



To improve the overall sustainability in aquaculture, producers, feed manufacturers and scientists have long been working on alternative ingredients for fishfeeds.

Photo: Jörg Böhling

Aquaculture feeding – problematic, but not without alternatives

Animal production is a major contributor to climate change and greenhouse gas emissions, mainly due to the feed production and global trade. Aquaculture is no exception when considering the species which are “fed”, i.e. species depending to a large degree on feed supplied by the operators. Our author describes current feeding practices in aquaculture and the problems they involve and gives an account of progress in research on alternative protein sources.

By Timo Stadtlander

Globally, around 120 million tons of animals and plants were produced in aquaculture in 2019 (FAO 2021). Of these, around 34.7 million tons were plants, primarily macroalgae (seaweeds and kelp) but also some microalgae (i.e. *Spirulina* spp.), while the other 85.3 million tons were animals: fish (e.g. salmon, rainbow trout, carps, tilapia), crustaceans (mainly shrimps and prawns) and molluscs (e.g. blue mussels, oysters or snails). Some of these animals are produced in rather extensive natural systems with no or only few inputs, but most of them come from more intensified or even highly intensive systems depending largely or wholly on feeds. The nutrient requirements are mainly species- and life-stage-specific, but

in general, high trophic-level animals (carnivorous species) require more and higher quality protein compared to lower trophic-level species (herbivorous or omnivorous species; also see Box on page 32).

Fishmeal has been the traditionally most important source of proteins in aquaculture. At around four to six million tons, the annual supply of fishmeal has been more or less stable over the last decades. Around one third is produced from so-called trimmings – the leftovers of filleted wild-caught or cultured fish. While fishmeal production from trimmings is more sustainable than targeted fishmeal production (also called reduction fisheries), being

a by-product from industrial fishery and aquaculture operations, it results in other problems derived from high mineral content. The higher phosphorous (P) content in trimmings fishmeals can cause increased P-emissions, which can lead to increased eutrophication of surrounding water bodies. Also, the protein content of trimmings fishmeal is usually about five per cent lower than that of conventional fishmeal. And targeted fishmeal production is also in direct competition to human consumption: according to a report by Cashion et al. (2017), 90 per cent of fish destined for fishmeal production were of either food or prime food grade and could therefore directly be consumed by humans.



Insect larvae production is among the most advanced and promising ways of increasing animal protein production – not only as animal feed.

Photo: Thomas Alfvöldi



Duckweed can be grown on nutrient rich wastewaters. Its protein content corresponds to that of fresh soybean.

Photo: Timo Stadtländer



Photo: Thuy An

Although, at around 80 per cent of global production, aquaculture is the most important consumer of fishmeal, over the last decades, the relative amount of its inclusion into aqua-feeds has significantly decreased as seen in salmon feeds with an estimated 45 per cent of fishmeal content in 1995 versus 18 per cent in 2010 (Tacon and Metian 2008). Fish feed is like a cake with various ingredients including not only fishmeal but also e.g. wheat flour, soy beans or sunflower oil. The crucial aspect of the feed formulation is its nutrient content. Thus, without substantially raising available fishmeal production, a significantly larger amount of fish can be produced, albeit with “diluted” fishmeal, as it were.

Since fishoil is a co-product of fishmeal production, it follows the same production and sustainability issues and challenges. It is rich in unsaturated fatty acids, especially the two important fatty acids EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) when the fishoil is derived from marine fish. These are the most important omega-3 fatty acids discussed as highly beneficial for human (especially cardiovascular) health. However, while fishoil remains an important lipid source for fed aquaculture species (mostly for high trophic level carnivorous marine fish species) for which alternative lipid sources are researched and developed similarly to alternative protein sources, this article focuses on protein sources.

