PROTEOMICS IN AQUACULTURE: UNLOCKING THE MOLECULAR MACHINERY FOR SMARTER FARMING

By Sarah Carroll

By tapping into the molecular machinery of fish, aquaculture is gaining new tools for precision health, nutrition and welfare. An example is proteomics which can be defined in layman's terms as the study of proteins, what they do and how they respond to changes in the environment. In addition to other parameters, proteomics can be used to identify biomarkers for disease detection and assess the impact of feed formulations, thus optimising sustainable fish growth, ensuring the quality and safety of aquatic feeds, and promoting business growth and profitability.

Credit: MariHealth Soultions

Figure 1. Key concerns across the aquaculture industry—from feed costs to biosecurity—can benefit from deeper biological insight powered by proteomics.

Just like in human health, where decoding proteins helps personalise medicine, the aquaculture industry is beginning to see the transformative power of omics technologies, and indeed, proteomics – a deep-dive into all the proteins that make an organism tick. As someone who has spent the last few years immersed in this space, I can say this: we're only just scratching the surface of what's possible.

With aquaculture growing rapidly to meet global seafood demand, the sector is also grappling with complex challenges, from rising feed costs and environmental pressures to persistent disease outbreaks and welfare concerns. But what if we could understand fish health and performance not just by how they look or grow, but by what's happening inside them at a molecular level?

Proteomics: Not just for scientists

Think of DNA as the instruction manual. Proteins? They're the workers following those instructions. Proteomics is the study of all these proteins – what they are, what they do, and how they respond to changes in the environment.

Thanks to tech advances, we can now measure thousands of proteins from a single sample. This gives us an incredibly detailed picture of fish biology in action. It might sound like laboratory coat territory, but the real-world applications for farmers and feed producers are tangible, timely and powerful. For instance, rather than relying solely on external symptoms, proteomics can reveal the earliest signs of physiological changes, long before they become visible. That opens the door to a new level of decision-making, where producers can act earlier and with greater precision.

Tackling aquaculture's core pain points

Let's face it: disease, feed costs and welfare aren't just scientific problems; they're business problems. Proteomics is helping us:

- Spot disease before it becomes visible or spreads;
- Fine-tune feed for better performance and less waste; and
- Understand how stress affects fish at a physiological level.

As aquaculture systems become more intensified and complex, the need for precision tools has never been greater. Environmental pressures like fluctuating temperatures, low oxygen levels, and pollution can trigger invisible stress responses that reduce growth, suppress immunity, and increase disease risk. Proteomics allows us to track those molecular responses.

Diagnosing disease before the crash

Traditionally, we react to disease when symptoms appear, often too late. Proteomics flips this on its head by detecting subtle protein changes that signal the early stages of infection or inflammation. In Atlantic salmon, for instance, we now know that proteins like galectin-3-binding protein spike when Heart and Skeletal Muscle Inflammation (HSMI) is developing. Spotting these signals early allows for targeted responses that can save stock, time, and resources.[1]

This approach is also useful in differentiating between similar disease presentations. Where traditional diagnostics might struggle, proteomics can clarify what's happening under the surface. It gives us a nuanced view of host-pathogen interactions and the immune response, which is critical when developing targeted vaccines. Beyond diagnostics, proteomics is proving valuable in therapeutic development, identifying candidate antigens for vaccines or pinpointing metabolic pathways to target with functional feed ingredients. All of this contributes to a more proactive, less antibiotic-reliant industry.

[1] Fæste CK, Rangel-Huerta OD, Anonsen JH, Tartor H, Kuiper RV, Dahle MK. 2024. Potential plasma biomarkers for the onset of heart and skeletal muscle inflammation from Piscine orthoreovirus-1 infection in Atlantic salmon (Salmo salar). Aquaculture. 15; 590.

Figure 2. Insect-based proteins, like these black soldier fly larvae, are emerging as sustainable alternatives in aquafeeds. Proteomics helps verify their metabolic and immune impacts in fish.

