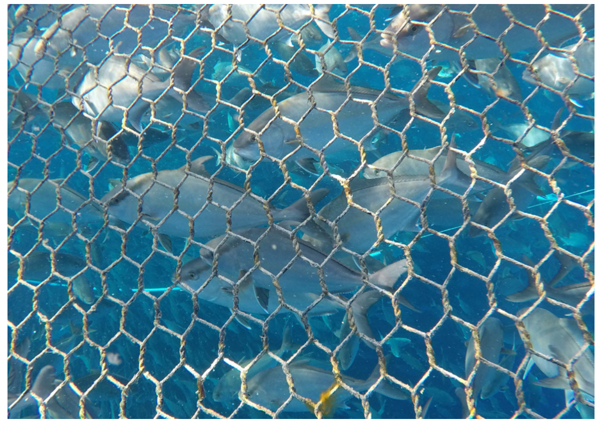
Getting cameras under the water has particular advantages in a field where fish cannot easily be observed from the surface. With image recognition, farmers can spot outbreaks of disease, monitor animal growth, and, in some instances, recognize and track individual fish. Most relevant is the ability to monitor schooling behavior, which often correlates with animal appetite. While automated feeders have existed for a while, syncing them with real-time information about schooling behavior allows for optimized feeding operations. For example, smart feeders can detect when fish are hungry or sated, and turn on and off feeding accordingly; they can also distribute feed over the course of the day and throughout the production system, ensuring a more even size distribution across all the animals in a pond, tank, or pen as opposed to delivering the feed in one big batch a few times a day, which biases feeding towards the most aggressive animals in the system.

ML is a relatively new innovation to aquaculture, and still has some ways to go to cross the gap between observed phenomena and accurate insights, but there is a high ceiling for innovation opportunities. For example, recent advancements have enabled analysis even in turbid waters, which are common in pond-based aquaculture, and opened a new potential market for AI/ML monitoring solutions.[86] Players in underwater monitoring should be mindful of the opportunities beyond precise feeding, including monitoring volume of uneaten feed, animal health, size, activity, and disease detection.

Finally, given the data-driven value proposition of hardware-driven solutions, such as automated feeders and underwater monitoring, it comes as little surprise that players in aquaculture ET are utilizing their data to launch a variety of new service lines and offer more vertically-integrated platforms to farmers and feed producers. Examples include financial services, an online feed marketplace, feeding analytics, and a platform to analyze the potential for new ingredients.

3. Challenges for adoption

Aquaculture ET is not as advanced as land-based agriculture, although the story is somewhat split. In developed countries with established aquaculture industries (e.g., Norwegian salmon farming), where



Enabling technologies offer potential to reduce feed waste at the farm level.

> "Automated feeding is one of the biggest opportunities to improve economic FCR."
>
> *— Evan Hall, CEO & Co-Founder, Wittaya*

the market is more consolidated and the companies that dominate the market have resources to invest in technologies, farmers are better able to try innovative practices. But in low- and middle-income countries, where aquaculture is growing the fastest, the market is far more fragmented, with small farms dominating the aquaculture landscape (e.g., shrimp farming in Southeast Asia). These farmers are, on average, less able to invest in upfront capital expenditures for novel technology systems and have less access to financing. Aquaculture ET platforms are complex systems that can require specialized knowledge to operate. In some low- and middle-income countries, more fundamental infrastructure such as mobile networks or WiFi, which are usually necessary to operate the IoT systems, may be of insufficient quality or nonexistent. Indonesia's eFishery has done an admirable job tackling these issues, although its technology still is not used by the vast majority of shrimp farmers that make up its target market.

4. Startup activity in aquaculture ET

- eFishery (Indonesia), which provides a vertically integrated digital platform for fish farmers, including access to feed, distribution, and automated smart feeders, raised a $90MM Series C in 2022—then the largest ever by an aquaculture tech company.[87] More recently they raised a $200MM Series D at a valuation of over $1B.[88]
- Similar to eFishery, India's Aquaconnect provides fish and shrimp farmers with an app-based farm management platform, a marketplace for inputs, market links for product sales, and access to financing and insurance. It raised a $15MM Series A in 2022.[26]
- Poseidon-AI (Singapore) raised an $80K seed round for their hardware and software to optimize aquaculture feed and other operations. Entrepreneurs First invested.[89]
- DELOS secured an $8MM seed round in March 2022 for their shrimp farm management platform, focused on the Indonesian shrimp aquaculture market.[90]
- California-based Scoot Science, which provides ocean data and fish health data services to salmon aquaculture, raised a $4.1MM seed round in 2022.[91]
- Aquabyte, another California-based startup that combines underwater vision and AI to deliver fish health and performance insights, raised a $24MM Series B in 2022.[92] Aquabyte has raised a total of $46mm to date.[93]
- Umitron, a Japanese company developing machine learning systems to optimize aquaculture feed, raised $9.2MM in debt and an undisclosed amount through a Series A in 2022.[94]
- Wittaya Aqua is a Canadian company that offers a farm management platform for farmers and also data-informed formulations for farmers and feed producers. Wittaya recently opened a Singapore office as part of a $3MM funding round.[95]
- Manolin is a Norwegian company that uses data to perform real-time monitoring of fish health, and provides farmers with alerts of disease outbreaks.
- Minnowtech is an American startup that has developed a biomass reader for shrimp ponds, so farmers know how much shrimp they actually have.
- ReelData.ai provides AI-based monitoring and automation services specifically for the RAS industry, including feed automation and health assessments via body condition.[96] ReelData closed an $8MM Series A earlier this year led by Buoyant Ventures.[97]
- Bluegrove is a Norwegian startup providing autonomous feeding systems that utilize acoustic data to better optimize feeding practices. They raised a $13MM Series B in early 2022.[98]

