Harvesting the benefits of nutritional research to address global challenges in the 21st century

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Abstract

Substantial progress has been made over the past twenty years in improving feeds and feeding for most aquaculture species. There have been notable improvements in feed efficiency (through a better understanding of requirements and improved feed management) and ingredient sustainability (through increased capability to use a wider range of ingredients). While advances have been made in understanding the requirements of many of the main aquaculture species, there is still much to be done on defining requirements, especially for many of the species being farmed in the developing world. Gains in the efficiency of feeds is slowing for developed species, but such gains are still appreciable for less developed species. There is a growing need to more precisely prescribe the required levels of essential nutrients and various additives in the diet based on age, genotype, environment, and immune status to deliver a "precision nutrition" approach to farming aquaculture species. Plant resources remain the dominant ingredient used in compound feeds across the world. Whereas marine resources remain an important inclusion in many feeds, they are increasingly seen as a low-volume high-value resource with strategic applications. As a source of omega-3, marine resources still dominate supply, though microalgal and genetically modified crop options are emerging. There is still further need to diversify our ingredient options to provide greater resilience, as the sustainability of different feed ingredient sources, including possible climate change impacts, is becoming a growing issue. There is an increased demand for biocircularity in our feed ingredient supply chains. Fundamentally what is needed to sustain future feed ingredient needs are sustainable sources of cost-effective protein, some essential amino acid additives, some omega-3 resources, plus various minerals, and vitamin additives. The increasing use of new and varied resources will ensure that food safety remains an important issue throughout the world. Feed manufacturing has evolved from a simplistic exercise to a highly complex science with state-of-the-art engineering. However, the application of such advanced feed manufacturing is not consistent across all sectors and further support is needed, as there is still widespread use of pelleting, mash, and trash-fish feeding in the developing world. Similarly, feed management has also dichotomised between the developed and developing world, with a high reliance on manual skilled labour in the developing world, whereas more advanced aquaculture systems are becoming increasingly reliant on automated computer-controlled feeding systems.

Key Messages

- There has been substantial progress in improving feeds and feeding for most aquaculture species, with notable improvements in feed efficiency (through a better understanding of requirements and improved feed management) and ingredient sustainability (through increased capability to use a wider range of ingredients).
- While advances have been made in understanding the requirements of some of the main aquaculture species, there is still much to be done on defining requirements, especially for many of the species being farmed in the developing world.
- Gains in the efficiency of feeds is slowing for developed species, but such gains are still appreciable for less developed species.

- There is an emerging need to adopt a "precision nutrition" approach to the supply of essential nutrients and various additives in the diet based on age, genotype, environment, and immune status.
- Plant resources have become the dominant ingredient used in feeds across the world. Although marine resources remain an important inclusion in many feeds, they are increasingly seen as a low-volume high-value resource with strategic applications. Marine sources of omega-3 still dominate supply, though microalgal and genetically modified crop options are emerging.
- There remains a need to diversify our ingredient options to increase resilience, as the sustainability of different feed ingredient sources, including possible climate change impacts, is becoming a growing issue. There is an increased demand for biocircularity in our feed ingredient supply chains. The increasing use of new and varied resources will ensure that food safety remains an important issue throughout the world.
- Feed manufacturing has evolved from a simplistic exercise to a highly complex science with state-of-the-art engineering. However, the application of such advanced feed manufacturing is not consistent across all sectors and further support is needed, as there is still widespread use of pelleting, mash, and trash-fish feeding in the developing world.
- Feed management has also dichotomised between the developed and developing world, with a high reliance on manual skilled labour in the developing world, contrasting advanced aquaculture systems that are increasingly reliant on automated computer-controlled feeding systems in the developed world.
- Improved feed design, manufacturing and management systems are supporting better feeds and feeding, resulting in faster growing fish (through better specifications and higher intakes) and lower FCRs (through more efficient feeds and less wastage), but declining employment in the sector as automation increases.

Introduction

With any science-based prediction of the future and of which path to follow (essentially a navigation exercise) we need to understand where we are and where we have been. It is only once we understand this context of our situation that we can then begin to make some rational prediction about where we are heading. As such, in this paper we examine the three key themes that underpin the feeds and feeding process (requirements /ingredients /management) and have framed our review of this journey in terms of the past-present-future. Additionally, it needs to be noted that the top seven species groups (carps, tilapia, catfish, shrimp, freshwater spp., salmonids, and marine spp.), collectively comprise close to 90% of all aquaculture production and as such form the focus on the paper. While increasingly, each of these species' groups are being produced intensively and are reliant on compounded feed for their sole nutritional inputs, this is not equally the case among all seven groups. Substantial production, particularly of carps, which comprise almost 50% of global aquaculture production, are still produced in small-scale extensive, semi-intensive and integrated polyculture systems. Notably, feed specifications, ingredient use and feeding practices also vary regionally across the world. As such, in this paper we have attempted to generalise on those issues that affect the three key themes that underpin the feeds and feeding process across the world.

Requirements

Past (before 2010)

The terms nutrient “requirement” and “specification” have frequently been used interchangeably. While “specification” is the detailing of the design instructions for something (e.g., a diet containing 40% protein), the actual nutrient requirement of an animal is more based around the need for a particular nutrient required by the animal on a certain body weight basis per defined duration (e.g., mg protein / $kg^{0.7}$/ d), and for defined physiological functions such as maintenance, maximal growth, or optimal health. The process of establishing these nutritional requirements (optimum dietary levels) for aquaculture species has been a big challenge not only because of the difficulties associated with feeding an aquatic animal, but also considering the increasing number of species of commercial importance (Hua et al., 2019; Boyd et al., 2020). This contrasts with what has happened with terrestrial domestic species, such as poultry and pigs, where the definition of nutritional requirements is generally focused on a single species (NRC, 1981). Additionally, finfish and shellfish requirements vary not only among species, but can also depend on their developmental stage and in some cases different environmental constraints (NRC, 2011). Moreover, requirements may further depend on the farming system used and regionality. In many cases production of key aquaculture species was undertaken in extensive, semi-intensive and integrated polyculture systems meaning that a holistic systems approach to nutrition had to be used rather than a monoculture approach. Aquaculture was notable in being much more varied in the nutritional requirements of its species than in livestock production.

Traditionally the definition of requirements for essential nutrients (energy, protein, lipid, amino acids, fatty acids, vitamins, and minerals) for most species was undertaken on a gross nutrient basis only (Cowey, 1992; Boonyaratpalin, 1997; NRC, 2011). Requirements were typically defined based on empirical experiments and limited to small animal sizes and laboratory environments. This served well in terms of defining the distinct differences among many of the species and between aquatic and terrestrial animals (NRC, 2011).

Initially, the definition of nutrient requirements for many species led to big gains being made in feed efficiency, with improvements in FCR values from 1.8 - 3 to 1.2 – 1.8 being achieved for many species. However, as time has passed there have been diminishing returns on any improvements in the definition of nutrient requirements across most species' groups (Figure 1).

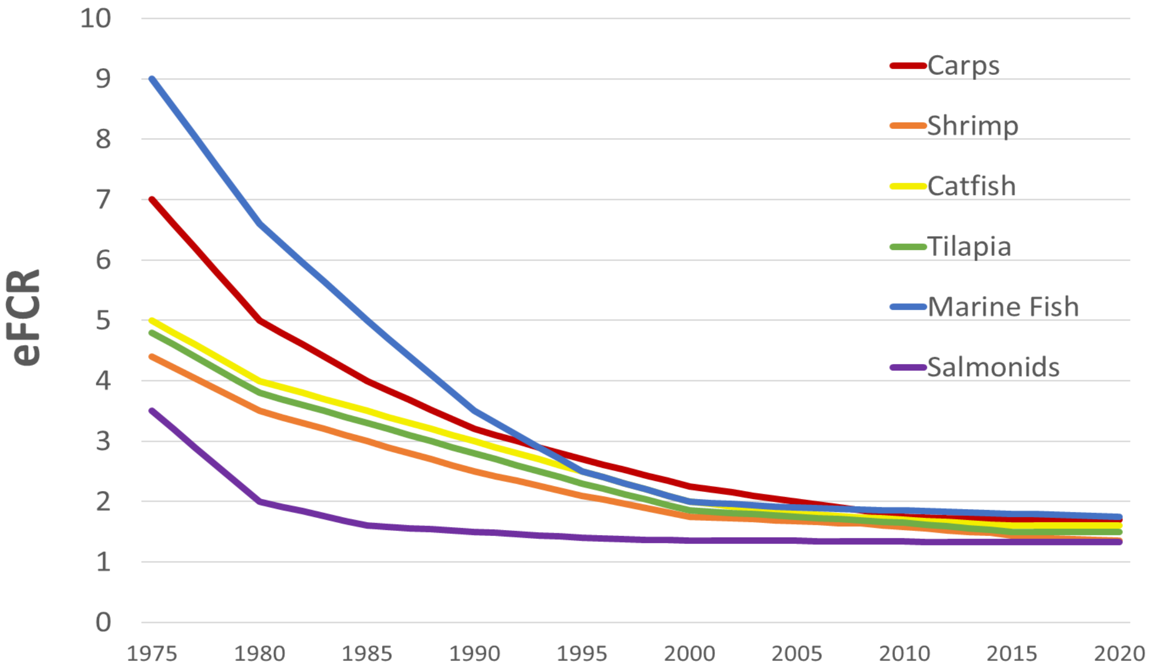

Figure 1. Changes in economic feed conversion ratios (eFCR) of major aquaculture species groups over the past forty-five years.

Prior to 2010, there was also an introduction in the use of various modelling systems to define requirements for energy and some macronutrients and explore various physiological processes (Shearer, 1995; Dumas et al., 2010). These models were largely derived from similar approaches used for terrestrial species but had to include various empirically derived features to account for the differences between poikilotherms and endotherms (Cho & Bureau, 1998; Lupatsch et al., 2001). Different iterations of either nutrient flow or nutrient demand models were developed, that were largely based around factorial bioenergetic processes (Cho & Bureau, 1998; Glencross, 2008).

