CHAPTER 12

Current status and future horizons in sustainable aquafeed certification and circular production practices

*M.D. Cyrus, R.C. Neil, K. Condon and L. Nankervis**

Centre for Sustainable Tropical Fisheries and Aquaculture (CSTFA), College of Science and Engineering, James Cook University, Australia
**Correspondence: Leo.nankervis@jcu.edu.au*

Abstract

Progress in the certification sector has not kept pace with the speed of innovation in alternative aquafeed components, particularly when incorporating the impact of including agricultural waste streams. Assessing the sustainability of the diverse range of agricultural waste into aquafeed ingredients has necessitated a review of assessment matrices to adequately capture the impact of aquafeeds across a large range of supply chains. Moving away from relatively simplified matrices relating to fish meal usage, current assessments in sustainable practices are moving towards Life Cycle Analysis. Life Cycle Analysis captures the transfer of nutrients and energy within a system to assess the long-term sustainability of the process. The application of the LCA tool however risks overestimating the impact of aquafeed ingredients by attributing the impact of the entire production line of agricultural products into life cycle footprint of aquafeed production. Ironically, the process of LCA inadvertently leads to poor assessment outcomes that contradict the benefits of circularity in efficiently reducing and utilising waste streams to productive food outputs or improved ecological performance. Consequently, the traditional LCA tool is not ideal, and further developments such as current efforts towards economic allocation of environmental burden of co-products show promise.

Although aquaculture has turned to LCA as a measuring tool, the potential to utilise the tool to develop rather than measure more sustainable practices has rarely been recognised. Developing circularity and integrated processes like IMTA present opportunities to utilise nutrient cycling to substantially improve production both through contributions in feed and waste usage as well energy retention. However, IMTA is a complex system, with a large technical barrier to entry and success. To date there has been little government support to motivate businesses to integrate their production systems. Certification could become the driver in the next evolu-

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tionary step towards sustainable practice in aquaculture. This chapter outlines the contribution and evolution of certification programs to drive aquafeed innovation and presents the prospect that a similar drive in innovation could be achieved with certification programs that recognise the sustainability in harnessing nutrient cycling via circularity in aquaculture.

1 Background and context

As global demand for seafood increases, aquaculture continues to emerge as a pivotal solution to meet the needs of the future while simultaneously relieving pressure on wild fisheries. However, the growth of the aquaculture sector must occur in tandem with environmental and social responsibility. Sustainability refers to the capacity of aquaculture systems to meet current production needs without compromising the health of natural ecosystems or the ability of future generations to meet their own needs (Garlock et al., 2024). Sustainable practice includes minimizing resource depletion, maintaining ecosystem services, and ensuring economic and social equity. Sustainable aquaculture certification programs have evolved as both the impetus and illustration of sustainable practices in the aquaculture sector. Aquafeeds are the predominant mechanism for nutrient flow in aquaculture, and as such carry the major burden of environmental impact and economic cost through the aquaculture value chain. Aquafeeds have therefore emerged as a focal point of measuring and certifying sustainable production in aquaculture.

2 Certification of sustainable aquafeeds

Certification programs to demonstrate sustainable aquaculture first emerged in the 1990s through the work of Organics International to create a framework for aquaculture to ensure seafood quality without creating ecological damage (Saha, 2022). As the aquaculture sector evolved, multiple entities have created sustainability certifications, and standards have become more complex to incorporate a range of matrices to demonstrate economic, environmental and socially acceptable practice.

Certification programs have delivered a mechanism to drive change towards sustainability within the aquaculture sector by delivering clearly defined criteria that promote business innovation whilst also providing a point-of-sale mechanism to enable the conscientious consumer to provide an economic return to certified businesses. The programs vary considerably and have evolved into complex standards that contain elements beyond core criteria of food safety, efficient use of resource, animal welfare and habitat destruction.

Interestingly, in contrast to terrestrial livestock production, certification programs are rarely mandated in the country of production but rather compliance in sustainable practice has been driven by access to import markets. With an estimated global value of $192 Billion USD large import consumers in the EU (32%) and USA (17%) have particularly driven the need for demonstrated sustainable practice in global seafood production (FAO, 2024). Critical to the integrity of these programs is the third-party certification system, where the quality assurance auditing is performed independently of both the certified business or certifying body. However, uptake of the programs has been limited with the combined two largest certification programs, ASC (Aquaculture Stewardship Council) and BAP (Best Aquaculture Practices), accounting for approximately 3% of global aquaculture production (Naylor et al., 2021).

To complement certification programs which target the farmer and supply chains, the sustainable certification environment also includes ratings programs aimed at guiding the consumer towards purchasing of sustainably rated options in seafood. Ratings programs do not require subscription by producers and with an estimated 53% of global aquaculture rated by US Seafood Watch (Naylor et al., 2021) fill a significant gap to drive sustainable practice through the ethical consumer. In addition to aquaculture production several certifications have emerged within the aquafeed ingredient sector. Aquaculture certification and ratings environment include aquafeed assessment programs at the level of:

a. aquaculture producers (certification)
b. aquafeed ingredient producers (certification)
c. retail consumer (ratings)

2.1 Scale of Impact of certification on global aquaculture practice

Naylor et al. (2021) estimated 30–50 voluntary certification, labelling and rating schemes have been introduced with the intent to address sustainable aquaculture production. Until recently, the programs acted without collaboration or harmonisation which undermined both the efficacy of the certification program and presented a disjointed message to farmers, stakeholders, and consumers.