> "Farmers need to ensure that they do not take their eye off the ball on feed quality—it drives FCR, assimilation, and product flavor."
>
> *— Neil Sims, Founder & CEO, Ocean Era, Inc.*

FOCUS AREA 4

Forward looking perspective on areas for innovation

As the global aquaculture industry grows and matures, it will resolve some challenges, as well as uncover new and emerging issues, while providing exciting opportunities for bluetech startups and investors to combine economic gains with environmental and social benefits. Key opportunities for impact investing may occur where new startups aim to address some of the largest and most persistent challenges in global aquaculture. A sample of these key issues, relating to the most important farmed species, and which are not presently captured by any current company, are included below. Innovations that can make meaningful impacts on any of these issues could be of particular interest to aquaculture investors.

> "Off flavor is a common challenge in RAS production which must be mitigated—if RAS products don't taste as good or better than net-pen cultivated products, then there is no business opportunity."
>
> *— Eric Pedersen, President & CEO, Idealfish*

1. Diseases in shrimp farming: Asche et al. (2021) wrote that "shrimp is not only one of the world's most valuable aquaculture species, but also a species that encounters high economic losses due to diseases. Diseases are sufficiently important to influence global supply and prices for longer periods."[99] Impacts of shrimp diseases can range in the region of billions of US dollars. The global shrimp farming industry is once again ramping up production after the latest disease, AHPND, devastated the industry after emerging in 2010. Many shrimp diseases still have lasting effects, as tracked by the World Organisation for Animal Health (OIE). FFIs that improve survival and growth rate in the presence of AHPND and White Spot Syndrome Virus (WSSV) would likely be particularly desirable, as well as those that mitigate the impacts of the emerging parasitic disease, Enterocytozoon hepatopenaei (EHP).

2. Sea lice in salmon farming (global): Sea lice are a crustacean parasite of salmonids, including Atlantic salmon. Sea lice are highly adaptable, eventually becoming resistant to several parasiticides used to control their population. Controlling sea lice costs the global industry hundreds of millions of dollars each year, with many farming regions impacted (although by different species of lice), including the two largest global farmed salmon producers: Norway and Chile. Marine net pen farms may amplify these parasites in the wild, impacting wild salmon populations and reducing aquaculture's social license to operate, which has led to calls for whole sectors of the industry to close farms (e.g., in British Columbia, Canada) or limit the future growth of the industry, such as in the coastal regions of Norway. FFIs that reduce the impact of sea lice on the industry, including treatment costs, could be highly desirable.

3. Salmon Rickettsial Syndrome (SRS) in the Chilean Atlantic salmon farming industry: Chile is the second largest producer of Atlantic salmon in the world, producing over 1,000,000 metric tons in 2020, and is the main supplier of the fish into the US market (accounting for over 600,000 metric tons worth over $5 billion dollars).[100] SRS is a bacterial disease that causes significant mortality (>50%) in salmon[101] if untreated, and it resulted in the Chilean industry using over 450 metric tons of antibiotics in 2021.[102] The ongoing use of antibiotics at this scale is a major economic challenge, as well as a critical consumer and environmental concern with the spread of antibiotic-resistant bacteria. FFIs that reduce the impact of SRS, while reducing or eliminating

Parasitic sea lice are a persistent issue for salmon farming in marine waters.

antibiotic usage in the Chilean industry, could also be highly desirable.

4. Using feed to address constraints in RAS: In the US and abroad, there are a growing number of land-based finfish aquaculture projects using RAS.[103] Key components of RAS include reusing the water during production, which requires stripping wastes using mechanical and biological filters, and controlling the farm environment (including water quality, temperature, salinity, etc.), as well as feed, particularly when fish are raised in densely stocked holding facilities (e.g., tanks and raceways).[104] Feeds for RAS must address both the needs of the fish and also the particular needs of the production system, meaning that feeds designed for marine net pen aquaculture may not be ideal for RAS.[105]

"Novel feed ingredients need to fit into the ingredient basket, with realistic inclusion levels of 2–5% rather than 20%."

— Evan Hall, CEO & Co-Founder, Wittaya

ETs and FFIs that are tailored to the specific needs of the growing RAS industry may also be highly beneficial in improving the economic viability and growth of these land-based aquaculture systems.

CONCLUSION

Aquaculture is at a crossroads. With about 90% of global fisheries being either fully fished or overfished, the preferred way to meet future seafood demand is for aquaculture to become more efficient, more responsible, and more commonly used as a production method of seafood for global food security.

As the sector continues to grow, traditional feed production—which makes up the largest single cost area for most fed aquaculture operations, and represents the largest swath of the environmental footprint for farming operations - remains reliant on globally limited supplies of marine ingredients. At the same time, the adage that "you are what you eat" is as true for fish as it is for people, and feed ingredients have a direct impact on the nutritional value of the harvested animal. The industry needs to maximize the utilization of existing marine ingredients, while also finding novel sources of key nutrients that are environmentally responsible, consistent in quality and quantity, and produce outcomes as good as or superior to animals fed a marine ingredient-based diet. Innovations in new ingredients and enhanced technologies for developing feeds, automating their delivery, and monitoring their usage offer a variety of pathways for the industry to scale solutions.