Present (2010 – 2020)

Since 2010, smaller improvements in feed efficiency have been made, with typical changes from FCR's of 1.5 - 2 to 1 – 1.5 for some species (Figure 1). Such gains were mainly due to the increasing knowledge about nutritional requirements but also due to better management practices following the intensification of growing systems (NRC, 2011). An increasing level of replacement of fish meal with plant proteins as the main ingredients in commercial feeds demanded a better knowledge of amino acid requirements. Although fish meal has an amino acid balance close to that of many fish requirements most plant protein do not, thus meeting fish demands for growth with plant proteins required a deeper knowledge about amino acid requirements in terms of amounts and balance (Kaushik & Seiliez, 2010).

This was especially important for carnivorous species which have higher demand for amino acids, but it was also important for omnivores such as tilapia and shrimp, where the high cost of fish meal limited its use in commercial feeds. A deeper knowledge about the requirement of other nutrients such as taurine, n-3 fatty acids, and various vitamins and minerals also became important with increasing levels of fish meal replacement, since these nutrients are less available or even absent in plant sources (Gatlin et al., 2007; Dominguez et al., 2020a, 2020b).

During the 2010-2020 decade, after the NRC publication (NRC 2011), there was an increasing level of definition of requirements for animals of different sizes and in some cases different environmental constraints (e.g., hypoxia, temperature, salinity, etc). Both, age, and environmental conditions may markedly affect fish physiology and modulate the expression of key genes, affecting nutrient utilization and nutritional requirements (Izquierdo & Koven, 2011; Fernández-Palacios et al., 2011; Hamre et al., 2013; Lund et al., 2019; Torno et al., 2019). However, such information is still scattered and absent for some species (e.g., Seriola, Sole) (Sicuro and Luzzana, 2016; Valente et al., 2019). Industrial breeding programs are rapidly progressing, based in the recently developed customized genomic tools for marker-assisted selection, and are producing fast growing animals with improved FCR that may have different requirements for specific nutrients (Glencross et al., 2013; Janssen et al., 2017; De Verdal et al., 2018; Ferosekhan et al., 2021). Moreover, nutritional history (protonutrition) and nutritional programing affect the utilization of dietary nutrients and therefore could affect fish requirements (Turkmen et al., 2019). The main drivers for such development were the high cost of aquafeed, that typically represents 50% of the variable production cost of intensive aquaculture, together with the increasing pressure for producing more sustainable diets able to address the Sustainable Development Goals established by UN. This implies knowing more about the requirements of the various species to sustain optimal growth and produce high quality and healthy animals. In many of those species already produced at large scale, requirements for macro-nutrients and most micro-nutrients are now well established for early/larval, juvenile, grower, and broodstock stages of the production cycle. But most non-mainstream species still need clearer definition of many of the basic nutrient requirements and their response to environmental constraints remains largely unknown. Modern aquaculture today uses diets that rely on a variety of alternative raw materials that need to be balanced with additives including certain amino acids, minerals, and vitamins to ensure the optimal use of the feed. However, to face various growing environmental and production challenges, the currently established requirements of many amino acids and other micronutrients may need to be revisited to assure fish growth and robustness into the future (Prabhu et al. 2014; Kousoulaki et al. 2021; Hamre et al. 2016; Aas, Ytrestøyl, and Åsgård 2019; Berntssen et al. 2018).

The last comprehensive compilation of nutritional requirements of fish and shrimp was published on 2011 (NRC 2011). This publication included the requirements of various freshwater and marine fish as well as shrimp of commercial importance. Despite organizing and facilitating the access to nutritional requirement information for various important aquaculture species, it also made clear several unknowns not only on micronutrient (vitamins and minerals) but also on amino acid requirements. Notably, the compiled requirement specifications were largely defined from animals in juvenile stages and based on using highly digestible diets and animals maintained in optimal growing conditions. In most cases, requirements were presented as a single recommendation for each species and did not consider changes in requirements throughout the various production stages. Therefore, despite the increasing use of farming system environments to undertake research and provide industrially relevant information for some species such as salmon, this is not so for many other species (Ng & Romano 2013).

Most feeds in the world are still formulated on a crude composition basis, though there is increasing formulation of feeds on a digestible nutrient basis in the developed world for some species, like Atlantic salmon. The quality of the formulation depends on various knowledge sets, including the accurate understanding of the nutrient requirements, the nutritional composition of the ingredient being used and their nutrient digestibility and/or bioavailability, and the processes being used to form the feed into a physical pellet. The feed of salmon is highly efficient. However, the feed efficiency of most other cultured fishes or shrimp lags that of salmon.

This is mainly due to the rapid development of aquaculture with high diversity and complexity of cultured species and feed ingredients used in developing countries, and the lack of comprehensive knowledge of essential nutrient requirements of so many cultured animals and of the digestibility or the bioavailability of non-traditional ingredients or their nutrients. For example, nutritional studies published in China have been conducted on more than 200 species representing a wide geographic distribution, different feeding habits (herbivorous, carnivorous, omnivorous, and filter feeders), and different culture modes. It is evident from the information provided in the NRC (2011) that the tables listing the nutritional requirements of salmonids are mostly complete, while those for many other important marine or freshwater species are either incomplete or mostly blank (Hardy et al., 2021). Despite the already high number of species produced in aquaculture, increasing pressure in the last decade for further species diversification has brought attention to several either low trophic species or very fast growing or endangered species (Naylor et al. 2021; Boyd et al. 2020; Cottrell et al. 2021; Newton et al. 2021).

Over the past decade, there has been a growing use of factorial and nutrient-flow (or demand) modelling systems to define requirements for energy and macronutrients for an increasing number of species. Such models are now being widely used to iteratively define nutritional requirements for various species across their production size ranges and within varying environmental conditions (Glencross & Bermudes, 2012; Chowdhury et al., 2013). There has been increasing levels of adoption of modelling by the commercial aquaculture sector as a means of refining feed design and improving feed management. Furthermore, the development of mechanistic models has further advanced our understanding of the interrelationships between different metabolic pathways and nutrient use and how this influences growth and body composition (Bar et al., 2007; Bar & Radde, 2009).

A growing understanding of the role of the microbiome in nutrient supply/utilisation has emerged. Brought about by low-cost methods to evaluate microbial diversity using 16S ribosomal RNA sequencing technologies. This has enabled an increased understanding of the physiological interaction between the microbiome and its host. However, its potential to mediate how organisms respond to multiple environmental factors remains poorly understood. For example, most aquafeeds contain carbohydrate-based binders (e.g., starches) which do not exist in the aquatic environment. These complex carbohydrates are influential in the development of a particular microbiomes. Differences in microbiome structures have been observed between fish fed either extruded or non-extruded pellets containing starch (Barreto-Curiel et al., 2018). So, it is apparent that the gelatinization process is influential to the structure of the different microbial communities. Understanding the impacts of such dietary changes on the resulting microbial communities will be helpful to identify those strategies that are beneficial or not (Fuentes et al., 2020). Another important aspect is the differences in microbiome structures in organisms subjected to stress, whether due to effects of system intensity, environmental contamination, temperature, and/or nutritional deficiencies. Studies have shown that stress, particularly chronic stress, and microbial manipulation (probiotics or prebiotics) influences the microbiome structure of the fish gut (Serradell et al. 2020; Rimoldi et al. 2020; Anker-Ladefoged et al., 2021).

However, there is still insufficient information on the influence of nutritional or environmental factors on the microbiome on fish growth and health to assess the economic benefits of adding probiotics in the feed or water.

The growing need for immune enhancing diets comes back to issues of poor definition of micro-nutrient supply under prevailing conditions linked to large-scale marine ingredient replacement without tacking all the requirement issues comprehensively. Consequently, functional feeds are being developed to enhance animal health. Such functional feeds must have optimized nutrient composition and are supplemented with some functional additives, allowing the farmer to not only to meet the needs for better growth, but also improve the immunity, stress resistance and health status of aquaculture animals, whilst ensuring the quality and safety of the products.
The most common functional additives used in aquafeeds include preservatives (antioxidant), nutritional supplements (amino acids, vitamins, trace elements), enzymes, pigments (carotenoids), palatants, and immunomodulators (probiotics, prebiotics, plant extracts, and nucleotides). The mechanistic action of such functional additives is multi-dimensional. They can act directly and/or indirectly on the animal, such as antioxidation, modification of gut microbe profiles, improvement of digestive tract morphology, elevation of digestive enzyme activities and nutrient absorption, and enhancement of immunity and disease resistance (Tacchi et al., 2011; Aguirre-Guzmán et al., 2012; Torrecillas et al., 2014; Hoseinifar et al., 2017; Hayatgheib et al., 2020). In the future, further studies are needed on the functional mechanisms of individual additives and also their interactions, especially their synergistic effects. Usage of many such additives is however under strict regulations that vary widely among countries, though there are levels of regulation exerted on their use through global efforts such as Codex Alimentarius (http://www.fao.org/fao-who-codexalimentarius/home/it/).

Future (2020 and beyond)

Analysis of the changes in the FCR values for most mainstream species demonstrates that improvements have been plateauing for some time and only smaller gains are now being made, leading to a point of diminishing returns for many species (Figure 1) (Naylor et al., 2009; Ytrestøyl et al., 2015; Tacon, 2020). Any future work on defining requirements needs to focus more precisely on refining estimates with further consideration of nutrient interactions and the use of new and more stable delivery forms, that help reduce nutrient wastage and increase efficiency. In the coming decades, aquaculture sustainability will remain a major concern. Water quality remains vital for aquaculture production and inadequate nutrition and feeding practices are known to deteriorate water quality. Thus, designing more efficient feeds through better knowledge of nutrient requirements, their appropriated balance and effective delivery forms, will improve nutrient stability and absorption and minimize nutrient waste. Likewise, refining feeding management practices to avoid excess nutrient load in the water will limit (or reduce) the increased oxygen demand following eutrophication which can compromise fish health, welfare, and growth.

There is a growing need to prescribe the required levels of essential nutrients in the diet more precisely based on age, genotype, nutritional history, environment, farming system, and immune status to deliver a "precision nutrition" approach to farming animals. This will necessitate the use of various modelling (using big data), internet-of-things (IoT), and artificial intelligence (AI) approaches to support aquaculture production and feed specification management. An integration between traditional models with more mechanistic approaches will lead to better prescription of nutrient and energy requirements based on an increasing number of input parameters. Advances in such modelling systems are now already accommodating demands for amino acids and net energy demands for various species (Hua & Bureau, 2019; Glencross, 2021).