Five certification or ratings programs including the Aquaculture Stewardship council (ASC), Fair Trade USA, Marine Stewardship Council (MSC), Monterey Bay Aquarium Seafood Watch Program and the Sustainable Fisheries Partnership Foundation (SFP) recently formed the Certification and Ratings Collaboration (C&RC). The C&RC website www.certificationandratings.org hosts the Sustainable Seafood Data Tool (SSDT) (https://certificationandratings.org/datatool/) that summarises assessment data from each of their member platforms. In addition, organisations within the Global Seafood Alliance's Best Aquaculture Practices (BAP) program and Qingdao Marine Conservation Society are captured and the SSDT provides a significant resource for consolidation of data on environmental performance and human rights abuses and risks in seafood production. Latest results from the SSDT indicate approximately 52.9% of worldwide seafood production has been certified or rates for environmentally sustainable practice but within the seafood sector, when aquatic plants are excluded only 5.05% (4,965,478 mt) of aquaculture is certified by a third party certification program and a further 35% (34,468,531 mt) rated as green choices by ratings organisations (33,052,917 mt) (Seafood Certification & Ratings Collaboration 2025; www.certificationandratings.org accessed 24/4/2026).

3 Evolution of aquafeed certification: adoption to alternative ingredients

In recognition of the major contribution played by aquafeed on the three pillars of sustainable practice (economic, social and environmental), contemporary certification programs have extended criteria from production systems to also evaluate feed mills and aquafeed ingredients. At its most basic, the mass balance between feed consumed and fish growth is represented by feed conversion ratio (FCR). While FCR describes the biological transformation of feed mass to fish growth, in practice there are losses of stock associated with escapes or mortality, and feed is not entirely eaten. FCR is therefore often specified as biological (bFCR) and economic FCR (eFCR) to better describe feeding efficiency in aquaculture practice.

FCR or bFCR = Feed intake (g) / animal growth (g)

eFCR = Feed offered (kg) / biomass gain (kg)

Where biomass gain is the entire weight gain of the population for the given period.

Early recognition of the dependence of aquaculture on limited resources were initially primed towards use of wild fishery catches to produce fish meal and fish oil (Tacon & Metian, 2008). Using average yield of fish meal (22.5%) and oil (5%) from pelagic fisheries and applying an economic feed conversion ratio (eFCR) a Fish in: Fish out ratio was used to describe the degree to which wild fish was converted into more valuable aquaculture products. Thus, fish meal and oil were combined in a single value, representing the dependence of the aquaculture activity on reduction fisheries; those that primarily catch fish for processing into fish meal and oil rather than for more direct uses. In this context, the terms ‘wild’, ‘reduction’ and ‘forage’ are used interchangeably.

$$FIFO = eFCR\ x\ \frac{\%\ fish\ meal\ inclusion + \%\ fish\ oil\ inclusion}{Fish\ meal\ yield\ (22.5\%) + Fish\ oil\ yield\ (5\%)}$$

FIFO values less than one describe net production of fish, meaning that the aquaculture practice produces more fish than consumed in its feed. Efficiency of resource use into aquafeeds has improved in the first two decades of this century, with eFCR reported to have reached an average of 0.71 across the global aquaculture industry, with an average FIFO of 0.27 (Glencross et al., 2024). These values are skewed by the predominance of cyprinids in global aquaculture volume (FAO, 2024), however all species groupings are now reported to have FIFO less than one, apart from turtles, frogs and eels (Glencross et al., 2024). While production of these net fish consumers generally converts lower value forage fish into higher value products, the concept of value can be very subjective. Sustainability credentials are challenged by ascribing a higher value based on financial gain compared to social benefits of directly consuming forage fish.

Further challenges with FIFO arise through the calculation of yield from reduction fisheries. Even though they are derived from the same fisheries, fish meal and oil differ in their importance across aquafeeds, with salmon farming notably using similar inclusion of fish meal and oil despite the disparity of yields from source fisheries (Aas et al., 2022). A single calculation may not adequately describe dependency on the limiting components of the fishery effectively, leading to the development of separate forage fish dependency ratio calculations for fish meal and fish oil (Tacon et al., 2022).

Over time, the proportion of fish meal and oil has increasingly come from trimmings, with FAO (2024) estimates at 34.5 and 53.4% for trimmings contribution to global fish meal and oil supply, respectively, in 2022. FIFO was originally used to highlight the dependence of aquaculture on reduction fisheries, and trimmings were excluded from the calculation to support the reuse of these by-products. The literal interpretation of FIFO to include all fish inputs compared to all fish outputs may lead to inconsistency in allocation of trimmings. Therefore the Forage Fish Dependency Ratio (FFDR) was developed to intentionally articulate a reduction fisheries resource utilisation efficiency, while also dividing the calculations for meal ($FFDR_{FM}$) and oil ($FFDR_{FO}$). The FFDR also facilitates specific targets to be set for oil and meal utilisation efficiencies depending on the state-of-the-art nutrition science for different industries.

$$FFDR_{FM} = \% \text{ reduction fish meal/ fish meal yield } (24\%) \times eFCR$$

$$FFDR_{FO} = \% \text{ reduction fish oil/ fish oil yield } (5\%) \times eFCR$$

Further refinements on apportioning dependency on wild fish stocks have been suggested based on nutrient dependency (Ytrestøyl et al., 2015) or cost (Kok et al., 2020). Both methods recognise allocation based on motivation and value of the ingredient. In particular, economic Fish In: Fish Out (eFIFO) has been applied to capture the value of the fish input compared to the aquaculture product. For example, the eFIFO recognises fish by-products, which would typically enter the waste disposal stream, have a higher value in aquafeed than direct consumption of the by-product (Glencross et al., 2024).