In addition, the industry faces other impediments that innovations can address, such as off flavor, increased disease incidence, backfilling nutritional requirements, and the ever present need to improve feeding efficiencies, growth rates, and reduce time to market. FFIs can benefit all these areas, and many companies have created high-tech feed ingredients boasting a slate of performance attributes. However, they often face an uphill battle in supporting their claims to the satisfaction of other stakeholders in the space. Effective and representative trial designs, along with open communication with end users to better understand what attributes and use cases (e.g., inclusion rates) would be most valued are critical to achieving traction for FFIs.

"My biggest impediment to growth right now is 100% access to capital."

– Timothy Bouley MD, CEO & Founder, BioFeyn

Opportunities also exist to enhance the methods by which the industry designs feed, delivers it to animals, and monitors its consumption and impact on the environment. These ET solutions are perhaps some of the fastest and easiest ways to improve the sustainability of aquaculture by enhancing the utilization and efficacy of existing feeds. This sector also has a great deal of potential for investors interested in sustainable aquaculture plays, as there are lower barriers to entry and capital requirements than with feed ingredient plays.

The growth and maturation of the global aquaculture industry will provide exciting opportunities for bluetech startups and investors to combine economic gains with environmental and social benefits. As innovation and investment extends from the local to global level, aquaculture will continue to benefit from new and better ways to drive environmentally responsible seafood production. The development and maturation of aquaculture, when well-planned and executed, will be a critical part of a sustainable future that can benefit thoughtful investors and our planet.

GLOSSARY

Term	Definition	Reference
Aquaculture	Aquaculture is the farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants.	www.fao.org
Aquafeed	Any feed given to aquatic farmed animals as part of aquaculture. Fish (both farmed and wild) require a balanced mix of essential nutrients such as amino acids, fatty acids, and vitamins to thrive.	www.fisheries.noaa.gov
Byproduct	Byproducts are the trimmings of fish (heads, frames, skin and tails) from processing for direct human consumption and are a valuable and increasingly valued side-stream raw material which can then be turned into marine ingredients.	www.IFFO.com
Circular economy	The circular economy is an evolution of the way the world produces and consumes both goods and services, redefining the economy around principles of reducing waste and pollution, keeping products and materials in use for as long as possible.	www.IFFO.com
DHA	DHA (docosahexaenoic acid; 22:6n-3), refers to a long-chain omega-3 fatty acid abundant in marine ingredients that have an important role as the substrate for several hormones and as an important building block for brain, nerve and eye tissues.	www.IFFO.com
Enabling technologies	hardware and/or software solutions that can increase the efficiency of feed use on the farm, thereby reducing overall ingredient use and waste release to the environment	This whitepaper
EPA	EPA (eicosapentaenoic acid; 20:5n-3) refers to a long-chain omega-3 fatty acid abundant in marine ingredients that have an important role as the substrate for several hormones.	www.IFFO.com
Feed Conversion Ratio (FCR)	Ratio between the dry weight of feed fed and the weight of yield gain. Measure of the efficiency of conversion of feed to fish (e.g. FCR = 2.8 means that 2.8 kg of feed is needed to produce one kilogram of fish live weight).	FAO Term Portal
Fish in fish out ratio (FIFO)	A calculation to determine the ratio of wild harvested marine ingredients used per unit mass of farmed aquatic animal, usually on a wet weight basis. Alternative terms include forage fish dependency ratio, or forage fish equivalency ratio.	www.ourGSSI.org
Fish oil	Fish oil is a lipid (fat) source made from the processing of fish fats, notable for containing high levels of the essential omega-3 fatty acids.	www.IFFO.com
Fishmeal	Fishmeal is a nutrient dense and highly palatable feed ingredient made from the processing of fish proteins.	www.IFFO.com

Functional feed ingredients	Feed ingredients that may be included in small amounts in feeds and can provide significant health or performance benefits for the aquatic animals	This whitepaper
Heterotrophic algae	Can utilize photosynthesis in light environments as well as organic sources of carbon (e.g., sugars) and energy in dark environments	Ruiz, J., Wijffels, R.H., Dominguez, M. & Barbosa, M.J. (2022). Heterotrophic vs autotrophic production of microalgae: Bringing some light into the everlasting cost controversy. Algal Research 64: 102698
Illegal, unreported, and unregulated fishing (IUU)	Illegal, unreported and unregulated fishing (IUU) includes all fishing that breaks fisheries laws and regulations or occurs outside their reach. Illegal fishing usually means without a license, in an area where fishing is banned, with prohibited gear, over a quota, or for protected species. Very often it's a vessel entering a nation's water with no fishing license, or fishing with a license but catching more than is allowed.	www.IFFO.com
Novel ingredients	Relatively new ingredients such as algae, single cell, and insect-derived materials. They are mostly still emerging in the market and at a much lower technology readiness level, being only available in smaller quantities compared with traditional ingredients.	www.IFFO.com
Omega-3s	A class of fatty acids, defined by the position of the first double (unsaturated) bond in the fatty acid being three carbons from the end of the chain. Found in both plant and fish sources in either short-chain or long-chain forms and provides a range of health benefits.	www.IFFO.com
Recirculating aquaculture system (RAS)	Recirculating aquaculture systems are indoor, tank-based systems in which fish (or other aquatic species, such as shrimp) are grown at high density under controlled environmental conditions. Generally, farmers adopt a more intensive approach (higher densities and more rigorous management) than other aquaculture production systems.	Business Queensland
Salmonids	Fish from the family (Salmonidae) including Atlantic salmon, rainbow trout, coho salmon and Arctic char.	
Single cell protein (SCP)	Protein derived from the cells of microorganisms such as yeast, fungi, algae, and bacteria.	www.IFFO.com