The improved definition of requirements for key nutrients (energy, amino acids, fatty acids) on a digestible and net basis is still required for most species and especially those in the developing world. The future of aquaculture nutrition will increasingly be based on precision and smart farming that will require a clear definition of nutrient requirements on a digestible and a net basis. This is particularly important in the context of encouraging the utilisation of locally sourced ingredients. The shift towards increasing use of alternative ingredients in recent years has made it even more important to formulate diets on a digestible nutrient basis, not only due to the presence of antinutritional factors that can interfere with nutrient utilization, but also due to the variability in the bioavailability of the nutrients required to formulate balanced diets (Boyd et al. 2020).
Some of these new ingredients have complex matrices that limit digestion and/or absorption of nutrients (e.g., algae) (Valente et al., 2021), highlighting the relevance of formulating on a digestible basis as is already done in many other species.

Tailoring fish diets to produce valued-added products able to respond consumer’s expectation will also gain importance in the future. This will include nutrient fortification of fish via their diet for children, pregnant women, and elderly people, by enrichments in omega-3 (especially EPA and DHA), selenium, vitamin D and iodine. The capacity of farmed fish to not only increasingly supply protein for the world, but to also do so in a way that enhances the nutrition of the young and at risk will become increasingly important (Thilsted, 2012; Tacon & Metian, 2013). This food fortification/enhancement combined with a growing focus on food safety will enhance the role of nutrition as a critical control point in aquaculture.

Functional diets for challenging production periods and conditions will gain increasing prominence. Climate change and growing levels of intensification and the use of recirculating aquaculture systems (RAS) will increase the susceptibility of fish to alterations in environmental conditions that will increase stress which will need to be mitigated. Functional diets that contain ingredients or additives that affect animal robustness and health will become increasingly important. Because production system environmental changes are expected with the growing intensification of aquaculture, it will be necessary to further investigate what positive effects functional diets will have, by identifying the most adequate ingredients and/or additives that result in improved animal performance and health. The formulation of diets for challenging times in the fish production process will be increasingly required. The use of various feed additives to help or mitigate the effects of stress through the year or seasonally will become increasingly common. Although the potential for formulating marine ingredient free diets already exists for a vast majority of species, it is usually not cost-effective in most cases for carnivorous species. Such diets are also often associated with chronic health issues and poor animal robustness, so formulating based on nutrients (amino acids and fatty acids) will further require the search for additives that can be used to improve the general health status and robustness of different aquaculture species in a future with constraints on marine ingredient use.

Over the past 40 years, the rapid development and increasing intensification of aquaculture across a broad range of species and geographies have led to problems arising in some cases. Issues such as environmental deterioration and stress, sometimes leading to disease outbreaks and then subsequent abuses of antimicrobials and other chemical drugs have been reported in various sectors. These issues threaten food safety and sustainability of aquaculture. Misuse of antimicrobials not only leads to drug residues, affects food safety, but also potentially leads to drug-resistant pathogens, that can then lead to public health issues. Many countries have legislated to prohibit the use of antimicrobials as growth promotors in animal feed (since 2006 in EU), and many are gradually restricting its use for medical purposes to tackle the emergence of bacteria and other microbes resistant to antimicrobials. In addition, due to constraints on further growth in the production of fish meal, fish oil and other marine-derived ingredients, many non-traditional ingredients have been used to replace fish meal and fish oil in aquafeeds.

In many cases, this has resulted in growth retardation and impaired health of fish and shrimp as the changes were often not supported by science or backed up with required alternatives to bring a positive outcome. Hence, in the future, we must look for new technologies or nutritional approaches (e.g., functional feeds) to mitigate the negative aspects of substitutions of marine-derived ingredients and the reduction in the use and overall stewardship of antibiotics to ensure the good growth, health, product safety of aquaculture animals and to enable the sustainable development of aquaculture. In parallel, there is also an opportunity to tailor flesh quality to increasing consumer's demand for healthier products.
The fortification of aquafeeds with omega-3 (especially EPA and DHA), vitamin D and minerals (e.g., selenium and iodine) can help providing adequate nutrition for vulnerable population groups (Thilsted et al., 2014; Kwasek et al., 2020).

Having defined the nutritional requirements of the various aquaculture species, there is additionally a need to find the appropriate raw materials (ingredients) from which to provide these nutrients and energy. This supply of raw materials also needs to develop sustainable supply chains to enable the aquaculture sector to continue to grow amongst the various sustainability challenges that production of aquaculture feeds faces (MacLeod et al., 2020; Naylor et al., 2021).

Ingredients

There have been marked shifts in ingredient use for aquaculture feeds over the past several decades. In this section we review the practices of the past and the present to predict future trends and needs. While not all aquaculture uses industrially produced compounded feeds, this is the fastest growing feed sector in the world and indicators suggest that more and more aquaculture production is becoming increasingly intensified and reliant on the provision of external feed inputs.

Past (before 2010)

From the late 20th century to 2010, global aquafeed production grew from <5Mtonnes in 1990 to ~30Mtonnes in 2010. Fish meal and fish oil were considered critical ingredients in feeds for many carnivorous fish and crustacean species, and their global production averaged ~6Mtonnes and 1MTonnes per annum respectively over this period. Fish meal use in aquaculture feeds peaked during 2005 – 2010 at ~3.6 Mtonnes per annum (Figure 2). Fish oil use peaked a bit before this at around 0.9Mtonnes per annum. Recognition that such marine ingredients were limited in supply led to a global effort to move towards more use of alternative ingredients in aquafeeds. Early fish meal alternatives were primarily of animal origin due to availability, cost, and protein content. Since then, the perceived risks associated with inclusion of rendered animal by-products in aquafeeds have seen their restriction in several geographic regions (primarily within European countries) due to concerns of pathogens and zoonotic disease transmission (Glencross et al., 2020). Plant proteins were initially only a minor contributor to aquaculture feed protein and lipids for most carnivorous species, but by 2010 inclusion levels reached about 28% of the total feed inputs for salmon feeds globally, up from 12% in 2000. At the same time fish meal reduced from up to 45% in 2000 to 23% of the diet in 2010 (Ytrestøyl et al., 2015). This switch was initiated by several El Nino events, which reduced the availability of fish meal and forced the prices up. The feed production sector responded primarily by increasing use of soy and some (wheat and corn) gluten meals. While much of the use of fish meal and fish oil prior to 2010 was driven by economy of nutrients, plant proteins were seen to have significant limitations, often containing lower protein content, antinutritional factors, and imbalanced nutrient profiles (Gatlin et al., 2007).

Although these constraints still existed for plant ingredients, reduced fish meal supplies, and increased costs drove the demand for alternative protein sources. Terrestrial plant ingredients were generally considered as being more sustainable and gained a more significant position in aquafeeds with new processing technologies leading to the creation of a variety of plant protein concentrates that could compete with the higher price and protein content of fish meal. Although still not widely used in feeds for carnivorous species, plant proteins and oils were already by this time the major contributor to aquaculture feed protein and lipids for omnivorous and herbivorous species. Soybean meal was already a widely used ingredient in feeds for omnivorous and herbivorous species, with other grains being used included a range of cereal, oilseed, pulse, and various grain legume seed products. Typical inclusion levels of soybean meal in feeds for such omnivorous and herbivorous species ranged from 15% to 45% (Tacon et al. 2011).

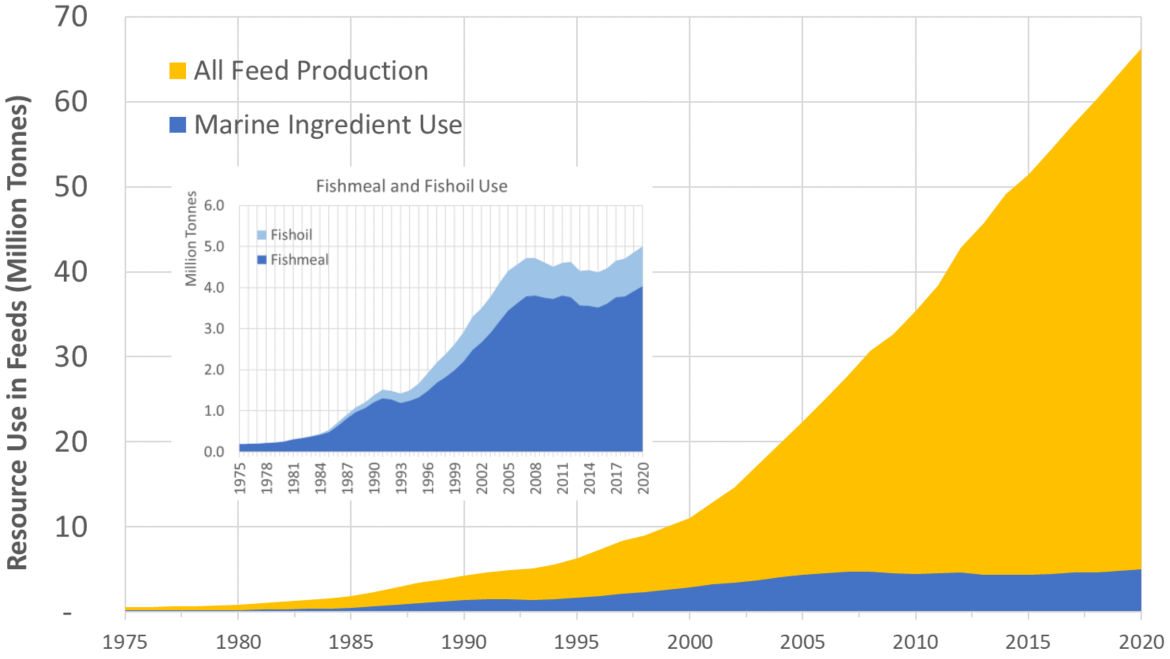

Figure 2. Estimated feed production for all fed aquaculture species sector from 1975 to 2020, with concurrent marine ingredient use across the aquaculture sector. Shown in the inset is a magnified set of the marine ingredient (fish meals + fish oils) use data across the same time. Data derived from FishStat 2020 and IFFO 2021.