Both the Aquaculture Stewardship Council (ASC) and Best Aquaculture Practices (BAP) contain standards for Feed Mills in addition to efficiency matrices within species specific aquaculture standards (grow out and hatchery) that assess sustainability of feed usage. Many criteria within Feed Mill certifications of both BAP and ASC relate to food safety and hygiene standards. However, both programs also require demonstrated traceability of feed ingredients that ensures both product providence along with assurance that employment at the ingredient source is neither child labour nor modern slavery conditions.

BAP Farm standard (3.1) for certification requires efficient use of fishmeal and fish oil for all production systems. The standard applies to non-salmonid fish or salmonids farmed outside of traditional sea cage systems, with the latter production system covered separately under the BAP Salmon Farm Standard (Issue 3.0 due for implementation 2026). The farm standard specifies that the farm shall obtain feed from BAP feed mills or feed mills that comply with feed mill standards regarding species of fishery origins and responsibly sourced soy ingredients. Farms must comply with Fish In: Fish Out (FIFO) and Forage Fish Dependency Ratios (FFDR). FIFO limits have been set based on demonstrated efficient industry examples, differentiated between species where data is available; whiteleg (1.0) and black tiger shrimp (1.2), tilapia (0.5), pangasius (0.3) and channel catfish (0.3); rainbow trout (not raised in sea cages, 1.2) and Atlantic salmon (raised in recirculation systems only, 1.4). In addition, the BAP Salmon Farm Standards (V2.4, 2023) require FIFO of 1.5 or less for salmonid fish production in marine sea cage aquaculture. Species for which reliably efficient industry data is not yet available shall not exceed the FIFO value of 4 where byproducts are not included in the calculation or 5 if fish processing by products are included. In addition, the BAP Feed Mill Standard (Issue 3.3) also currently dictates that 75% of fish meal and oil must come from certified fisheries (e.g. Marin Trust, MSC) or recognised fishery improvement programs (FIPs), 50% of soy products and 100% of palm oil also must come from certified sources and feed additives must be listed in current EU Register of feed additives or equivalent register. This standard has a clear aim for all fish, soy and palm ingredients to be certified, with progressively staged targets to achieve 100% certification. The feed mill must also certify that the feed does not contain aquatic protein from the same species as being farmed, however hydrolysates <10,000 Daltons of the same species are permissible.

In 2023 the ASC established a Feed Standard (V1.1 effective 1st November 2025). Environmental risk management in the ASC Feed standard recognises the risk of harvesting raw materials contributing to marine resource depletion through overfishing, illegal-and-unregulated-fishing, deforestation and land conversion associated with agricultural practices to produce non-marine ingredients. Social risks with aquafeed production in the ASC standard also prevent the use of child and forced labour in agriculture and fisheries and the management of adverse impacts of feed mills on surrounding communities (smell and industrial discharges). ASC focusses on improvement, setting higher standards for implementation of certified ingredient supply chains over time. This is not dissimilar to BAP's approach, since BAP have recently increased from 50% of marine ingredient certification to 75% and have targets stretching to 100% by 2030. The staged approach enables the supply chain to adapt over time, driving improvement without leaving the supply chain with a material shortage that would impede certified aquaculture production.

3.1 Marine ingredients certification

The traceability and providence of a range of marine by-products used in aquafeed created logistical difficulties to demonstrate sustainable practice in aquafeed standards. Sustainable practice in marine sourced components can occur through the Marine Stewardship Council (MSC) which certifies fisheries however the MSC program does not certify the supply chain of the ingredients beyond the harvest. Consequently, supplier groups have created specialised Aquafeed ingredient certifications that support the use of marine by-products including programs devised by The International Fishmeal and Fish Oil Organisation (IFFO) (https://www.iffo.com) leading to the development of Marin Trust (https://www.marin-trust.com). Approximately 45% of marine ingredients are certified as Marin Trust compliant materials (https://www.marin-trust.com/impacts/global-impact). In addition, in areas where the certification standard cannot be met, Marin Trust has a Fisheries Improver Project that can be deployed towards reaching sustainable practice. The SSDT also contains a marine ingredients subsector which indicates only a small proportion of marine ingredients are ranked as certified (currently 6.5%; MSC or BAP certified), best choice (4.9%; Seafood Watch Green) or good alternative choices (5.8% Seafood Watch Yellow) with respect to environmental assessment due to the low uptake of MSC and BAP certifications worldwide.

3.2 Alternative ingredients

Assessment and certification of the range of ingredients beyond marine sources in aquafeed is difficult to compile as each sector has varying degrees of maturity towards demonstrating sustainable practice. The US Soybean Meal Association refers to the third party certification of the soy sustainability assurance protocol (American Soybean Association (ASA), 2025). The degree of detail within certifications varies depending on the end user application of the ingredient. Similarly, several certification collaborations have been formed by stakeholders of the palm oil industry such as the EU palm oil alliance and Roundtable on Sustainable Palm Oil (RSPO) which contains organisations that have entered a voluntary agreement to advance and promote sustainable palm oil production (https://palmoilalliance.eu/).