REFERENCES

1 Shu, C. (2023). Indonesian aquaculture startup eFishery nets $200M at unicorn valuation. Accessed 7-18-23. Available at: https://techcrunch.com/2023/07/07/efisher-series-d/

2 The Guardian (2016). Methane-eating bacteria could reduce the impact of our big appetite for fish. Accessed 7-18-23. Available at: https://www.theguardian.com/sustainable-business/2016/mar/17/methane-eating-bacteria-reduce-impact-fish-demand-feedkind-calysta

3 Rust, M.B., Barrows, F.T., Hardy, R.W., Lazur, A., Naughten, K. & Silverstein, J. (2011). The Future of Fish Feeds. NOAA Technical Memorandum NMFS F/SPO-124. Available at: https://media.fisheries.noaa.gov/dam-migration/the_future_of_aquafeeds_final.pdf

4 U.S. Food and Drug Administration (FDA) (2019). FDA Announces New Qualified Health Claims for EPA and DHA Omega-3 Consumption and the Risk of Hypertension and Coronary Heart Disease. Accessed 3/2/23. Available at: www.fda.gov/food/cfsan-constituent-updates/fda-announces-new-qualified-health-claims-epa-and-dha-omega-3-consumption-and-risk-hypertension-and

5 Hamilton, H.A., Newton, R., Auchterlonie, N. & Müller, D.B. (2020). Systems approach to quantify the global omega-3 fatty acid cycle. Nature Food 1(1): 59-62.

6 Food and Agriculture Organization of the United Nations (FAO) (2022). State of Fisheries and Aquaculture 2022. Available at: https://www.fao.org/3/cc0461en/cc0461en.pdf

7 IFFO (2022) By-product. Accessed 7-17-23. Available at: www.iffo.com/product

8 Conservation Alliance for Seafood Solutions (2021). A common vision for sustainable seafood. Accessed 7-18-23. Available at: https://solutionsforseafood.org/wp-content/uploads/2021/02/A-Common-Vision-for-Sustainable-Seafood-01-21.pdf

9 Jones. S.W., Karpol, A., Friedman, S., Maru, B.T. & Tracy, B.P. (2020). Recent advances in single cell protein use as a feed ingredient in aquaculture. Current Opinion in Biotechnology 61: 189-197

10 Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., Little, D. C., Lubchenco, J., Shumway, S. E., & Troell, M. (2021, March 24). A 20-year retrospective review of Global Aquaculture. Nature News. Retrieved February 19, 2023, from https://www.nature.com/articles/s41586-021-03308-6

11 Wan, A.H., Davies, S.J., Soler-Vila, A., Fitzgerald, R. and Johnson, M.P. (2019). Macroalgae as a sustainable aquafeed ingredient. Rev Aquacult, 11: 458-492. doi.org/10.1111/raq.12241

12 Kamunde, C., Sappal, R., & Melegy, T. M. (2019, July 15). Brown seaweed (aquaarom) supplementation increases food intake and improves growth, antioxidant status and resistance to temperature stress in Atlantic salmon, Salmo salar. PloS one. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6629153/

13 Nagappan, S., Das, P., AbdulQuadir, M., Thaher, M., Khan, S., Mahata, C., Al-Jabri, H., Vatland, A.K., & Kumar, G. Potential of microalgae as a sustainable feed ingredient for aquaculture. Journal of Biotechnology 341: 1-20.

14 Kauffman, J. (2020). The Rise of Novel Feed Ingredients. Algae Adoption from Research to Retail. Corbion webinar recording 6/4/2020. Accessed 2-27-23. Available at: https://vimeo.com/425944237

15 Corbion (2023). AlgaPrime™ DHA – sustainable, affordable, and at scale. Accessed 2-27-23. Available at: www.corbion.com/en/Products/Algae-ingredients-products/AlgaPrimeDHA

16 Sarker, P. K. (2023, February 9). Microorganisms in fish feeds, technological innovations, and key strategies for Sustainable Aquaculture. MDPI. Accessed 2-20-23. Available at: https://www.mdpi.com/2076-2607/11/2/439?type=check_update&version=2

17 Johnson, J.K. (2020). The Rise of Novel Feed Ingredients: Algae Adoption from Research to Retail. Accessed 7-18-23. Available at: https://www.linkedin.com/pulse/rise-novel-feed-ingredients-algae-adoption-from-jill-kauffman-johnson/

18 Veramaris (2023). Omega-3 From Natural Marine Algae. Accessed 2/27/23. Available at: www.veramaris.com/what-we-do-detail.html

19 Albrektsen, S., Kortet, R., Skov, P.V., Ytteborg, E., Gitlesen, S., Kleinegris, D., Mydland, L., Hansen, J.O., Lock, E., Mørkøre, T., James, P., Wang, X., Whitaker, R.D., Vang, B., Hatlen, B., Daneshvar, E., Bhatnagar, A., Jensen, L.B., & Øverland, M. (2022) Future feed resources in sustainable salmonid production: A review. Rev Aquac. 14(4): 1790- 1812. doi:10.1111/raq.12673

20 Sprague, M., Walton, J., Campbell, P., Strachan, F., Dick, J. & Bell, J. (2015) Replacement of fish oil with a DHA-rich algal meal derived from Schizochytrium sp. on the fatty acid and persistent organic pollutant levels in diets and flesh of Atlantic salmon (Salmo salar, L.) post-smolts. Food Chem. 185: 413–421

21 Benedicto, K. (2023). Personal communication 03/12/23

22 Alfiko, Y., Xie, D., Astuti, R.T., Wong, J., & Wang, L. (2022). Insects as a feed ingredient for fish culture: Status and trends. Aquaculture and Fisheries 7: 166-178