On step towards more sustainability: reducing the feed conversion ratio

Overall, aquaculture contributes significantly to global food security but encounters similar problems as terrestrial animal production, although on a smaller scale given lower global production volumes. Therefore, the issues and challenges associated with aquaculture animal nutrition and feedstuff production are basically the same as for terrestrial animal production – with some exceptions. The majority of aquatic animals are poor converters of carbohydrates, making proteins and lipids more important compared to terrestrial animals. While aquatic animals can use proteins and lipids as an energy source, proteins are the most expensive feed ingredient (Kim et al. 2019) and when used as an energy source also increase excretion of nitrogen (N), thus wasting it, besides raising the feed cost. A high N or protein retention is crucial, since using protein as an energy source contradicts the notion of sustainability. The so-called protein sparing effect was already identified in the early 1970s and afterwards studied and described very well (NRC 2011). The goal would be to supply the animals with all necessary protein and essential amino acids but not to over-supply protein.

Lipids are a cheaper energy source which does not raise N emission when over-supplied. Therefore a good knowledge of the protein, amino acid and energetic requirements of the animals produced (especially the optimal dietary protein to energy ratio) and of the nutritional content and chemical composition of the feedstuffs is key to sustainable animal production. One indicator of a good performing

The fish in to fish out ratio (FIFO)

In 2012, around 70 per cent (35.7 mill. t) of all aquaculture fish and crustaceans were “fed”. Carps contributed most to global aqua-feed consumption (11.03 mill. t in 2012), followed by tilapias (6.66 mill. t), shrimp (6.18 mill. t), catfishes (including pangas catfishes; 4.27 mill. t), salmon (2.98 mill. t) and trout (1.14 mill. t) (Tacon and Metian 2015). One often calculated parameter is the so called fish in to fish out ratio, or simply FIFO. The higher it is, the more fishmeal (and oil) is fed to that specific species in relation to its overall production volume. In a 2021 review, the estimated global FIFO of the 11 most important fish and shrimp species showed that all considered high trophic level species (eel, salmon, trout and marine fish such as sea bass or sea bream) were net consumers of fishmeal with values between 1.25 (marine fish) and 2.98 (eel), while low

trophic level species (carps, tilapia, catfishes and shrimp) were net seafood producers with values between 0.82 (shrimp) and 0.02 (fed carps) (Naylor et al. 2021).

The trophic level of a species

The trophic level of a species describes its position in the food chain (or rather the food web, given the various interactions between different trophic levels). The lowest trophic level (either 0 or 1, depending on definition) are the primary producers – usually the plants (mostly macro- and microalgae in aquatic ecosystems). The higher an animal is positioned in the food web, the higher its trophic level and share of animal prey in the respective species’ natural food, up to the apex predator, which is always the highest trophic level, usually between 4–6, depending on the amount of trophic levels in the respective ecosystem, and not considering humans.

feed in aquaculture is the feed conversion ratio (FCR). A low FCR is therefore essential in a sustainable aquaculture operation, and reducing the FCR is often the fastest way to increase sustainability.

Alternative protein sources and their pros and cons

To improve overall sustainability in aquaculture production, it has been proposed to reduce the trophic level of the fish feeds (i.e. increase the amount of plant ingredients), even for carnivorous fish and especially concerning the marine ingredients (Olsen 2011). For several decades, the aquaculture sector (producers, feed manufacturers and scientists) has worked on alternative ingredients. These can be sub-divided into ingredients of plant and of animal origin and into primary products and secondary or by-products derived from other industries and utilised as animal feed. The Table on page 34 includes an overview with a selection of examples, some of which are already in use. It ought to be mentioned that while carbohydrates play a minor role in aquatic animal nutrition, certain fish species (e.g. carps) can utilise carbohydrates and starches sufficiently well, especially when extrusion-cooked.

In aquaculture production, the most important **plant-based** aqua-feed ingredients are soybeans which are among the crops produced most in the world, and around 85 per cent of global production is processed and almost exclusively used as animal feed (Kim et al. 2019). Soybeans show an excellent amino acid profile but contain several anti-nutritional factors inhibiting digestion and utilisation if not treated accordingly (Francis et al. 2001). In more recent years, soybean production has increasingly been criticised for its own set of sustainability issues and challenges, but their nutritional value is undisputed. Sustainable soy production could contribute significantly to increased aquaculture sustainability. Other more conventional protein sources are the protein fractions of major crops such as wheat (wheat gluten), canola/ rapeseed or maize (Hardy 2010), already in use for many years.