The multitude of stakeholders within the aquafeed sector creates a complex network of data collection to meet the needs of certification of the aquaculture product. Global Good Agricultural Practices (Global G.A.P.) has recognised the challenges that alternative practice poses to certification and has adopted a life cycle analysis approach for assessment of sustainable practice.

3.3 Life cycle analysis

Life cycle analysis (LCA) recognises that however well intentioned, the adoption of ingredients derived from plants, single cell culture and animals proposed to replace fish meal and fish oil, can result in burden shifting rather than improved environmental/economic or social outcomes. For example, the assessed environmental benefit of the use of soybean meal to replace fish meal may be reduced if habitat destruction and use of water to grow the soy crop is considered in the assessment matrix over improvements to the FIFO ratio (Clawson et al., 2025).

Life Cycle Analysis (LCA) has been proposed as a robust matrix to ensure legitimate improved environmental outcomes is achieved with feed ingredient purchasing decisions (e.g. Maiolo et al., 2020). The LCA approach evaluates the impacts of aquafeed ingredients from "cradle to grave" which includes all stages of production of the ingredient from cropping to processing and distribution, consumption and waste disposal. In the case of many alternative ingredients, LCA is somewhat controversial as the approach creates a matrix that is in direct conflict with the intent of the LCA. In the case of agricultural or livestock by-product to create aquafeed ingredients, the assessment of environmental contributions in the production of the ingredient incorporates the entire product supply chain history rather than starting at the point of "by-product" generation. The extended supply chain history of circular products therefore expands the LCA footprint, making reuse of byproducts appear less environmentally sustainable than linear supply chain alternatives. In contrast, removing any allocation of by-products to LCA calculation impacts the scope of the analysis and ignores the increasing economic return that occurs as by-products transition to co-products. A promising approach to solve this issue comes in the allocation of LCA impact based on economics rather than mass. Where ingredients are traditionally assigned burden based on mass, environmental impacts are equally divided between primary and secondary products. However, in a similar manner to described for eFIFO above, economic allocation to LCA divides impact based on the drivers of production, and likely better represents practical environmental impacts. This approach has recently been applied to poultry by-products, demonstrating an order of magnitude difference in LCA measures for rendered animal materials, demonstrating lower impacts than fish meal and oil (Campos et al., 2020).

Feed clearly has the largest impact on sustainable production of animal products. Regardless of the approach taken to assess sustainability, the impact of feeds is largely dictated by the amount of the feed used per unit production of aquaculture product. The ingredients themselves have importance, however optimised sustainable production requires efficient use of nutrients as they are upscaled to more highly valued forms. Therefore efficient feed practices and optimising feeds towards species-specific nutrient requirements is a critical need for aquaculture sustainability. Similarly, retaining nutrients in the value chain and maximising production per nutrient input are further pillars of aquaculture sustainability.

3.4 Is circularity in nutrient cycling the next step toward sustainable aquaculture?

In aquaculture, circularity largely involves the reuse of nutrients and organic matter, valorisation of by-products, and development of feed and farming systems that align with natural cycles (Cunningham et al., 2022). When properly implemented, circular approaches can enhance sustainability by improving resource efficiency, reducing environmental impacts, and creating additional value streams, often in the form of alternative crops or co-products (Chary et al., 2024). When circular economy practices are embedded into operational models of well-managed aquaculture systems, the synergistic nature of sustainability can simultaneously improve environmental, economic, and social performance (Garlock et al., 2024). The ability to implement circularity varies depending on the aquaculture production system and associated nutrient streams.

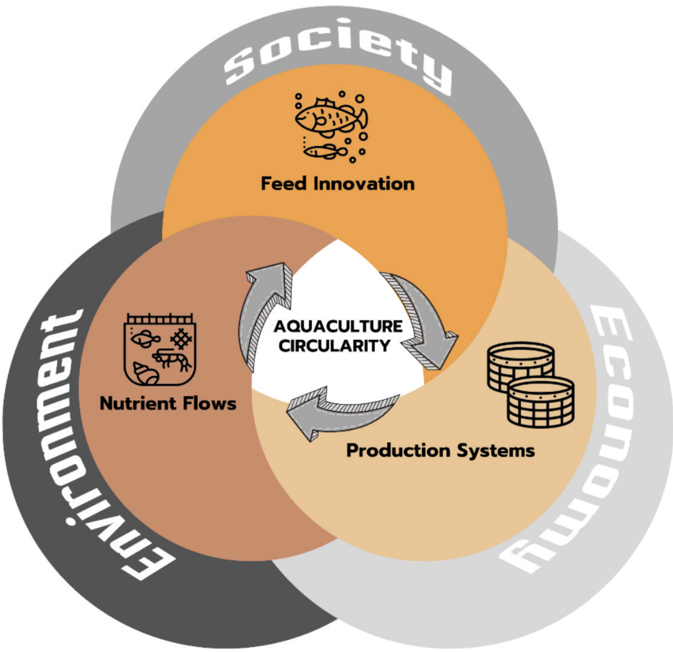

FIGURE 12.1 Interaction of the 3 pillars of sustainability (Environment, Society and Economy) with 3 key focus areas required for aquaculture circularity (feed innovation, production systems, and nutrient flows)

The concept of circularity builds on closing resource loops, transforming linear production models that follow a 'take-make-dispose' trajectory into regenerative systems where waste is minimized, and outputs are reused. The concept of circularity is relevant to aquafeed because circularity models involve the conversion of waste into aquafeed ingredients however, circularity potential can be added to both ends of the production chain to optimise the retention and value of nutrients.