Present (2010 – 2020)

Presently there is ~60Mtonnes of aquafeed production globally, of which fish meal is now only ~4MT, fish oil is ~1MT and the rest (~55MT) is mostly plant derived resources (IFFO, 2021). Use of marine ingredients (proteins and oils) in aquafeeds has stabilised since 2010 and they are now seen more as strategic ingredients, with a growing use of by-product fish meal now contributing to >30% of all marine ingredient use in manufactured feeds (Hamilton et al., 2020; IFFO, 2021).

Plant proteins continue to be the main contributor to aquaculture feed protein and lipids for most aquaculture species, but their use is also seen as contentious in some circumstances (e.g., soybean use and associated deforestation concerns). Notably, feeds for carnivorous species are now predominantly composed of plant proteins and oils (Ytrestøyl et al., 2015). The increasing use of processing to produce protein concentrates from soy, peas, and other legumes as well as cereal glutens has occurred. This processing maximises the protein concentration, quality and suitability for use in feeds, whilst minimising the non-nutritive factors (Drew et al., 2007). To balance the amino acids, the use of plant proteins and the concurrent reduction in fish meal has led to a much more complicated formulation, now involving a greater number of protein sources with addition of some crystalline essential amino acids to create a balanced diet to support high growth performance and healthy fish. This broader raw material array brings some advantages to the feed sector, in that it is not reliant on any one ingredient – so there is more resilience to supply chain threats (such as poor harvests). But plant proteins also bring some sustainability challenges to address (Malcorps et al., 2019).

The focus on soy and deforestation is probably foremost, which has led the feed industry to work with their soy suppliers in Brazil to set deforestation and conversion free cut-off dates in 2020 for their entire supply chain. Plant proteins also typically have a much higher carbon footprint than fish meal, which has pushed the overall footprint of the feed up over the last 20 years (MacLeod et al., 2020). Carbon footprint is increasingly of interest, as the carbon impact of food systems has been publicly highlighted. Here aquaculture is in a very good position, being a typically low greenhouse gas (GHG) emitter compared to other food systems, but it also has a great opportunity to improve. It has been suggested that replacing 20-30% of fish meal in shrimp feeds with plant protein ingredients could result in a 63% increased demand for freshwater, 81% increase in land requirements, and a need for 83% more phosphorus (Malcorps et al., 2019).

Across a broader range of life cycle assessment impact factors, it has been argued that there is insufficient land for the expansion of animal feed crop production (Popp et al., 2017), as it currently occupies roughly one-third of global croplands (Robinson et al., 2018). Furthermore, there are additional pressures on land use due to population growth, climate change, and demands for food and biofuels (Spiertz & Ewert, 2009; Godfray et al., 2010). In their discussion, Malcorps et al. (2019) remind us that Sustainable Development Goals of the United Nations include food security, hunger reduction, and protection of life on land and in the sea. They emphasize that minor price changes to crops resulting from increased pressure on land-based food production systems could have dire consequences in developing countries, where 50% of the household income is spent on food (Spiertz & Ewert, 2009).

The current focus is not only on the reduced reliance on fish meal and fish oil derived from capture fisheries, but also increasingly on the overall sustainable supply of terrestrial and plant feed ingredients. Some of the raw materials used in aquaculture feeds can be consumed by humans, resulting in food-feed competition. There is also a consideration of whether raw materials which could be consumed directly by humans should be used for animal feeds.

The shift towards plant-based ingredients in aquaculture feed also faces competition from livestock and agriculture sectors as well as biofuel production. Marine and terrestrial ingredient sources are both vulnerable to climate change, which may cause disruption and decrease in supply and higher costs for aquaculture feeds (FAO, 2018). There is thus a trend towards increased use of by-products as feedstuffs in aquaculture and livestock feeds with a growing focus on bio-circularity of resources. However, consumer concerns have been raised in some markets around the use of by-products, in particular animal by-products which could bring a good nutritional input but are blocked from use in some supply chains due to perceived health risks and social objections (Glencross et al., 2020). In parallel, circular proteins such as insects and microbial biomass are being increasingly advocated as sustainable alternatives, as they can convert various waste streams such as food waste, household waste, plant by-products, sludge into high-quality nutrients. High production and processing costs still limits their large-scale production, and a range of regulations still limit their application in certain markets.

Both microalgal and genetically modified crops have been commercialised that produce long-chain omega-3 in industrial volumes (>1000 tonnes). Due to an urgent need for fish oil alternatives, a range of omega-3 rich ingredients are emerging, e.g., microbial ingredients (microalgae), oil seeds with high level of LC-PUFAs (rapeseed and camelina), and increased use of fish by-products, and lower-tropic marine species (e.g., krill, mesopelagic fish) (Hamilton et al., 2020). Up to eight relatively new sources of EPA and DHA with industrial potential for aquafeeds have been recently described (Tocher et al. 2019). These products included five microalgal sources, two genetically modified seed crop oils, and one yeast biomass. Identification of cost-effective, alternative lipids high in the LC-PUFAs EPA and DHA remains a substantial hurdle for the future of aquaculture. Both microalgal and genetically modified crops will undoubtedly play an increasingly important role in aquafeeds for those species requiring LC-PUFAs. Perhaps equally important is the need to fortify fish feeds toward the improvement of human health.

Food safety is a considerably overlooked aspect of much fish nutrition research but is increasingly highlighted socially and politically (Glencross et al., 2020a). As an example, perceptions over the use of food waste for livestock and fish feeding has limited efforts in this area, particularly in developed countries, and yet there is an estimated 1.3 billion tons of human food lost and wasted each year (Gustavsson et al., 2011). Concerns over genetically modified feed ingredients also limit options in certain parts of the world, but others are readily adopting this technology. Food safety risks are associated with the possible chemical contaminants and biological hazardous materials present in ingredients and feeds, which might be passed to humans who consume aquaculture products. Concerns have been raised about antimicrobial residues, persistent organic pollutants, heavy metals, mycotoxins, and industrial contaminants (Tacon et al. 2008; Glencross et al., 2020). Additional concerns over microplastics in fish meal have been raised recently (Hanachi et al. 2019; Gündoğdu et al. 2021; Thiele et al. 2021).

Future (after 2020)

It has been suggested that by the year 2050 that aquaculture production is going to double and intensify. Fundamentally what it will need to feed that production is sustainably sourced, economic, good quality protein, some essential amino acid (EAA) additives, some omega-3 options, various mineral and vitamin additives, and cost-effective energy sources. To do that will mean we need another 50MT of resources that we currently do not have or are presently being used in other sectors. Although gains in crop productivity have kept pace with demand through most of the 20th century, they are not keeping up with demands more recently (Grassini et al., 2013; Schauberger et al., 2018). Notably, most currently used plant protein resources are also used in pig and poultry feeds (so a competition issue exists).

There is additionally the concern that many of these plant protein resources can be used directly to feed humans rather than animals. Add into the equation that there is a declining availability of freshwater, phosphates, and arable land, and it is obvious that terrestrial crop products are not the only solution going forward. Further competition for ingredients of plant origin is also occurring for human food and non-food products such as biofuels. While many plant source ingredients are considered economically sustainable, questions have been raised about their social and environmental sustainability, notably products from soy and palm oil production (Hospes 2014; Okereke and Stacewicz 2018). These constraints provide a strong argument for the development of non-traditional protein and oil sources.

Fish meal and fish oil are still considered among the most nutritious ingredients as they are rich sources of essential nutrients and have a high level of palatability in virtually all aquaculture species. Increasingly fish meal and oil production will come from by-product resources from fish caught for direct human consumption (e.g., Alaskan pollock) or aquaculture by-product. By 2030 more than one third of all fish meal and oil will come from by-product sources (IFFO, 2021). The continued reduction in the reliance on fish meal and fish oil, combined with the concurrent increased use of alternative raw materials in aquaculture feeds highlights the need for an approach based on complementarity of ingredients (Turchini et al., 2019). The increasing use of alternatives brings about the need for a range of feed additives to supplement specific essential nutrients including essential amino acids, essential fatty acids, and trace elements. We may also see greater usage of bioactive compounds, prebiotics, probiotics and other immunostimulants (Boyd et al., 2020). It is critical to find additional, cost-effective ingredient sources to meet the growing nutrient demand. This burgeoning demand, growing ingredient competition, and heighted sustainability awareness provide a strong argument for the development of non-traditional protein and oil sources, especially those part of the circular bioeconomy like such as insects, microalgae, microbial biomass, and food waste.

Technologies that produce protein, amino acids, and omega-3 using non-competitive processes based on non-food grade resources (e.g., bacteria, yeasts, and algae; single-cell ingredients [SCI]) perhaps offer the most potential to generate the additional resources needed (Glencross et al., 2020b). As biotechnology advances, a broader range of substrates from various waste streams will be used in the fermentation process to reduce costs and increase profitability of SCI production. This will include the downstream processing to enhance the nutritional value of the microbial ingredients. As the competition for natural resources increases and the technology advances, production of microbial ingredients will shift from being dependent on photosynthesis and products from this process as substrates, towards use of cheaper input factors (e.g., organic acids, CH_4, H_2 and CO_2 gas) from industrial waste or other renewable sources.

Additionally, there will be increasing pressure to source ingredients locally for feed production and reduce dependence upon imported sources. This will demand more effort be given to use of local ingredients, the adoption of nutrient recycling and use of innovative raw material processing techniques. This will probably be coupled with the use of renewable energies as the type of fuel used for processing has a remarkable life cycle impact on such ingredients (Campos et al. 2020). In the future there is likely to be more competition for natural resources; driven by factors such as population growth, development of the bioeconomy, and climate change. Aquaculture production will play an increasing role in meeting the global protein supply and the need for feed to sustain this production will clearly increase.

Sustainability of different feed ingredient sources, including possible climate change impacts, is becoming a growing issue. For the global aquaculture sector to grow sustainably, it must have a sustainable supply of the nutrients to make the feeds.