Several potential alternative plant-based protein sources which are mostly by-products from food oil production of different oil-seeds have been looked at as aquaculture feed ingredients. These include pumpkin seed press cakes (Greiling et al. 2018a), sunflower seed press cakes (Greiling et al. 2018b), kernel meals or protein isolates from *Jatropha curcas*



Using bamboo sticks as substrate for periphyton communities could help improve global aquaculture production, as controlled experiments in Vietnam have shown.

Photo: Marc Verdegem

(Nepal et al. 2017), pea seed meal (Davies and Gouveia 2010) and lupine kernel meal (Weiss et al. 2020). Potential primary plant-based protein sources comprise various marine macroalgae and seaweeds such as the green alga *Ulva rigida* (Azaza et al. 2008), the red algae *Porphyra yezoensis* (Stadtlander et al. 2013) and *Gracilaria* sp. or microalgae such as *Schizochytrium* sp. (Stoneham et al. 2018) or *Spirulina* spp. (Olvera-Novoa et al. 1998).

Duckweed, consisting of small floating aquatic plants (see Photos on page 32), can be grown on nutrient rich wastewaters and shows very high growth and biomass production rates (around 70 t of dry matter/ hectare/ year) as well as a protein content similar to fresh soybeans, with up to 45 per cent (Mbagwu and Adeniji 1988). This combination enables the plants to produce between five and ten times the protein amount per unit time and area compared to soy (Xu et al. 2011). The plants can be produced on different animal slurries and could therefore be integrated into other animal production cycles (pigs, cattle, poultry) to improve the N and P efficiencies and afterwards be fed to various fish (Fasakin et al. 1999, Xu et al. 2011, Stadtlander et al. 2019) or other animal species such as pigs or poultry (Haustein et al. 1994, Gwale and Mwale 2015). However, they are mostly used in extensive systems and have reached commercial-scale production in only a few places.

One very important **animal-based** protein source being developed globally is insect meals. Insects could be produced relatively



Farmers showing periphyton on sticks they keep submerged in their pond in the background. This provides extra food for the fish and protects against poaching at night.

Photo: Marc Verdegem

sustainable when fed with true wastes such as (pre-consumer) food waste or animal manures. One African company even uses human night soil, which would not be possible in Europe due to biosafety concerns. However, it is a good example of really closing the nutrient cycle, provided effective R&D and disinfection measures can ensure biosafety. Insect meals have proven to be excellent fishmeal replacements, and the most prominent insect species here is the black soldier fly (*Hermetia illucens*), which has been tested in different fish species (Kroeckel et al. 2012, Lock et al. 2015, Stadtlander et al. 2017).

Moringa oleifera (the drumstick tree) is another potential candidate for a fishmeal substitute, but contrary to insects or duckweed, it would not close nutrient cycles but requires targeted production. The leaves and kernels are consumed in several areas as food. So certain competition to human nutrition would arise. Nevertheless, both leaves and kernels are rich in macro- and micronutrients and especially the leaves have been discussed as a potential measure against micro-nutrient deficiency for many low-income countries (Thurber and Fahey 2009, Stadtlander and Becker 2017).

The way forward

There are many potential alternatives for fishmeal both of animal and plant origin. However, the ideal substitute would need a high protein content, a favourable amino acid profile, not compete with human nutrition, and

contribute to closing nutrient cycles. Since such an ideal protein source does not exist (probably with the exception of insects), using otherwise under- or unutilised nutrients for biomass production or by-products can be a big step towards more sustainable global animal production, including in aquaculture.

Another option would be to increase the production and consumption of low trophic level filter feeding aquatic animals such as mussels, clams or snails instead of increasing production of high trophic (and high-value) carnivorous or even medium trophic omnivorous species which need feed as well.