23 Van Spankeren, M.. (2023). Life cycle assessment for insect ingredients sets a new industry standard. Aquafeed: Advances in Processing & Formulation 15(1): 27-29

24 Sandström, V., Chrysafi, A., Lamminen, M. et al. Food system by-products upcycled in livestock and aquaculture feeds can increase global food supply. Nat Food 3: 729–740. doi.org/10.1038/s43016-022-00589-6

25 Aquafeed (2023). Could plastic-fed waxworms be an aquafeed ingredient for farmed fish? Accessed 7-18-23. Available at: www.aquafeed.com/newsroom/news/could-plastic-fed-waxworms-be-an-aquafeed-ingredient-for-farmed-fish/

26 The Fish Site (2018). Insect meal gains US fish feed approval. Accessed 3-27-23. Available at: https://thefishsite.com/articles/insect-meal-gains-us-fish-feed-approval

27 Krishfield, L. & Olson, S. (2020). Future Fish Feed: Forecasting Alternative Aqua Feed Ingredients. Lux Research

28 Rabobank (2021). No Longer Crawling: Insect Protein to Come of Age in the 2020s. Accessed 12/2/22. Available at: research.rabobank.com/far/en/sectors/animal-protein/insect-protein-to-come-of-age-in-the-2020s.html

29 Meticulous Research (2022). Black soldier fly market - global opportunity analysis and industry forecast (2022-2033). Black Soldier Fly Market by Size, Share, Forecasts, & Trends Analysis. (n.d.). Accessed 2-22-23. Available at: https://www.meticulousresearch.com/product/black-soldier-fly-market-5074

30 Sarker, P. K. (2023, February 9). Microorganisms in fish feeds, technological innovations, and key strategies for Sustainable Aquaculture. MDPI. Accessed 2-20-23. Available at: https://www.mdpi.com/2076-2607/11/2/439?type=check_update&version=2

31 Bryne, J. (2023). Finnish protein innovator eniferBio raises 11m EURO from investors. Accessed 7-18-23. Available at: https://www.feednavigator.com/Article/2023/04/19/Finnish-protein-innovator-enifer-Bio-raises-11m-from-investors

32 Jackson, L. (2023). Black soldier fly larvae meal producers get innovative, Collaborative - Responsible Seafood Advocate. Accessed 7-18-23. Available at: https://www.globalseafood.org/advocate/black-soldier-fly-larvae-meal-producers-get-innovative-collaborative/

33 Food and Agriculture Organization of the United Nations (FAO) (2022). The Growth of Single-Cell Protein in Aquafeed. Accessed 7-18-23. Available at: www.fao.org/3/cc0732en/cc0732en.pdf

34 Frost and Sullivan (2018). Emerging Protein Sources for Fish Feed— Future Tech TechVision Opportunity Engine. TechVision Opportunity Engines / D835 / 31. November 23, 2018.

35 Glencross, B.D., Huyben, D. & Schrama, J.W. (2020). The Application of Single-Cell Ingredients in Aquaculture Feeds—A Review. Fishes 5(3): 22; https://doi.org/10.3390/fishes5030022

36 Perishable News (2011). Verlasso Breakthrough Brings Harmony to Aquaculture. Accessed 3-29-22. Available at: www.perishablenews.com/seafood/verlasso-breakthrough-brings-harmony-to-aquaculture/

37 The Guardian (2013). Will a failure to consider GM hold back sustainable fish farming? Accessed 3-29-23. Available at: www.theguardian.com/sustainable-business/blog/failure-gm-sustainable-fish-farming

38 Intrafish (2019). Verlasso farms moving to Magallanes; fish using new feed formulation. Accessed 3-29-23. Available at: www.intrafish.com/aquaculture/verlasso-farms-moving-to-magallanes-fish-using-new-feed-formulation/2-1-515639

39 OAA (2021). 5 Things to Know About Aquafeeds. Accessed 7-18-23. Available at: https://www.fisheries.noaa.gov/feature-story/5-things-know-about-aquafeeds

40 Voorhees, T. (2023). Personal communication 3-24-23.

41 The Fish Site (2023). NovoNutrients raises $4.7 million. Accessed 2-8-23. Available at: https://thefishsite.com/articles/novonutrients-alternative-aquaculture-feed-ingredientsraises-4-7-million

42 Sabbagh, J. (2017). Calysta, Cargill starts construction of FeedKind's US facility. Accessed 7-18-23. Available at: https://www.aquaculturenorthamerica.com/calysta-cargill-starts-construction-of-feed-kinds-us-facilit-1464/

43 Iowman, V. (2021). Calysta announces $39 million investment to fund Global Expansion Plans. FeedKind®. Accessed 2-8-23. Available at: https://feedkind.com/calysta-announces-39-million-investment-fund-global-expansion-plans/

44 Calysta (2013). Calysta completes $3 million Series a financing. Accessed 12-4-23. Available at: calysta.com/calysta-completes-3-million-series-financing/

45 Calysta (2015). Calysta Completes $10 Million Series B Financing. Accessed 12-4-23. Available at: calysta.com/calysta-completes-10-million-series-b-financing/

46 Calysta (2016). Calysta Completes $30 million Series C Financing, Accelerating the Introduction of FeedKindTM Protein at Commercial Scale. Accessed 12-4-23. Available at: calysta.com/calysta-completes-30-million-series-c-financing-accelerating-the-introduction-of-feedkind-protein-at-commercial-scale/