4 Aquaculture production systems and nutrient flow

Aquaculture production systems vary widely in complexity, intensity, and environmental footprint. These systems generally fall into categories such as extensive pond systems, open-water cages, flow-through raceways, and Recirculating Aquaculture Systems (RAS), each interacting with their environment differently and presenting trade-offs in energy, land, and water use. However, in general standard monoculture systems retain less than 45% of nitrogen and 40% of phosphorus from feed inputs in the harvested biomass (Boyd, 2003; Dalbem Barbosa et al., 2024; Summerfelt & Penne, 2007), with the remainder entering the receiving environment if not managed adequately.

Extensive pond systems, which often rely on natural productivity (e.g., plankton, detritus), typically require little or no commercial feed. However, they can still generate nutrient-rich sediments and discharges that may affect nearby ecosystems, particularly when not integrated with crop or livestock production. Feed addition and energy use increase with the shift from extensive to semi-intensive farming practices, broadening the impact due to a more complex supply chain. However, efficiency through increased management and increased yield in semi-intensive systems can offset additional feed burden when expressed per unit production (Wilfart et al., 2013). Open cage systems typically have low infrastructure and energy needs but release nutrients and organic matter into surrounding waters, contributing to local eutrophication and benthic degradation if management or the farm environment are not conducive to nutrient dispersion. RAS, by contrast, excel in waste capture and water reuse (recycling up to 99% of water), but their high energy demands (especially for pumping, filtration, temperature control) can elevate greenhouse gas emissions particularly when powered by non-renewable energy. In general, though, intensification improves both bFCR and eFCR, outweighing other impacts on LCA metrics and improving sustainability measures (Ghamkhar et al., 2021).

All these systems, do however, ultimately result in the release of nutrient waste in the form of uneaten feed, faeces, and metabolic by-products into the surrounding environment be it at varying levels. Improving nutrient retention is therefore consistently identified in LCAs as a critical pathway for reducing aquaculture's environmental footprint and improving sustainability (Bohnes et al., 2019). Traditionally viewed as a liability, nutrient waste is increasingly being reconsidered as a potential resource within Circular Economy frameworks. One approach that aims to improve aquaculture circularity by addressing feed innovation, production systems, and nutrient flows simultaneously is Integrated Multi-Trophic Aquaculture (IMTA). IMTA is a sustainable method that enhances the production of aquatic organisms from multiple functional groups by leveraging nutrient flows within the same system. This is achieved through transforming waste into resources for reuse and recycling. Through this process, organic waste from higher-trophic species, such as fish, abalone or prawns, becomes a nutrient source for lower-trophic extractive species like bivalves (which filter particulates) and macroalgae (which absorb dissolved nutrients). Macroalgae such as *Ulva*, *Gracilaria*, and *Cladophora* are highly efficient at assimilating dissolved nitrogen and phosphorus from aquaculture effluents (Hughes et al., 2025; Morais et al., 2020; Moreira et al., 2022; Prazukin et al., 2024). Nederlof et al. (2022) estimate that well-balanced IMTA systems can retain up to 75% of nutrients from feed inputs, depending on species choice, water flow, and stocking ratios. When cultivated within IMTA systems, algae can transform otherwise polluting nutrients into valuable biomass often of improved quality compared to both wild and monocultures sources.

Importantly, macroalgae is currently establishing a competitive position within the global feed additive market, which was valued at $38.86 billion in 2022 and is expected to grow at a CAGR of 3.9% through to 2030 (World Bank, 2023). Trends indicate that the macroalgae based segment alone could reach a value of $1.12 billion by 2030. This growth is driven largely by increasing recognition of their nutritional advantages for animal health and the rising demand for sustainable, natural feed solutions. Numerous studies highlight the potential of macroalgae as supplementary and functional feed additives/ingredients in animal feed. Feeding fresh *Ulva* for instance can partially replace formulated feeds in abalone and sea urchin feeding regimes, enhancing growth and consumption while positively influencing health, physiology, pigmentation and gut microbiome to support improved metabolic and immune function (Brand, 2023; Cyrus et al., 2015). Similarly, *Gracilaria* and *Ulva* have shown promise in aquatic feeds at inclusion levels up to 20%, without compromising growth performance (Cyrus et al., 2013; Hughes et al., 2025; Wan et al., 2019). Wan et al. (2019) reviewed >50 finfish feeding trials with macroalgae and reported positive or no negative effects with inclusion levels between 5–30% of diet. In these trials macroalgae was often used to replace other dietary ingredients like of fishmeal and/or soy which could help to reduce feed costs and improve overall sustainability. Optimum inclusion was often species specific but inclusions of 15% and bellow did not impair growth in many formulations, except in those fed to carnivorous fish, which had lower limits of between 5–10% (Wan et al., 2019). Given the success of macroalgae inclusion of up to 20% as a supplementary feed ingredient in formulations to produce the 3rd largest aquaculture finfish species group worldwide, Cichlids (6,628,000 tonnes in 2022, FAO (2024)), the potential for its development in the aquafeed industry is very positive. El-Tawil (2010) demonstrated improved FCR's with up to 20% inclusion in diets fed to red tilapia (*Oreochromis* sp.). Carvalho et al. (2025) tested 0, 5, 10, 15% *Ulva lactuca* meal, inclusion produced in an integrated system, on juvenile tilapia (*Oreochromis niloticus*). Results showed no differences in growth performance or carcass composition among treatments. However, 5–10% inclusion improved antioxidant capacity and stress resilience relative to higher inclusions. *Cladophora* spp., contain up to 60% carbohydrate, 25% protein, and demonstrated digestibility and growth performance benefits in fish and livestock diets (Prazukin et al., 2024).