Conventional and alternative examples of protein sources for aqua-feeds

Protein source	Distribution and global annual production	Origin (animal, plant, other)	Typical protein content in dry matter	Conventional or alternative*
Fishmeal	Globally available; different qualities; 4-6 mill. t	Animal Targeted fishery or trimmings	50-75 %	Conventional; disputed sustainability for targeted catch
Soybeans	Widely available; globally traded; soybean production > 350 mill. t	Plant Agricultural production	38 % (whole beans); 80 % (soybean protein isolate)	Conventional, most important protein source in aquaculture; sustainability depends on production area and system, limited availability of protein isolates
Wheat	Globally available; wheat production > 760 mill. t	Plant	12 % (flour); 80 % (wheat gluten meal)	Conventional, availability of wheat gluten meal limited in low-income countries
Canola/ Rapeseed	Widely available, production ca. 70.5 mill. t	Plant	38 % (rapeseed meal, solvent extracted)	Conventional, availability somewhat limited
Sunflower press cake	Widely available, production ca. 56 mill. t	Plant	46.5 % (sunflower meal, solvent extracted, de-hulled)	Alternative, underutilised resource in aqua-feeds
Algae (macro and micro; red, green or brown)	Widely available, production around 30-35 mill. t	Plant	20-40 % depending on species, location and environmental conditions	Alternative, not utilised in larger scale, experimental application mostly
<i>Jatropha curcas</i> , kernel meal	Not widely distributed	Plant	65 % (kernel meal, solvent extracted)	Alternative, not in use, experimental stage
Insect meal, different species, most prominent: black soldier fly <i>Hermetia illucens</i>	Distribution range increasing, locally in commercial production	Animal	40-60 %, depending on species, production and processing	Alternative, utilisation in aqua-feeds increases, can close nutrient cycles when produced with food waste or manures
Duckweed, different species	Distribution range very limited	Plant	20-45 %, depending on species and production	Alternative, mostly experimental stages, little commercial production, can close nutrient cycles
Distillers grains and solubles	Global distribution, by-product from beer brewing or ethanol production	Plant	26-44 % (depending on grain type)	Alternative, underutilised
<i>Moringa oleifera</i> , leaf or kernel meal	Limited distribution, mostly tropical and subtropical	Plant	19-38 % (kernel usually higher in protein)	Alternative, locally used but usually underutilised or directly consumed as food (leaf)
Animal by-products (e.g. hydrolysed feather meal, blood meal)	Globally distributed, utilisation as feed ingredient regionally strongly regulated	Animal	40-80 %, depending on by-product	Underutilised but regionally in use, where legislation allows

* Conventional: already in use; alternative: not in use due to experimental stage or underutilised.
Note: This list provides only a short overview and is far from being complete.

A large share of global aquaculture production could also be improved, sometimes with relatively simple methods such as the periphyton system (see Photos on page 33). In a controlled experiment, the production of fertilised carp polyculture ponds could be tripled by using bamboo sticks as substrate for periphyton communities (also called “Aufwuchs”) consisting of microbes, cyanobacteria and algae providing food for small invertebrates which then serve as natural food source for certain fish or shrimp species (Azim and Little 2006). By providing more substrate to the periphyton communities to grow on, the ponds were basically structurally enriched, providing additional ecological niches and thus increasing overall nutrient use efficiency.

In the current global food system(s) around one third of total food production is either lost or wasted, accounting for an estimated 1.3 billion tons per year and an estimated 990 billion US dollars in economic losses, without considering environmental impacts (FAO 2011, Schanes et al. 2018). Given the capacity of insect larvae to utilise organic wastes, they appear to be ideally suited to recycle at least a certain part of the food wastes into protein, while the food losses need to be addressed as well. Insect larvae production is among the most advanced and promising ways of increasing (animal) protein production in general, be it as animal feed or probably even human food. However, while insects are often considered as the most sustainable alternative to fishmeal, the true sustainability of the various existing insect production technologies and insect species needs to be evaluated by life cycle assessments in parallel to technological advancement. Some studies, including one (as yet unpublished) at FiBL, point towards potentially high greenhouse gas emissions which would then need to be addressed.

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