The key sustainability issues vary from ingredient to ingredient and the historical approach was to focus just on one feed ingredient at a time – such as fishmeal or soy. Sustainability of different feed ingredient combinations will become a key defining characteristic of their utility, with increasing use of independent certification systems to verify claims. Going forwards, we will see an increasing focus on the sustainability of the feed ingredient supply chains. The discussion should move beyond whether an individual ingredient is sustainable or not, to one of whether that supply chain is. For example, fishmeal can be supplied sustainably – from sustainably managed fisheries. Soy can be farmed sustainably, on land which was not recently converted from native vegetation. Independent certification schemes have been established to provide verification of claims. There are a broad range of schemes with different levels of value and credibility, but all add cost to the overall supply chain. However, the expectation is that the use of certification to verify sustainability claims will continue to grow. As the topics covered by sustainability increase, the number of schemes is likely to continue to grow. For example, through moving beyond fisheries and deforestation issues to addressing issues of human rights, carbon footprint, land, and water use. The level of complexity to be managed will increase, but the information to do this has to keep pace, so good decisions are made on the latest reliable data. This can only be supported by a full value chain commitment to change – led from the consumer and retail end to support the upstream supply side's transformation. Without commitment from the market, changes will be harder to implement and value. Assessment of the sustainability of feed ingredients varies depending on the type of ingredients as their social, economic, and environmental impacts all differ considerably. There is a need for harmonisation of various aquaculture related sustainability certification standards to ensure consistency (Kok et al., 2020). The adoption of certification schemes will continue to reduce or eliminate ingredients from unsustainable sources.

Food safety will become an increasingly important issue in the future. Driven by consumer perception, politics and some level of science, consumers will gravitate toward those products that align with their attitudes, preferences, and expectations. Food safety will continue to be important for feed manufacturers and fish producers to meet consumer demand for disclosure of credence attributes. In addition to safety, these include origin, sustainability, and nutritional content. As such, both mandatory and voluntary labelling will continue to be strong drivers of the seafood market.

Feed Management and Manufacturing

Past (before 2010)

Feed rationing systems and management of how much and when feed was delivered to the animal were largely based on prior experience or demand based, relying on the animal providing feedback to the person feeding them. Most feeding was manual, using hand, blower, or other simple delivery systems. As such feeding was a labour-intensive process (Ibrahim & Sultana, 2006). Traditional feeding regimes were based on experience of the operators, considering factors such as weather, water colour, season, and animal behaviour among other things. The diet was selected based on price and/or feed manufacturer recommendations. The focus was on fish growth. Traditional end points for manual feeding were judged by farmers making decisions based on their experience and skills. This primarily entailed deciding what feed, when, and how much was delivered to the animal (Jobling et al., 1995; Paspatis & Boujard et al., 1996). Assessments of animal behaviours and interactions with feeds and the feeding process were somewhat subjective, though for certain species some simple tools, like feed trays, were used to assist the process (Tacon, 2002). For technologically advanced sectors, sensor-based feeding systems were emerging (Kadri et al., 1998).

Historically, many feeds were based on the use of trash-fish and/or made on-farm by the farmers. These may have initially been fed as intact trash-fish or made into a moist mash with the use of other materials and binders or made into dried pellets using simple pelleting manufacturing systems (Hasan & New, 2013). With the growth and increasing technical demands on the sector, specialist feed compounders emerged and brought advancements in the various processes used in feed manufacturing. Additionally, the feed manufacturing sector played an important role in helping farmers, not only in the provision of feed inputs, but more importantly in the management of the feed on the farm and in the use of appropriate environmentally sound husbandry practices. In many countries the feed manufacturers were the closest contact in the value-chain between the farmer and the government legislature (Tacon et al., 1995). Notable among the manufacturing introductions during this period was that of expansion extrusion, which was introduced into some sectors from 1980’s onwards and by the 2000’s became widely used across the developed world for most fish species, and increasingly was being applied in the developing world.

Present (2010 – 2020)

In the present day, feed management systems in technologically advanced sectors are becoming increasingly computerised in modern developed-world aquaculture. Automated centralised pneumatic feeding systems using in-cage cameras and computer-based decision-making tools are widespread resulting in a reduced level of labour (Aas et al., 2011; Waagbo et al., 2013). However, in the developing world where the majority of aquaculture still occurs, feeding is still largely a manually controlled and managed process with important labour demands and continues to be a significant rural employer (El-Sayed, 2013; Hung & Quy, 2013; Ng & Romano, 2013). Feeding end points are still largely judged by farmer decisions in combination with computerised algorithms. The interpretation of the fish responses is experience-based and depends on the experience and skills of the individual farmer.

The use of growth and energetics models are increasingly being applied for the evaluation and management of feeding regimes for various species (Cho & Bureau, 1998; Zhou et al., 2005; Glencross & Bermudes, 2012; Liu et al., 2018). The application of modelling helps reduce both the feed cost and the waste being discharged (Bueno et al., 2017). Historically, modelling focused only on evaluating the feeding rate, but increasingly, diet formulation, environmental factors, feeding frequency, feeding rhythm and even animal behaviour are all being taken into consideration.

Manufacturing of feeds in the developed world is now mostly based on modern extrusion technologies (Barrows et al., 2007). There has been considerable development of engineering technological capabilities in this area, allowing considerable control over the forming, cooking and densification attributes of the feeds. Such engineering systems are highly complex but offer a substantial level of control on the pellet forming process, enabling the user significant control on pellet density, durability, and oil infusion capacities (Sørensen, 2012). Despite these advancements, and the increasing level of industrialisation of feed manufacturing, some sectors (e.g., shrimp farming), have still tended to stay with manufacturing approaches like pelleting, while other sectors in the developing world, particularly small-scale aquaculture operations, have continued to use an on-farm mash feed manufacturing approach. Shrimp feeds, despite being still predominantly pelleted, are beginning to emerge as extruded products through some companies (Obaldo et al., 2000; Soares et al., 2021). In the developing world there is still widespread use of pelleting, mash, and trash-fish feeding, especially on-farm, although extrusion is increasingly being used by commercial feed suppliers in these parts of the world (Edwards et al., 2004; Xu et al., 2007; Tacon & Metian, 2009; Merican, 2021).

Future (after 2020)

To increase sustainability of fish production and optimise fish product quality and animal welfare, it is becoming even more important to monitor and control the animal production process (Antonucci & Costa, 2020). By reducing the feed conversion ratio, farmers will have less waste and loss of nutrients to the water they farm in, and they will tend to reduce their overall carbon footprint. To achieve this, we need a better understanding of feed intake and its physiological points of regulation and how this is affected by production system (e.g., RAS, pond, or cage) and a range of other abiotic factors. In the future we will see increasing use of mechanised and automated feeding in the developing world, matching that already being undertaken in much of the developed world. This use of mechanised and automated feeding will aid in improving production efficiencies (through less wastage) and animal growth rates (through higher intakes), by allowing for the better alignment of feeding with the needs of the animals being farmed, but it will correspondingly reduce labour demands and employment in the sector. Already there are signs of increasing use of autonomous feeding systems in the developing world, occurring through the development of a variety of low-cost automatic feeding systems (e.g., https://www.efishery.com/).

The use of artificial intelligence (AI) in feeding systems is emerging. AI is going to impact businesses of all shapes and sizes across all industries (Marr, 2020). The increasing use of centralised computer-controlled feeding systems and in-cage / in-pond sensors and cameras will increasingly make an internet-of-things system of control more feasible for feeding aquaculture species (Martos-Sitcha et al., 2019; Måløy et al., 2019; Mustapha et al., 2021). The development of complex algorithms and AI that monitors feeding behaviour will be used to help make decisions about feeding management (Jones et al., 2012; Zhou et al., 2018). Coupled with more precisely defined energy and nutrient demands over various size classes, environments, genotypes and in situ bio-loggers, the inclusion of a precision nutrition approach will complement completely automated feeding (Hvas et al., 2020; Zhang et al., 2020).

The use of automation and AI will lead to precision and smart farming increasingly becoming a focus. The use of big data applications may play a major role in improving the efficiency of the entire supply chain, with focus on food security, safety, and sustainability (Gilpin, 2015). These will provide an increasing focus on the application of principles of precision fish farming (PFF) to shift feeding management from comprising largely experience-driven processes to become a more knowledge-driven procedure (Føre et al., 2018). PFF feeding regimes based on animal demands and farm targets, including specialised diet formulations, considerations of environmental factors, animal health and/or quality and/or water quality will be included into the AI system to provide precise decisions for management of computer-controlled systems. Biological and system informatics will become combined to increase the precision control of fish farming. The use of intelligent sensors and monitoring, will support the application of predictive models and simulation systems, leading to improved decision management and integration of operations that will enhance the overall precision control of fish farming operation (Fore et al., 2018). The use of models to predict environmental fluctuations and adjust feed distribution accordingly and autonomously to minimise feed waste and improve efficiency should be a primary goal for improved production efficiency in aquaculture. The optimal solution should be the use of real-time techniques that can determine the actual feeding behaviour of the fish. Therefore, to ensure efficient feeding in aquaculture, it is necessary to develop a smart feeding regime system that can analyse the appetite status of farmed fish (Adegboye et al. 2020).

There will continue to be increasing use of extrusion feed production with greater uptake in the developing world and development of novel extrusion applications for non-traditional species based on improved feed technical qualities and flexibility of the manufacturing systems used.

This increasing shift to manufactured feeds across the developing world will result in an overall improvement in feed quality and resource utilisation by the sector, further aiding a move away from the use of trash-fish and farm-made feeds. Additionally, because of the increased use of automatic feeders, there will be increased demand for the use of high-physical quality non-clogging extruded feeds in these feeding systems. The increasing demand for functional feeds with specialist additives will see the emergence of nanotechnology to precision deliver certain high-valued compounds to the fish, by preventing them to be digested or metabolised at certain stages of the absorption process, allowing for targeted nutrient and nutraceutical delivery. Such novel encapsulation methods will enable the protection of certain labile functional ingredients from the damaging forces involved in extrusion.

END NOTE

Many of the advances in nutritional understanding of aquaculture species over the past twenty years has come from an intense focus on a few species. However, it should be clearly acknowledged that part of the challenge of aquaculture nutrition is the diversity of species involved and that their requirements can be just as diverse. There is an urgent need to bring our understanding of many of the non-focus species into the same level of understanding. Additionally, although marine derived ingredients are still widely used in feeds, even salmon farming has now become a net producer of seafood. Globally around 4 MT of fishmeal and 1MT of fish oil is contributing to the production of more than 40MT of farmed fish and shrimp, an almost ten times multiplier effect. The widespread use of plant proteins and oils has underpinned the growth of aquaculture over the past twenty years. The capacity for aquaculture to achieve this has been the result of decades of nutrition research (Naylor et al., 2020). The future will require further work in developing the potential of a range of sustainable feed protein and oil options, particularly those from the circular bioeconomy.