Building better feeds

Feed makes up the bulk of production costs, and tweaking formulations is both a science and an art. Proteomics takes out some of the guesswork by showing exactly how alternative ingredients like insect-based proteins affect metabolism, gut health and immune function. We've seen, through detailed protein profiling, that some insect meals enhance lipid metabolism and avoid triggering unwanted immune reactions. This kind of information is gold when you're formulating next-gen diets that need to be both effective and sustainable.

Proteomics also helps us understand nutrient bioavailability and absorption efficiency. By comparing the proteomes of high-performing and low-performing fish under the same diet, we can identify proteins associated with superior feed conversion, digestion or stress resilience. This supports selective breeding or targeted supplementation.

Even beyond ingredient testing, proteomics gives us insight into how environmental changes (such as heatwaves or poor water quality) affect nutrient use. This can guide feed adjustments that help buffer fish against short-term stressors.

A new lens on welfare

Fish stress is real, but it's not always obvious. Crowding, handling, poor water quality – all of these take a toll. Proteomics can pick up on physiological stress signatures long before fish start behaving abnormally or showing external symptoms. In trout, researchers have identified distinct protein shifts in the liver after acute crowding stress. These biomarkers can one day help farmers monitor welfare in real time and adjust conditions proactively, rather than reactively.[2]

Fish welfare is no longer just a moral imperative; it's a productivity issue. Chronic stress reduces growth, suppresses immunity, and increases susceptibility to disease. But until recently, we lacked objective, reliable biomarkers to measure it. With proteomics, we can identify proteins that fluctuate under stress and track how long recovery takes. This is essential not just for farming protocols, but also for informing transport practices, harvest procedures, and grading systems that prioritise animal health.

Zooming in: What we learned from smoltification in salmon

In 2024, MariHealth Solutions, supported by Nova Sea and Helgeland Smolt, conducted a larger-scale study of smoltification – the critical transition Atlantic salmon make from freshwater to seawater. This is a notoriously tricky period with high mortality and performance variability, but it's also a perfect use case for proteomics.

By collecting blood samples across four time points (pre-smolt, smolt, 3 weeks and 3 months post-seawater transfer), the molecular shifts driving adaptation were mapped, as illustrated in Figure 3.

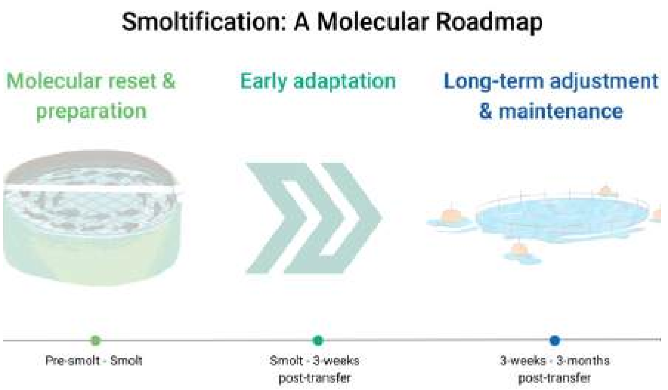
- In the freshwater stages, there was intense reprogramming of protein production.

[2] *Naderi M, Keyvanshokooh S, Ghaedi A, Salati AP. 2018. Effect of acute crowding stress on rainbow trout (Oncorhynchus mykiss): A proteomics study. Aquaculture. 495: 106–14.*

- The early seawater stage (3 weeks) showed activation of osmotic and oxidative stress pathways – essentially the fish learning to cope with their new salty home.
- Even 3 months post-transfer, the fish were still showing immune system modulation, indicating that adaptation is a longer process than we might think.

The implications go beyond academic curiosity. Understanding this physiological timeline offers producers a roadmap to:

- Better schedule transfers based on biological readiness.
- Adjust feed formulations to support energy-intensive adaptation.
- Develop tailored treatments that strengthen immune function during vulnerable stages.