47 Ngige, L. (2023). Entocycle lands $5m Series A from Climentum, Lowercarbon Capital to roll-out precision ag tech for insect farms. Accessed 7-18-23. Available at: https://agfundernews.com/breaking-entocycle-lands-5m-series-a-from-climentum-lowercarbon-capital-to-roll-out-precision-ag-tech-for-insect-farms

48 CBInsights (2023). Ittinesct. Accessed 7-18-23. Available at: https://www.cbinsights.com/company/ittinsect

49 CBInsights (2023). Brilliant Planet. Accessed 7-18-23. Available at: https://www.cbinsights.com/company/susewi

50 CBInsights (2023). Nasekomo. Accessed 7-18-23. Available at: https://www.cbinsights.com/company/nasekomo

51 CBInsights (2023). Symbiobe. Accessed 7-18-23. Available at: https://www.cbinsights.com/company/symbiobe

52 AFN (2022). Brief: Nutrition Technologies lands $20m to expand insect-protein operation across Asia. Accessed 7-18-23. Available at: https://agfundernews.com/asias-first-industrial-insect-company-nutrition-technologies-closes-20m-equity-round

53 CBInsights (2023). Biovolf. Accessed 7-18-23. Available at: https://www.cbinsights.com/company/biovolf

54 CBInsights (2023). InnovaFeed. Accessed 3-2-23. Available at: https://www.cbinsights.com/company/innovafeed

55 BNN Bloomberg. (2023). The World's Biggest Bug Farm Wants to Decarbonize Fishmeal. Accessed 7-18-23. Available at: https://www.bnnbloomberg.ca/the-world-s-biggest-bug-farm-wants-to-decarbonize-fishmeal-1.1913809

56 Reidy, J. (2022). Innovafeed reaches $450 million financing. Accessed 12-4-23. Available at: www.meatpoultry.com/articles/27294-innovafeed-reaches-450-million-financing

57 Fletcher, R. (2023). The startup that plans to scale-up land-based Artemia production. Accessed 12-4-23. Available at: thefishsite.com/articles/the-startup-that-plans-to-scale-up-land-based-artemia-production-aquanzo

58 Rosati, F. (2023) Biotech startup Ittinsect raises €750,000. Accessed 12-4-23. Available at: ittinsect.com/en/news-en/biotech-startup-ittinsect-raises-euro-750000/

59 Rossingh, D. (2022). Insect breeder protix raises €50m as impact investors catch the bug. Accessed 7-18-23. Available at: https://impact-investor.com/insect-breeder-protix-raises-e50m-as-impact-investors-catch-the-bug/

60 Burwood-Taylor, L. (2017). Protix Raises $50m in Largest Insect Farming Investment on Record. Accessed 12-4-23. Available at: agfundernews.com/protix-raises-50m-in-largest-insect-farming-investment-on-record

61 Soto, J.O., de Jesús Paniagua-Michel, J., Lopez, L., & Ochoa, L. (2015). Functional feeds in aquaculture. In Springer Handbook of Marine Biotechnology (pp. 1303– 1319). Berlin Heidelberg: Springer.

62 Leal, C.L. & Calado, R. (2019). The key role of functional aquafeeds to achieve a more sustainable aquaculture. J. World Aquacult. Soc. 50: 1044-1047. Available at: https://onlinelibrary.wiley.com/doi/epdf/10.1111/jwas.12674

63 Stentiford, G.D. (2019). Solving the $6 billion per year global aquaculture disease problem. Marine Science Blog. Accessed 3-31-23. Available at: marinescience.blog.gov.uk/2017/02/02/solving-the-6-billion-per-year-global-aquaculture-disease-problem/

64 Kumar, V., Roy, S., Behera, B. K., Bossier, P., & Das, B. K. (2021. Acute hepatopancreatic necrosis disease (AHPND): Virulence, pathogenesis and mitigation strategies in shrimp aquaculture. Toxins 13(8): 524

65 Alune (2020). Everything you need to know about EMS in shrimp farming. Accessed 3-31-23. Available at: https://thefishsite.com/articles/everything-you-need-to-know-about-ems-early-mortality-syndrome-in-shrimp-farming

66 Holmyard, N. (2019). The sticky problem of sea lice – and what's being done to stop them. Accessed 3-31-23. Available at: www.seafoodsource.com/news/aquaculture/the-sticky-problem-of-sea-lice-and-what-s-being-done-to-stop-them#:~:text=They%20cause%20physical%20damage%20and,infestation%20can%20make%20salmon%20unmarketable

67 Meissner, D. (2023). Fisheries Department says it will shut 15 salmon farms off B.C.'s coast to protect wild fish. The Canadian Press. Accessed 3-31-23. Available at: https://www.cbc.ca/news/canada/british-columbia/fish-farms-not-renewed-1.6752997

68 Byrne, J. (2020). KnipBio says its SCP meal has benefits for RAS production. Feed Navigator. Accessed 8-2-23. Available at https://www.feednavigator.com/Article/2020/08/27/KnipBio-says-its-SCP-meal-has-benefits-for-RAS-production#:~:text=KnipBio%20reports%20that%20fish%20fed,flavors%20in%20RAS%2Draised%20fish.)