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References

Aas, T. S., Oehme, M., Sørensen, M., He, G., Lygren, I., & Åsgård, T. (2011). Analysis of pellet degradation of extruded high energy fish feeds with different physical qualities in a pneumatic feeding system. *Aquacultural engineering*, 44(1), 25-34.

Aas, T.S., T. Ytrestøyl, and T. Åsgård. (2019). 'Utilization of feed resources in the production of Atlantic salmon (*Salmo salar*) in Norway: An update for 2016', *Aquaculture Reports*, 15.

Adegboye, M. A., Aibinu, A. M., Kolo, J. G., Aliyu, I., Folorunso, T. A., & Lee, S. (2020). Incorporating Intelligence in Fish Feeding System for Dispensing Feed Based on Fish Feeding Intensity. *IEEE Access*, vol. 8, pp. 91948-91960. doi: 10.1109/ACCESS.2020.2994442.

Aguirre-Guzmán G., Lara-Flores M., Sánchez-Martínez G., Campa-Córdova A., González A., (2012). The use of probiotics in aquatic organisms: A review. *African Journal of Microbiology Research*, 6:4845-4857.

Anker-Ladefoged, C., Langkamp, T., Mueller-Alcazar, A. (2021). The potential impact of selected bacterial strains on the stress response. *Healthcare*, 9, 494. Doi:10.3390/healthcare9050494.

Antonucci, F., & Costa, C. (2020) Precision aquaculture: a short review on engineering innovations. *Aquaculture International*, 28, 41–57. https://doi.org/10.1007/s10499-019-00443-w

Bar, N. S., Sigholt, T., Shearer, K. D., & Krogdahl, Å. (2007). A dynamic model of nutrient pathways, growth, and body composition in fish. *Canadian Journal of Fisheries and Aquatic Sciences*, 64(12), 1669-1682.

Bar, N. S., & Radde, N. (2009). Long-term prediction of fish growth under varying ambient temperature using a multiscale dynamic model. *BMC Systems Biology*, 3(1), 1-19.

Barreto-Curiel, F., Ramirez-Puebla, S.T., Ringø, E., Escobar-Zepeda, A., Godoy-Lozano, E., Vazquez-Duhalt, R., Sanchez-Flores, A., Viana, M.T. 2018. Effects of extruded aquafeed on gut microbiome and growth performance of juvenile *Totoaba macdonaldi*. *Feed Science and Technology*, 245, 91-103. ISSN 03778401 10.1016/j.anifeedsci.2018.09.002

Barrows, F. T., Stone, D. A., & Hardy, R. W. (2007). The effects of extrusion conditions on the nutritional value of soybean meal for rainbow trout (*Oncorhynchus mykiss*). *Aquaculture*, 265(1-4), 244-252.

Berntssen, M. H., Betancor, M., Caballero, M. J., Hillestad, M., Rasinger, J., Hamre, K., ... & Ørnsrud, R. (2018). Safe limits of selenomethionine and selenite supplementation to plant-based Atlantic salmon feeds. *Aquaculture*, 495, 617-630.

Boonyaratpalin, M. (1997). Nutrient requirements of marine food fish cultured in Southeast Asia. *Aquaculture*, 151(1-4), 283-313.

Boyd, C. E., D'Abramo, L. R., Glencross, B. D., Huyben, D. C., Juarez, L. M., Lockwood, G. S., . . . Valenti, W. C. (2020). Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *Journal of the World Aquaculture Society*, 51(3), 578-633. doi:10.1111/jwas.12714

Bueno, G. W., Bureau, D., Skipper-Horton, J. O., Roubach, R., Mattos, F. T., & Bernal, F. E. M. (2017). Mathematical modelling for the management of the carrying capacity of aquaculture enterprises in lakes and reservoirs. *Pesquisa Agropecuária Brasileira*, 52(9), 695-706. https://doi.org/10.1590/

Campos, I., Valente, L. M. P., Matos, E., Marques, P., & Freire, F. (2020). Life-cycle assessment of animal feed ingredients: Poultry fat, poultry by-product meal and hydrolyzed feather meal. Journal of Cleaner Production, 252, 119845.

Cho, C. Y., & Bureau, D. P. (1998). Development of bioenergetic models and the Fish-PrFEQ software to estimate production, feeding ration and waste output in aquaculture. Aquatic Living Resources, 11, 199-210.

Chowdhury, M. K., Siddiqui, S., Hua, K., & Bureau, D. P. (2013). Bioenergetics-based factorial model to determine feed requirement and waste output of tilapia produced under commercial conditions. Aquaculture, 410, 138-147.

Cottrell, R. S., Metian, M., Froehlich, H. E., Blanchard, J. L., Sand Jacobsen, N., McIntyre, P. B., ... & Halpern, B. S. (2021). Time to rethink trophic levels in aquaculture policy. Reviews in Aquaculture, 13: 1583-93.

Cowey, C. B. (1992). Nutrition: estimating requirements of rainbow trout. Aquaculture, 100(1-3), 177-189.
Edwards, P., Tuan, L. A., & Allan, G. L. (2004). A survey of marine trash fish and fish meal as aquaculture feed ingredients in Vietnam (No. 437-2016-33834).

De Verdal, H.; Komen, H.; Quillet, E.; Chatain, B.; Allal, F.; Benzie, J.A.H.; Vandeputte, M. Improving feed efficiency in fish using selective breeding: A review. *Rev. Aquac. 2018*, *10*, 833–851.

Domínguez, D., Sehnine, Z., Castro, P., Robaina, L., Fontanillas, R., Prabhu, P.A.J., Izquierdo, M. Optimum selenium levels in diets high in plant-based feedstuffs for gilthead sea bream (*Sparus aurata*) fingerlings (2020a). Aquaculture Nutrition, 26 (2), 579-589.

Domínguez, D., Montero, D., Robaina, L., Hamre, K., Terova, G., Karalazos, V., Izquierdo, M. Effects of graded levels of minerals in a multi-nutrient package on Gilthead sea bream (*Sparus aurata*) fed a plantbased diet (2020b) Aquaculture Nutrition, 26 (4), 1007-1018.

Drew, M. D., Borgeson, T. L., & Thiessen, D. L. (2007). A review of processing of feed ingredients to enhance diet digestibility in finfish. Animal Feed Science and Technology, 138(2), 118-136.

Dumas, A., France, J., & Bureau, D. (2010). Modelling growth and body composition in fish nutrition: where have we been and where are we going?. Aquaculture Research, 41(2), 161-181.

El-Sayed, A. F. M. (2013). On-farm feed management practices for Nile tilapia (Oreochromis niloticus) in Egypt. On-farm feeding and feed management in aquaculture. FAO Fisheries and Aquaculture Technical Paper, 583, 101-129.

FAO 2018. Impacts of climate change on fisheries and aquaculture. Synthesis of current knowledge, adaptation and mitigation options. FAO Fisheries and Aquaculture Technical Paper 627. Food and Agriculture Organization of the United Nations. Rome.

Fernández-Palacios, H.; Norberg, B.; Izquierdo, M.; Hamre, K. (2011). Effects of Broodstock Diet on Eggs and Larvae. In *Larval Fish Nutrition*; John Wiley and Sons, Inc.: Hoboken, NJ, USA, 2011; pp. 151–181, ISBN 9780813817927.

Ferosekhan, S.; Turkmen, S.; Pérez-García, C.; Xu, H.; Gómez, A.; Shamna, N.; Afonso, J.M.; Rosenlund, G.; Fontanillas, A.; Gracia, A.; et al. Influence of Genetic Selection for Growth and Broodstock Diet n-3 LC-PUFA Levels on Reproductive Performance of Gilthead Seabream, *Sparus aurata. Animals 2021*, *11*, 519.

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.

Fuentes-Quesada, J.P., Rombenso, A.N., Viana, M.T., Guerrero-Rentería, Y., Lazo, J.P., Mata-Sotres, J.A. 2018. Enteritis induction by soybean meal in Totoaba macdonaldi diets: Effects on growth performance, digestive capacity, immune response and distal intestine integrity Aquaculture, 495, 78-89. Doi: 10.1016/j.aquaculture.2018.05.025 ISSN: 0044-8486

Gatlin III, D. M., Barrows, F. T., Brown, P., Dabrowski, K., Gaylord, T. G., Hardy, R. W., ... & Wurtele, E., 2007. Expanding the utilization of sustainable plant products in aquafeeds: a review. *Aquaculture research*, 38(6), 551-579.

Gilpin, L. (2015) How Big Data Is Going to Help Feed Nine Billion People by 2050. (Accessed: 2021) http://www.techrepublic.com/article/how-big-data-is-going-to-help-feed-9-billion-people-by-2050/

Glencross, B. D. (2008). A factorial growth and feed utilization model for barramundi, Lates calcarifer based on Australian production conditions. *Aquaculture Nutrition*, 14(4), 360-373.

Glencross, B. D., & Bermudes, M. (2012). Adapting bioenergetic factorial modelling to understand the implications of heat stress on barramundi (Lates calcarifer) growth, feed utilisation and optimal protein and energy requirements–potential strategies for dealing with climate change? *Aquaculture Nutrition*, 18(4), 411-422.

Glencross, B., Tabrett, S., Irvin, S., Wade, N., Anderson, M., Blyth, D., ... & Preston, N. (2013). An analysis of the effect of diet and genotype on protein and energy utilization by the black tiger shrimp, Penaeus monodon –why do genetically selected shrimp grow faster? *Aquaculture Nutrition*, 19(2), 128-138.

Glencross, B. D., Baily, J., Berntssen, M. H., Hardy, R., MacKenzie, S., & Tocher, D. R. 2020a. Risk assessment of the use of alternative animal and plant raw material resources in aquaculture feeds. *Reviews in Aquaculture*, 12(2), 703-758.