Credit: MariHealth Soultions

Figure 3. Smoltification is a gradual and complex physiological journey. Proteomics reveals how salmon adjust across each stage—from molecular preparation to long-term marine adaptation.

The insights gained from the study not only contribute to the limited proteomic research in this area, but highlight the energetically demanding nature of smoltification. It's not a one-off stress response but a prolonged physiological transition where immune resilience remains crucial. These findings provide a framework for designing smarter farming strategies during one of the most critical windows in salmon production. Additionally, specific protein markers that distinguish successful smolt adaptation from sub-optimal transitions, were identified. These could form the basis of predictive assays in future, helping producers flag underperforming batches before problems arise.

Looking ahead: the proteomics frontier

The industry is moving toward an era of precision aquaculture, and omics technologies are at the core of that movement. Paired with machine learning, proteomics now allows us to detect patterns and predict outcomes with increasing accuracy, be it in disease diagnosis, nutritional efficiency, or even breeding programs. For example, AI models trained on proteomics data could eventually predict when a population is approaching a stress threshold, or simulate how different feed ingredients would affect immune responses.[3] That's the level of insight we're heading toward. As tools become more affordable and databases more robust, proteomics will no longer be a luxury – it will be a necessity.

But hurdles remain. Analytical complexity, cost, and the need for bioinformatics expertise still limit widespread adoption. To truly scale, there is a need for open-access databases for aquaculture species; validation of key biomarkers in field conditions; and partnerships between industry, academia and tech providers.

Practical steps for adoption

Here's the best part: you don't need a mass spectrometer on your farm or operation. Strategic partnerships with companies like MariHealth Solutions allow producers to tap into proteomics through simple, non-lethal sampling and accessible reporting. Routine health assessments, welfare audits, feed trials, and even selective breeding can all benefit from proteomics-based insights. It's about integrating this molecular lens into day-to-day operations; not replacing what works, but enhancing it.

The next big push? Building species-specific protein databases, validating key biomarkers in the field, and embedding this data into decision-making software. This will bring proteomics out of the laboratory and into the hands of producers where it can do the most good.

Why it matters

Just like with AI, failing to adopt next-gen biotech tools like proteomics means flying blind. And in an increasingly competitive and regulated industry, that's not a luxury anyone can afford. Proteomics gives us the depth needed to make informed, timely and sustainable choices. We're not saying it replaces your vet or your feed supplier but it does offer a powerful new layer of insight that can help both do their jobs better. In many ways, proteomics is about going back to the basics – understanding the biology of the animal in front of us. It's about bringing nuance and precision to a field that has long relied on averages and assumptions.

As we face mounting pressure to improve efficiency, reduce environmental impact, and ensure fish welfare, the ability to listen to what the fish are telling us, at a molecular level, is an advantage we can't afford to ignore.

[3] *Sanches PHG, de Melo NC, Porcari AM, de Carvalho LM. 2024. Integrating Molecular Perspectives: Strategies for Comprehensive Multi-Omics Integrative Data Analysis and Machine Learning Applications in Transcriptomics, Proteomics, and Metabolomics. Biology. 13(11): 848.*

Dr Sarah Carroll *is the co-Founder and CEO of MariHealth Solutions (https://www.marihealthsolutions.com/), whose current technology offering stems from some of her PhD research. Being passionate about sustainability and climate change research, she believes that innovative biotech is key to tackling many of the challenges humanity faces in the next 25 years and is strongly motivated to drive change through tangible solutions, particularly in aquaculture and global food security. As Robert Swan said, the greatest threat to our planet is the belief that someone else will save it. Beyond this, Dr Carroll is passionate about supporting other female-led startups in the blue economy, believing they are an underrepresented but crucial driving force in paving the way towards more sustainable practices and use of our ocean resources.*