Macroalgae ingredients also offer bioactive benefits, such as antioxidant and antimicrobial properties, due to their high content of sulphated polysaccharides, phenolics, antimicrobial peptides (AMP's) and fatty acids (García-Vaquero, 2018; Morais et al., 2020; Silveira, 2022). Their incorporation supports organism health and resilience, which is particularly relevant in the context of reducing antibiotic use in production systems. AMPs in particular, have gained attention as a valuable feed additive due to their diverse biological functions and strong potential to limit the emergence of resistant microbes (Silveira, 2022). The extent to which macroalgae will be included in aquafeeds will however vary on a species by species bases and the purpose of these additions may therefore also be species dependent (eg: protein source vs antioxidant). This will be most evident when producing species who naturally consume algal or more generalist diets.

Even though the importance of algal feed additives is being recognised the development of seaweed-based feed additives is often constrained by several technical and logistical challenges. One of which is a reliable and traceable supply chain. To ensure access to large, continuous volumes of identified macroalgal products, downstream users have now started to investigate the potential of vertical integration in their production facilities, for which IMTA systems are ideally suited. When macroalgae are cultivated on farm (e.g., IMTA systems), their use as feed ingredients achieves dual circularity both from a nutrient recycling and feed generating perspective while simultaneously producing an improved quality product. For instance, *Ulva lactuca* grown in IMTA conditions has demonstrated protein contents as high as 33% dry weight and essential amino acid content suitable for inclusion in aquafeeds (García-Vaquero, 2018; Moreira et al., 2022). This localized on farm production and use also eliminate the need for transportation and reduces external resource usage. This type of site-specific circularity therefore creates value-added feedback loops. Moreover, localized production circumvents dependency on fluctuating global commodity prices. However, it is important to understand that these systems require careful species selection and nutrient balancing, as noted by Nederlof et al. (2022). The biomass production and nutrient uptake capacity of extractive species must be matched to the nutrient outputs of the fed species. Overstocking seaweed in nutrient-poor effluent can limit growth and reduce quality, while understocking may result in incomplete nutrient assimilation and increase environmental loading.

5 Could certification drive the next generation of sustainable aquaculture?

Despite growing awareness, Kusumowardani and Tjahjono (2020) found that the practical implementation of circular economy principles in aquafeed manufacturing remains low. As most companies do not yet incorporate circularity indicators into their design or procurement processes. A key barrier is the absence of standardized metrics and incentives. The benefits of circularity are not hypothetical and have been demonstrated through early adopters, for example those in the South African Abalone aquaculture sector. However, certification programs have not been established to accurately prescribe sustainable practice in circularity.

6 Case Study: commercial IMTA of Abalone & Ulva (South Africa)

South Africa presents one of the most established commercial applications of land-based Integrated Multi-Trophic Aquaculture (IMTA), where *Haliotis midae* (South African abalone) are integrated with the green seaweed *Ulva lacinulata*. This model highlights the core principles of circular economy in aquaculture by linking feed innovation, production system efficiency, and nutrient reuse in a closed-loop framework (Figure 12.3).

The IMTA approach employed on several South African farms involves the capture and treatment of effluent-rich water from abalone tanks using *Ulva* spp cultivated in adjacent paddle-raceway systems. The effluent, rich in dissolved nitrogen (ammonia, nitrate, nitrite), phosphate, and other organic matter, supports *Ulva* growth. This seaweed is then either reintroduced directly as a feed supplement or dried and processed into *Ulva* meal for formulated feeds. This process transforms a waste stream into a valuable resource, creating an internal nutrient loop that reduces environmental discharge and enhances input efficiency (Bolton, 2006; Bolton et al., 2016; Checa et al., 2024; Macey et al., 2024; Robertson-Andersson et al., 2008). Inclusion of up to 6% IMTA *Ulva* meal can also effectively replace equivalent levels of fish and soy meal and has been shown to enhance growth rates and feed utilisation in sub-adult (65–75 g) *H. midae* (Falade, 2023).