Glencross, B. D., Huyben, D., & Schrama, J. W. 2020b. The application of single-cell ingredients in aquaculture feeds—a review. *Fishes*, 5(3), 22.

Godfray, H.C.J., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Nisbett, N., Pretty, J., Robinson, S., Toulmin, C. & Whiteley, R., 2010. The future of the global food system. https://doi.org/10.1098/rstb.2010.0180

Grassini, P., Eskridge, K. & Cassman, K. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nat Commun 4, 2918 (2013). https://doi.org/10.1038/ncomms3918

Gündoğdu, S., Eroldoğan, O., Evliyaoğlu, E., Turchini, G., & Wu, X. (2021). Fish out, plastic in: Global pattern of plastics in commercial fishmeal. *Aquaculture*, *534*, 736316–. https://doi.org/10.1016/j.aquaculture.2020.736316

Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R. & Meybeck, A., 2011. Global food losses and food waste. https://www.madr.ro/docs/ind-alimentara/risipa_alimentara/presentation_food_waste.pdf

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

Hamre, K., Yúfera, M., Rønnestad, I., Boglione, C., Conceição, L.E.C., Izquierdo, M. Fish larval nutrition and feed formulation: Knowledge gaps and bottlenecks for advances in larval rearing (2013) *Reviews in Aquaculture* 5 (1), S26 - S58

Hamre, K., Sissener, N. H., Lock, E. J., Olsvik, P. A., Espe, M., Torstensen, B. E., ... & Hemre, G. I. (2016). Antioxidant nutrition in Atlantic salmon (*Salmo salar*) parr and post-smolt, fed diets with high inclusion of plant ingredients and graded levels of micronutrients and selected amino acids. *PeerJ,* 4, e2688.

Han, D., Xie, S., Zhu, X. & Yang Y. 2011.A bioenergetic model for Chinese longsnout catfish to estimate growth, feed requirement and waste output. The Israeli Journal of Aquaculture-Bamidgeh 2011, 63: 646.

Hanachi, P., Karbalaei, S., Walker, T., Cole, M., & Hosseini, S. (2019). Abundance and properties of microplastics found in commercial fish meal and cultured common carp (*Cyprinus carpio*). *Environmental Science and Pollution Research International*, *26*(23), 23777–23787. https://doi.org/10.1007/s11356-019-05637-6

Hardy, R.W., Kaushik, S.J., & Mai, K., 2021. Fish Nutrition-History and Perspectives. In: R. Hardy, ed. Fish Nutrition, 4th Edition. Elsevier Academic Press.

Hasan, M. R., & New, M. B. (2013). On-farm feeding and feed management in aquaculture. FAO fisheries and aquaculture technical paper, (583), I.

Hayatgheib N., Moreau E., Calvez S., Lepelletier & D., Pouliquen H., 2020. A review of functional feeds and the control of Aeromonas infections in freshwater fish. *Aquaculture International*, https://doi.org/10.1007/s10499-020-00514-3

Hoseinifar S., Dadar M., Ringø E., 2017. Modulation of nutrient digestibility and digestive enzyme activities in aquatic animals: The functional feed additives scenario. *Aquaculture Research*, 48(8):1-14. DOI: 10.1111/are.13368

Hospes, O. (2014). Marking the success or end of global multi-stakeholder governance? The rise of national sustainability standards in Indonesia and Brazil for palm oil and soy. *Agriculture and Human Values*, 31(3), 425–437. https://doi.org/10.1007/s10460-014-9511-9

Hua, K., Cobcroft, J. M., Cole, A., Condon, K., Jerry, D. R., Mangott, A., ... & Strugnell, J. M. (2019). The future of aquatic protein: implications for protein sources in aquaculture diets. One Earth, 1(3), 316-329.

Hung, L. T., & Quy, O. M. (2013). On farm feeding and feed management in whiteleg shrimp (*Litopenaeus vannamei*) farming in Viet Nam. In: M.R. Hasan and M.B. New, eds. On-farm feeding and feed management in aquaculture. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. pp. 337–357.

Hvas, M., Folkedal, O., & Oppedal, F. (2020). Heart rate bio-loggers as welfare indicators in Atlantic salmon (Salmo salar) aquaculture. *Aquaculture*, 529, 735630.

Hua, K., & Bureau, D. P. (2019). Estimating changes in essential amino acid requirements of rainbow trout and Atlantic salmon as a function of body weight or diet composition using a novel factorial requirement model. Aquaculture, 513, 734440.

Ibrahim, M. Y. & Sultana, S. (2006). Study on Fresh Fish Sorting Techniques," 2006 IEEE International Conference on Mechatronics, 2006, pp. 462-467, doi: 10.1109/ICMECH.2006.252571.

IFFO (2021). https://www.iffo.com/feeding-growing-population.

Izquierdo, M.S., Koven, W. (2011). Lipids. In *Larval Fish Nutrition*; John Wiley and Sons, Inc.: Hoboken, NJ, USA, 2011; pp. 47-82, ISBN 9780813817927.

De Verdal, H.; Komen, H.; Quillet, E.; Chatain, B.; Allal, F.; Benzie, J.A.H.; Vandeputte, M. Improving feed efficiency in fish using selective breeding: A review. *Rev. Aquac. 2018*, *10*, 833–851.

Jobling, M., Arnesen, A. M., Baardvik, B. M., Christiansen, J. S., & Jørgensen, E. H. (1995). Monitoring feeding behaviour and food intake: methods and applications. *Aquaculture Nutrition*, 1(3), 131-143.

Jones, H. A. C., Noble, C., Damsgård, B., & Pearce, G. P. (2012). Investigating the influence of predictable and unpredictable feed delivery schedules upon the behaviour and welfare of Atlantic salmon parr (Salmo salar) using social network analysis and fin damage. *Applied animal behaviour science*, 138(1-2), 132-140.

Kadri, S., Blyth, P. J., & Russell, J. F. (1998). Feed Optimisation in Finfish Culture Using an Integrated “Feedback” System. *Aquaculture Science*, 46(3), 423-426.

Kaushik, S. J., & Seiliez, I. (2010). Protein and amino acid nutrition and metabolism in fish: current knowledge and future needs. *Aquaculture Research*, 41(3), 322-332.

Kok, B., Malcorps, W., Tlusty, M. F., Eltholth, M. M., Auchterlonie, N. A., Little, D. C., & Davies, S. J. (2020). Fish as feed: Using economic allocation to quantify the Fish In: Fish Out ratio of major fed aquaculture species. *Aquaculture*, 528, 735474.

Kousoulaki, K., Krasnov, A., Ytteborg, E., Sweetman, J., Pedersen, M. E., Høst, V., & Murphy, R. (2021). A full factorial design to investigate interactions of variable essential amino acids, trace minerals and vitamins on Atlantic salmon smoltification and post transfer performance. *Aquaculture Reports*, 20, 100704.

Kwasek, K., Thorne-Lyman, A. L., & Phillips, M. (2020). Can human nutrition be improved through better fish feeding practices? a review paper. Critical Reviews in Food Science and Nutrition, 60(22), 3822-3835.

Liu X., Sha Z., Wang C., Li D. & Bureau, D. P. 2018. A web-based combined nutritional model to precisely predict growth, feed requirement and waste output of gibel carp (*Carassius auratus gibelio*) in aquaculture operations. *Aquaculture*, 492, 335–348.

Lund, I., Rodríguez, C., Izquierdo, M.S., El Kertaoui, N., Kestemont, P., Reis, D.B., Dominguez, D., Pérez, J.A. (2019). Influence of salinity and linoleic or α-linolenic acid-based diets on ontogenetic development and metabolism of unsaturated fatty acids in pike perch larvae (*Sander lucioperca*). *Aquaculture* 500: 550- 561.

Lupatsch, I., Kissil, G. W., & Sklan, D. (2001). Optimization of feeding regimes for European sea bass Dicentrarchus labrax: a factorial approach. *Aquaculture*, 202(3-4), 289-302.

MacLeod, M. J., Hasan, M. R., Robb, D. H., & Mamun-Ur-Rashid, M. (2020). Quantifying greenhouse gas emissions from global aquaculture. Scientific reports, 10(1), 1-8.

Malcorps, W., Kok, B., van't Land, M., Fritz, M., van Doren, D., Servin, K., van der Heijden, P., Palmer, R., Auchterlonie, N.A., Rietkerk, M. & Santos, M.J., 2019. The sustainability conundrum of fishmeal substitution by plant ingredients in shrimp feeds. *Sustainability*, *11*(4), p.1212.

Måløy, H., Aamodt, A., & Misimi, E. (2019). A spatio-temporal recurrent network for salmon feeding action recognition from underwater videos in aquaculture. *Computers and Electronics in Agriculture*, 167, 105087.

Marr, B. (2020). The Intelligence Revolution: Transforming Your Business with AI. Kogan Page. 224 pages.

Martos-Sitcha, J.A., Sosa, J. Ramos-Valido, D., Bravo, F.J., Carmona-Duarte, C., Gomes, H.L., Calduch-Giner, J.A., Cabruja, E., Vega, A., Ferrer, M.A., Lozano, M., Montiel-Nelson, J.A., Afonso, J.M., Pérez-Sánchez, J. (2019). Ultra-low Power Sensor Devices for Monitoring Physical Activity and Respiratory Frequency in Farmed Fish. Front. Physiol., 10, 667 DOI: 10.3389/fphys.2019.00667

Merican, Z. (2021). https://aquaasiapac.com/2021/05/05/aquafeeds-in-2019-pulled-by-market-demand/

Mustapha, U. F., Alhassan, A. W., Jiang, D. N., & Li, G. L. (2021). Sustainable aquaculture development: a review on the roles of cloud computing, internet of things and artificial intelligence (CIA). Reviews in *Aquaculture*. https://doi.org/10.1111/raq.12559

National Research Council (NRC) Subcommittee on Environmental, Stress. 1981. Effect of Environment on Nutrient Requirements of Domestic Animals (National Academies Press (US), Copyright © National Academy of Sciences.: Washington (DC)).

National Research Council (NRC). (2011). Nutrient requirements of fish and shrimp. National Academies Press, Washington D.C.

Naylor, R. L., Hardy, R. W., Bureau, D. P., Chiu, A., Elliott, M., Farrell, A. P., ... & Nichols, P. D. (2009). Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences*, 106(36), 15103-15110.