69 Einstein-Curtis, A. (2018). KnipBio's alt protein may support, boost growth in rainbow trout. Feed Navigator. Accessed 8-2-23. Available at https://www.feednavigator.com/Article/2018/12/06/KnipBio-s-alt-protein-may-support-boost-growth-in-rainbow-trout

70 Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., Little, D. C., Lubchenco, J., Shumway, S. E., & Troell, M. (2021). A 20-year retrospective review of Global Aquaculture. Nature 591: 551-563

71 Yanong, R.P.E. (2018). Use of vaccines in finfish aquaculture. Accessed 7-18-23. Available at: https://edis.ifas.ufl.edu/publication/FA156

72 The Fish Site (2022). How do oral vaccines work in aquaculture? Accessed 4-12-23. Available at: https://thefishsite.com/articles/how-do-oral-vaccines-work-in-aquaculture#:~:text=Oral%20vaccines%20can%20be%20delivered,rotifers%2C%20water%20fleas%20and%20Artemia

73 Alday-Sanz, V. & Smith, V. (2007). Shrimp lack appropriate cells, pathways to respond to specific pathogens and the long-term 'memory' to deal with recurring infections. Accessed 7-18-23. Available at: https://www.globalseafood.org/advocate/why-shrimp-cannot-be-vaccinated/

74 Feednavigator (2023). Disease management in aquaculture: 'it is about tipping the balance in favor of the animal'. Accessed 5-1-23. Available at: https://www.feednavigator.com/Article/2023/04/26/Disease-management-in-aquaculture-It-is-about-tipping-the-balance-in-favor-of-the-animal

75 Pedersen, E. (2023). Personal communication 4/14/23.

76 CBInsights (2023). BiOwiSH. Accessed 3-2-23. Available at: https://www.cbinsights.com/company/biowish-technologies-international

77 Hatchery International (2021). Sundew acquires MicroSynbiotiX with a potential oral vaccine against WSSV in shrimp. Accessed 7-18-23. Available at: https://hatcheryfm.com/products/suppliers-news/sundew-acquires-microsynbiotix-with-a-potential-oral-vaccine-against-wssv-in-shrimp/

78 Proteon Pharmaceuticals (2021). Proteon Pharmaceuticals Secures 21 million Euro to Accelerate Growth. Accessed 12-4-23. Available at: www.proteonpharma.com/proteon-pharmaceuticals-secures-21-million-euro-to-accelerate-growth-2/

79 Aquafeed (2022). Aqua-Spark invests in microalgae company Kuehnle AgroSystems. Accessed 12-4-23. Available at: www.aquafeed.com/products/suppliers-news/aqua-spark-invests-in-microalgae-company-kuehnle-agrosystems/

80 ViAqua Therapeutics (2023). ViAqua Therapeutics Announces $8.25M Investment Led by S2G Ventures to Scale RNA-Based Solutions in Aquaculture. Accessed 12-4-23. Available at: www.prnewswire.com/news-releases/viaqua-therapeutics-announces-8-25m-investment-led-by-s2g-ventures-to-scale-rna-based-solutions-in-aquaculture-301917390.html

81 Kramer, L. (2019). Norway-based Molofeed's microcapsules deliver slow-release larval feed. Accessed 8-25-23. Available at: https://www.globalseafood.org/advocate/early-stage-diet-innovator-secures-aqua-spark-investment/

82 Dauda et al. (2019). Waste production in aquaculture: Sources, components and managements in different culture systems. Aquaculture and Fisheries 4(3): 81-88

83 Wang et al. (2012). Discharge of nutrient wastes from salmon farms: environmental effects, and potential for integrated multi-trophic aquaculture. Aquacult Environ Interact 2: 267-283

84 Føre, M., Frank, K., Norton, T., Svendsen, E., Alfredsen, J.A., Dempster, T., Eguiraun, H., Watson, W., Stahl, A., Sunde, L.M., Schellewald, C., Skøien, K.R., Alver, M.O. & Berckmans D. (2018). Precision fish farming: A new framework to improve production in aquaculture. Biosystems Engineering 173: 176-193

85 PR Newswire (2022). Precision Aquaculture Market size worth $933.56 Million, Globally, by 2028 at 13.4% CAGR: Verified Market Research®. Accessed 7-18-23. Available at: https://www.prnewswire.com/news-releases/precision-aquaculture-market-size-worth--933-56-million-globally-by-2028-at-13-4-cagr-verified-market-research-301486374.html

86 Hung, C.-C., Tsao, S.-C., Huang, K.-H., Jang, J.-P., Chang, H.-K., & Dobbs, F. C. (2016, August 24). A highly sensitive underwater video system for use in turbid aquaculture ponds. Nature News. Retrieved April 3, 2023, from https://www.nature.com/articles/srep31810

87 The Fish Site (2023). Indonesian aquaculture startup breaks records with $90 million raise. Accessed 2-16-23. Available at: https://thefishsite.com/articles/indonesian-aquaculture-startup-breaks-records-with-90-million-raise

88 Shu, C. (2023). Indonesian aquaculture startup eFishery nets $200M at unicorn valuation. Accessed 7-18-23. Available at: https://techcrunch.com/2023/07/07/efisher-series-d/

89 CBInsights (2023). Poseidon -AI. Accessed 7-18-23. Available at: https://www.cbinsights.com/company/poseidon-ai

90 CBInsights (2023). DELOS. Accessed 3-2-23. Available at: https://www.cbinsights.com/company/delos

91 ScootScience. (2022). Scoot science announces $4.1M in seed funding. Accessed 5-5-23. Available at: https://www.scootscience.com/blog/seed_funding

92 Aquabyte (2022). AQUABYTE closes $25M series B funding to meet World's demand for healthy, sustainable fish. Accessed 5-5-23. Available at: https://aquabyte.ai/aquabyte-closes-25m-series-b-funding-to-meet-worlds-demand-for-healthy-sustainable-fish/

93 Aquabyte (2022). Aquabyte closes $25M series B funding to meet world's demand for healthy, sustainable fish. Accessed 12-4-23. Available at: aquabyte.ai/aquabyte-closes-25m-series-b-funding-to-meet-worlds-demand-for-healthy-sustainable-fish/#:~:text=With%20this%20Series%20B%20round