The economic and ecological incentives for this model are considerable. Cultivating *Ulva* on-site using effluent nutrients reduces reliance on wild-harvested seaweeds (e.g., kelp) and formulated feeds, thereby decreasing dependence on fishmeal and other resource-intensive inputs. Checa et al. (2024) demonstrated this using data from Buffeljags Abalone Farm (Viking Aquaculture), which produces 450 tonnes of abalone and 600 tonnes of *Ulva lacinulata* annually. Feed regimes at this farm incorporating IMTA-produced *Ulva* showed improved feed conversion ratios (FCRs) of 4.01 compared to 6.16 in monoculture systems. Uneaten feed fractions de-

FIGURE 12.2 An example of commercially operating Integrated Multitrophic Aquaculture (IMTA) in South Africa on Buffeljags Abalone Farm, owned by Viking Aquaculture. (A) Aerial photograph showing the entire farm and modular units; (B) Photograph of the module Abalone-*Ulva* Units (Photos: ASTRAL Project https://www.astral-project.eu)

creased from 1.14% to 0.71%, and feed linearity defined as the proportion of ingredients not sourced from valorisation dropped from 100% in monoculture systems to 71.42% in the abalone-*Ulva* IMTA system. Feed cost savings from *Ulva* supplementation were estimated at approximately 20% (Pers. comm. to Mark Cyrus; Macey et al. (2024) Macey et al., 2025). Furthermore, producing supplementary feed inputs on-site supports localized production cycles and enhances resilience to price fluctuations and supply chain disruptions (Chary et al., 2024; Checa et al., 2024).

From a system design perspective, South African IMTA farms exhibit high water recirculation levels (approximately 50%), significantly reducing water use and effluent output (Checa et al., 2024; Neori et al., 2004). *Ulva* serves both as a biofilter and a co-product removing up to 85% of total ammonia nitrogen while generating biomass for feed and potential secondary markets (e.g., nutraceuticals, fertilizers). The modular structure of these systems allows for spatial separation of species while maintaining functional connectivity via shared water and nutrient flows. Increased on-site recirculation also reduces the IMTA system's energy demand compared to monoculture systems, from 10.35 kWh to 6.80 kWh per ton of biomass harvested (Checa et al., 2024).

The integration of *Ulva* into abalone farming demonstrates how Circular Economy principles can be effectively implemented into aquaculture enterprises. Thereby contributing to aquafeed production through integrating waste recovery, on-site resource production, and ecological design demonstrating that circular aquaculture can deliver both economic and environmental benefits when appropriately implemented.

Challenges to its adoption currently still include spatial design, market value of co-products, and lack of integrated licensing (e.g., seaweed and shellfish may require separate permits). Nonetheless, the growing market for seaweed (food, feed, bioplastics, carbon credits) is improving IMTA viability.

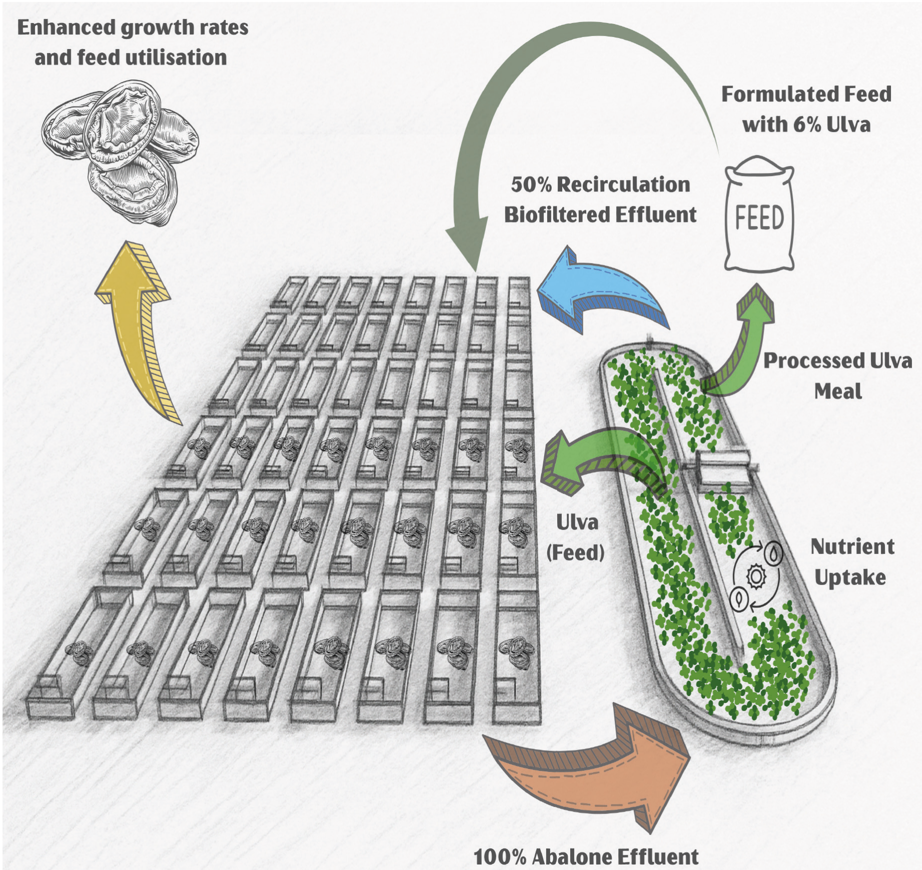

FIGURE 12.3 Diagram of a module abalone-*Ulva* Unit demonstrating the nutrient flows between the abalone tanks, effluent wastewater, *Ulva* raceways, recirculated biofiltered effluent, and co-products used for value adding in onsite feeding

7 Summary

The future of sustainable aquaculture lies in integrating innovations across feed development, production system design, and nutrient management. These focus areas, while distinct, are inherently interlinked and must be approached holistically to realize the full potential of circularity and sustainability.