Naylor, R. L., Hardy, R. W., Buschmann, A. H., Bush, S. R., Cao, L., Klinger, D. H., ... & Troell, M. (2021). A 20-year retrospective review of global aquaculture. Nature, 591(7851), 551-563.

Newton, R., Zhang, W., Xian, Z., McAdam, B., & Little, D. C. (2021). Intensification, regulation and diversification: the changing face of inland aquaculture in China. *Ambio*, 1-18.

Ng, W. K., & Romano, N. (2013). A review of the nutrition and feeding management of farmed tilapia throughout the culture cycle. *Reviews in Aquaculture*, 5(4), 220-254.

Obaldo, L. G., Dominy, W. G., & Ryu, G. H. (2000). Extrusion processing and its effect on aquaculture diet quality and shrimp growth. *Journal of Applied Aquaculture,* 10(2), 41-53.

Okereke, C., & Stacewicz, I. (2018). Stakeholder Perceptions of the Environmental Effectiveness of Multi-stakeholder Initiatives: Evidence from the Palm Oil, Soy, Cotton, and Timber Programs. *Society & Natural Resources*, 31(11), 1302–1318. https://doi.org/10.1080/08941920.2018.1482037

Paspatis, M., & Boujard, T. (1996). A comparative study of automatic feeding and self-feeding in juvenile Atlantic salmon (*Salmo salar*) fed diets of different energy levels. Aquaculture, 145(1-4), 245-257.

Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M. & Hasegawa, T., 2017. Land-use futures in the shared socio-economic pathways. *Global Environmental Change*, *42*, pp.331-345.

Prabhu,A.J., P., Schrama, J.W. and Kaushik, S. J. (2014). Mineral requirements of fish: a systematic review. Reviews in Aquaculture, 6, 1–48.

Rimoldi, S., Torrecillas, S., Montero, D., Gini, E., Makol, A., Victoria Valdenegro, V., Izquierdo, M., Terova, G. (2020) Assessment of dietary supplementation with galactomannan oligosaccharides and phytogenics on gut microbiota of European sea bass (*Dicentrarchus labrax*) fed low fishmeal and fish oil based diet PLoS ONE, 15 (4), art. no. e0231494.

Robinson, T.P.; Thornton, P.K.; Franceschini, G.; Kruska, R.L.; Chiozza, F.; Notenbaert, A.; Cecchi, G.; Herrero, M.; Epprecht, M.; Fritz, S.; et al. *Global Livestock Production Systems*; Rome, Food and Agriculture Organization of the United Nations (FAO) and International Livestock Research Institute (ILRI): Rome, Italy, 2011; p. 152. Available online: www.fao.org/docrep/014/i2414e/i2414e.pdf

Schauberger, B., Ben-Ari, T., Makowski, D. et al. Yield trends, variability and stagnation analysis of major crops in France over more than a century. Sci Rep 8, 16865 (2018). https://doi.org/10.1038/s41598-018-35351-1

Serradell, A., Torrecillas, S., Makol, A., Valdenegro, V., Fernández-Montero, A., Acosta, F., Izquierdo, M.S., Montero, D. (2020) Prebiotics and phytogenics functional additives in low fish meal and fish oil based diets for European sea bass (*Dicentrarchus labrax*): Effects on stress and immune responses Fish and Shellfish Immunology, 100, pp. 219-229.

Shearer, K. D. (1995). The use of factorial modeling to determine the dietary requirements for essential elements in fishes. Aquaculture, 133(1), 57-72.

Sicuro, Benedetto, and Umberto Luzzana. 2016. 'The State of Seriola spp. Other Than Yellowtail (*S. quinqueradiata*) Farming in the World', *Reviews in Fisheries Science & Aquaculture*, 24: 314-25.

Soares, R., Peixoto, S., Galkanda-Arachchige, H. S., & Davis, D. A. (2021). Growth performance and acoustic feeding behavior of two size classes of *Litopenaeus vannamei* fed pelleted and extruded diets. *Aquaculture* International, 29(1), 399-415.

Sørensen, M. (2012). A review of the effects of ingredient composition and processing conditions on the physical qualities of extruded high-energy fish feed as measured by prevailing methods. *Aquaculture nutrition*, 18(3), 233-248.

Spiertz, J.H.J. & Ewert, F., 2009. Crop production and resource use to meet the growing demand for food, feed and fuel: opportunities and constraints. *NJAS-Wageningen Journal of Life Sciences*, *56*(4), pp.281-300.

Tacchi L., Bickerdike R., Douglas A., Secombes C., Martin S., 2011. Transcriptomic responses to functional feeds in Atlantic salmon (Salmo salar). *Fish & Shellfish Immunology*, 31:704-715.

Tacon, A. G. (2002). Thematic review of feeds and feed management practices in shrimp aquaculture. Report prepared under the World Bank, NACA, WWF and FAO consortium program on shrimp farming and the environment. Work in Progress for Public Discussion. Published by the Consortium, 69.

Tacon, A. G. (2020). Trends in global aquaculture and aquafeed production: 2000–2017. *Reviews in Fisheries Science & Aquaculture*, 28(1), 43-56.

Tacon, A. G. J., & Metian, M. (2008). Aquaculture Feed and Food Safety. The Role of the Food and Agriculture Organization and the Codex Alimentarius. New York Academy of Sciences, 1140, 50–59.

Tacon, A. G., & Metian, M. (2009). Fishing for aquaculture: non-food use of small pelagic forage fish—a global perspective. *Reviews in Fisheries Science*, 17(3), 305-317.

Tacon, A. G., & Metian, M. (2013). Fish matters: importance of aquatic foods in human nutrition and global food supply. Reviews in fisheries Science, 21(1), 22-38.

Tacon, A. G., Phillips, M. J., & Barg, U. C. (1995) Aquaculture feeds and the environment: the Asian experience. *Water Sci Technol*., 31 (10): 41–59. doi: https://doi.org/10.2166/wst.1995.0363

Tacon, A.G.J., Hasan, M.R., & Metian, M. (2011). Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects. FAO Fisheries and Aquaculture Technical Paper 564. Food and Agriculture Organization of the United Nations. Rome.

Thiele, C., Hudson, M., Russell, A., Saluveer, M., & Sidaoui-Haddad, G. (2021). Microplastics in fish and fishmeal: an emerging environmental challenge? *Scientific Reports*, *11*(1), 2045–2045. https://doi.org/10.1038/s41598-021-81499-8

Thilsted, S. H. (2012). The potential of nutrient-rich small fish species in aquaculture to improve human nutrition and health.

Thilsted, S. H., James, D., Toppe, J., Subasinghe, R., & Karunasagar, I. (2014). Maximizing the contribution of fish to human nutrition.

Tocher, D.R., Betancor, M.B., Sprague, M., Olsen, R.E. & Napier, J.A., 2019. Omega-3 long-chain polyunsaturated fatty acids, EPA and DHA: bridging the gap between supply and demand. *Nutrients*, *11*(1), 89.

Torno, C., Staats, S., Fickler, A., De Pascual-Teresa, S., Izquierdo, M.S., Rimbach, G., Schulz, C. (2019) Combined effects of nutritional, biochemical and environmental stimuli on growth performance and fatty acid composition of gilthead sea bream (Sparus aurata) (2019) *PLoS ONE,* 14 (5), art. no. e0216611,

Torrecillas, S., Montero, D., Izquierdo, M. (2014). Improved health and growth of fish fed mannan oligosaccharides: Potential mode of action. *Fish and Shellfish Immunology* 36 (2), 525 - 544

Turchini, G. M., Trushenski, J. T., & Glencross, B. D., 2019. Thoughts for the future of aquaculture nutrition: realigning perspectives to reflect contemporary issues related to judicious use of marine resources in aquafeeds. *North American Journal of Aquaculture*, 81(1), 13-39.

Turkmen, S., Hernández-Cruz, C.M., Zamorano, M.J., Fernández-Palacios, H., Montero, D., Afonso, J.M., Izquierdo, M. (2019). Long-chain PUFA profiles in parental diets induce long-term effects on growth, fatty acid profiles, expression of fatty acid desaturase 2 and selected immune system-related genes in the offspring of gilthead seabream). *British Journal of Nutrition,* 122 (1), pp. 25-38.

Valente, L. M., Conceição, L., Sánchez-Vázquez, F. J., & Dias, J. (2019). Macronutrient nutrition and diet formulation. In The Biology of Sole (pp. 276-290). CRC Press, Taylor & Francis Group Boca Raton.

Valente, L. M., Cabrita, A. R., Maia, M. R., Valente, I. M., Engrola, S., Fonseca, A. J., ... & Freire, J. P. B. (2021). Microalgae as feed ingredients for livestock production and aquaculture. In Microalgae (pp. 239-312). Academic Press.

Waagbø, R., Berntssen, M. H. G., Danielsen, T., Helberg, H., Kleppa, A. L., Berg Lea, T., ... & Breck, O. (2013). Feeding Atlantic salmon diets with plant ingredients during the seawater phase–a full-scale net production of marine protein with focus on biological performance, welfare, product quality and safety. *Aquaculture Nutrition,* 19(4), 598-618.

Xu, Z., Lin, X., Lin, Q., Yang, Y., & Wang, Y. (2007). Nitrogen, phosphorus, and energy waste outputs of four marine cage-cultured fish fed with trash fish. *Aquaculture*, 263(1-4), 130-141.

Ytrestøyl, T., Aas, T. S., & Åsgård, T., 2015. Utilisation of feed resources in production of Atlantic salmon (Salmo salar) in Norway. *Aquaculture*, 448, 365-374.

Zhang, Y., Lu, R., Qin, C., & Nie, G. (2020). Precision nutritional regulation and aquaculture. *Aquaculture Reports*, 18, 100496.

Zhou, Z., Xie, S., Lei, W., Zhu, X. & Yang, Y., 2005. A bioenergetic model to estimate feed requirement of gibel carp, Carassius auratus gibelio. *Aquaculture*, 287-297.

Zhou, C., Xu, D., Lin, K., Sun, C., & Yang, X. (2018). Intelligent feeding control methods in aquaculture with an emphasis on fish: a review. *Reviews in Aquaculture*, 10(4), 975-993.