94 CBInsights (2023). Umitron. Accessed 3-2-23. Available at: https://app.cbinsights.com/profiles/c/ZKbx4/overview

95 Mullen, A. (2022). Wittaya Opening Singapore Office. Entrevestor. Accessed 8-2-23.

96 ReelData (2023). Artificial Intelligence for Land-Based Aquaculture: Maximize Growth, Minimize Costs, and Reduce Risk. Accessed 7-18-23. Available at: https://www.reeldata.ai/

97 ReelData AI. (2023). ReelData AI Announces $8M Series A Round. Entrevestor. Accessed 8-2-23. Available at: https://www.prnewswire.com/news-releases/reeldata-ai-announces-8m-series-a-round-301718664.html

98 Gezellus, H. (2022). Aqua-Spark's Bluegrove raises $13 million in first round of Series B funding. Accessed 8-25-23. Available at: https://www.intrafish.com/finance/aqua-spark-s-bluegrove-raises-13-million-in-first-round-of-series-b-funding/2-1-1146542

99 Asche, F., Anderson, J.L., Botta, R., Kumar, G., Abrahamsen, E.B., Nguyen, L.T., & Valderrama, D. (2021). The economics of shrimp disease. Journal of Invertebrate Pathology 186: 107397

100 USDA (2022). Salmon Overview. Accessed 4-6-23. Available at: apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Salmon%20Overview_Santiago_Chile_CI2022-0008.pdf

101 CAT (2023). Salmon Rickettsial Syndrome (SRS). Accessed 4-6-23. Available at: aquatechcenter.com/disease_challenge/salmon-rickettsial-syndrome-srs/#:~:text=Summary%3A,in%20Coho%20and%20Atlantic%20salmon.

102 Molinari, C. (2022). Chile's salmon farmers defend highest antimicrobial use since 2017. Accessed 4-6-23. Available at: https://www.seafoodsource.com/news/aquaculture/chilean-salmon-farmers-rush-to-defend-highest-antimicrobial-use-in-5-years-following-sernapesca-report

103 Miller, J.A. (2018). RAS in the USA: Fad or future? Accessed 4-12-23. Available at: www.globalseafood.org/advocate/ras-in-the-usa-fad-or-future/

104 Bregnballe, J. (2015). A Guide to Recirculation Aquaculture. Available at: www.fao.org/3/i4626e/i4626e.pdf

105 Innovasea (2021). Feeding is Fundamental to a Successful Recirculating Aquaculture System (RAS). Accessed 4-12-23. Available at: www.innovasea.com/insights/feeding-fundamental-to-successful-recirculating-aquaculture-system/

ABOUT NEW ENGLAND AQUARIUM AND SEAAHEAD, INC.

The New England Aquarium is a global leader in marine science and conservation, with a 50-year legacy of protecting the blue planet and advocating for oceans. Our scientists lead the way in marine research and data-driven conservation solutions, offering practical solutions to mitigate human impacts on the ocean. The Aquarium serves as a responsive community resource that attracts and involves the broadest possible audience; seeks a culturally diverse staff and governing board that reflects our community; adheres to the highest standards of animal stewardship; and is committed to delivering the highest quality visitor experience in a welcoming and enjoyable manner that inspires awe, curiosity, understanding, caring, and action. The Aquarium also provides mentors, experts, facilities, labs, and field-testing opportunities to guide start-ups and corporations, and is the only ocean-focused nonprofit institution in the hub of Boston, contributing $269M+ to the Boston and Massachusetts economies in 2019.

To learn more visit: **www.neaq.org**

SeaAhead is a public benefit corporation with the mission of increasing innovation for the ocean and creating a world-class hub for the New England bluetech cluster that supports venture development, technology commercialization and corporate innovation. SeaAhead founded the region's first dedicated Bluetech Innovation Hub, located at the Cambridge Innovation Center (CIC), and since its founding in 2018, the team has built up 80+ ocean-related startup members that range in scope from autonomous underwater vehicles to digitizing the seafood value chain to green and smart shipping. SeaAhead has also assembled and managed the BlueSwell Incubator in a previous and ongoing partnership with the New England Aquarium. SeaAhead's Blue Angels group was founded specifically to support early-stage bluetech innovators who were challenged to find resources, including funding and ocean-related expertise. Through the Blue Angels Investment Group, these bluetech innovators can bring their innovations and positive impact to reality through investment.

To learn more visit: **www.sea-ahead.com**

ABOUT THE AQUAFEED INNOVATION PROJECT LEADS

Luke Sawitsky, MBA/MS

Principal, SeaAhead

Luke has prior experience in fisheries, both as a seafood buyer and in permit and quota investing, in business development for single cell protein alternatives, and other roles at the intersection of innovation and the Blue Economy. At SeaAhead, Luke's work focuses on the SeaAhead Blue Angels investor group and other work focused on bringing catalytic capital to early-stage bluetech startups. Luke has an MBA and MS in Sustainable Systems from the University of Michigan, and a BA in Political Science and International Studies from Northwestern University.

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Matt Thompson, MS

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Matt has over fifteen years of experience collaborating with industry, NGOs and other stakeholders to promote environmentally responsible aquaculture practices throughout the global seafood and marine extracts industry. Through his work he has helped set global certification standards for responsible aquaculture practices, advises the Aquarium's corporate partners on strategies and sources to build environmentally responsible supply chains, and mentors startups with innovative solutions to aquaculture's biggest challenges through the BlueSwell bluetech incubator program. Matt has a master's degree in aquaculture from Stirling University in the UK.

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