Circularity in aquaculture particularly regarding aquafeeds is often framed as a system of closed loops or cycles. However, the progressive flow of materials, energy, and value through different stages of the aquaculture system is more accurately illustrated as a vertical spiral. Multiple modes of circularity can operate simultaneously at various levels, each contributing uniquely to overall sustainability. We therefore propose an adaptation of the circularity model; (SPINE™ Sustainable Production of Integrated Network Efficiency) which represents a dynamic framework for understanding and implementing circularity in aquaculture systems. SPINE captures how sustainability is advanced through interconnected pathways that integrate resources, emphasize practical application, and strengthen linkages across production scales from external resource loops to market-driven impacts. Unlike closed-loop models, the vertical spine concept reflects the layered, adaptive nature of circularity, enabling upward and downward feedback that accelerates transformation in aquafeeds, farm systems, and supply chains and provides the backbone to accelerate sustainable practice in aquaculture.

At the core of circular integration is the recognition that aquafeed formulation determines not just input efficiency, but also the scale and nature of waste outputs. High-quality, low-impact feeds reduce the demand on wild fish stocks, minimize land and water use, and influence the digestibility and nutrient retention of cultured species. Improved feed conversion ratios (FCRs), achievable through advanced nutrition, genetics and animal health, reduce the quantity of feed required per unit of biomass, thus decreasing environmental loading.

Nutrient flow and energy retention assessed in LCA ultimately tracks the fate of feed-derived nitrogen, phosphorus, and organic carbon thus becomes a focal point for both sustainability and circularity. The low nutrient retention efficiencies in conventional monoculture systems highlight the need for smarter waste management. Integrated Multi-Trophic Aquaculture (IMTA) provides a compelling model, where waste from one species becomes a resource for another. This not only mitigates environmental impacts but also creates diversified income streams and ecosystem resilience. The concept of circularity therefore amplifies sustainability by embedding feedback loops into the production cycle.

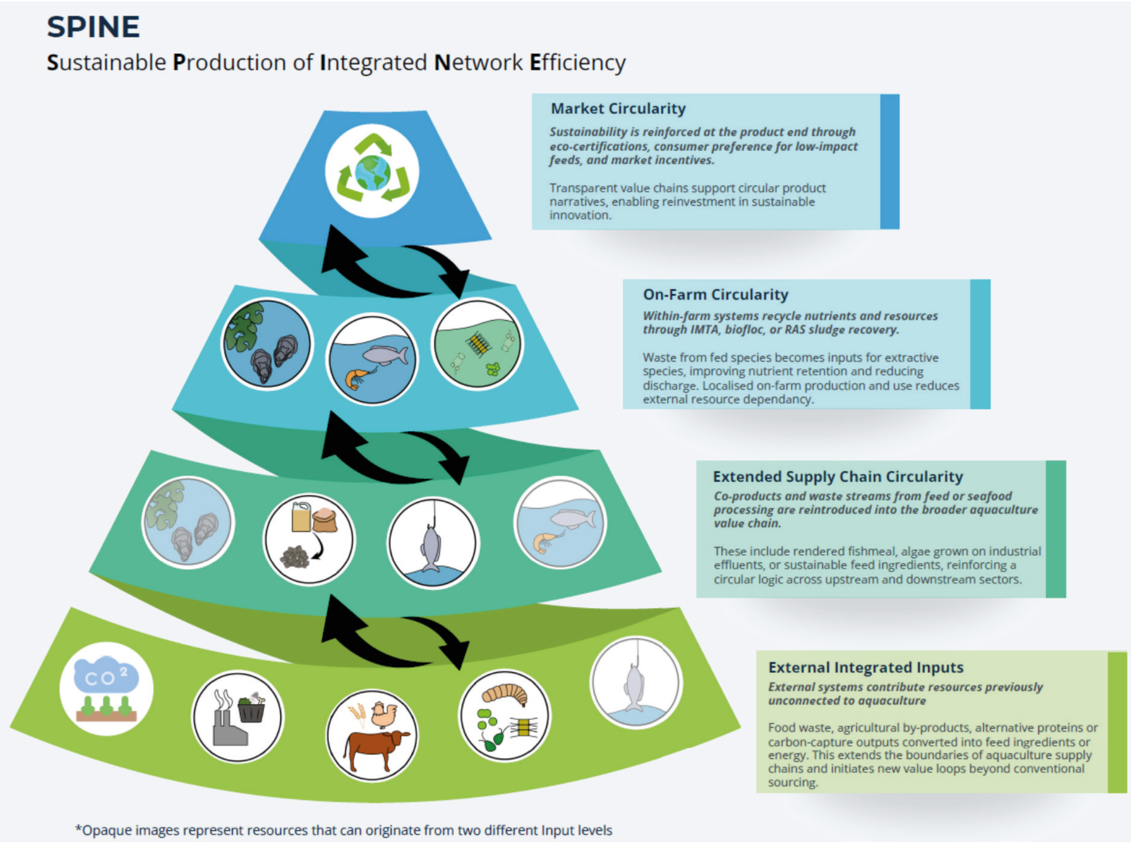

FIGURE 12.4 Visual representation of the SPINE (Sustainable Production of Integrated Network Efficiency) model, depicting how circularity in aquaculture and aquafeeds advances through an interconnected framework of integrated resources use, enabling upward and downward feedback, encompassing (1) External Integrated Inputs, (2) Extended Supply Chain Circularity, (3) On-Farm Circularity and (4) Market Circularity. *Opaque images represent resources that can originate from two different model levels.

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