Aquaculture Nutrition

doi: 10.1111/j.1365-2095.2010.00846.x

Aquaculture Nutrition **2011 17;** e798–e817

REVIEW ARTICLE

Nutrition in organic aquaculture: an inquiry and a discourse

E. MENTE[1,2], V. KARALAZOS[1], I.T. KARAPANAGIOTIDIS[1] & C. PITA[2,3]

[1] *School of Agricultural Sciences, Department of Ichthyology and Aquatic Environment, University of Thessaly, N. Ionia Magnisias, Greece;* [2] *Institute of Biological and Environmental Sciences, School of Biological Sciences, University of Aberdeen, Aberdeen, UK;* [3] *Aberdeen Centre for Environmental Sustainability (ACES), School of Biological Sciences, University of Aberdeen, Aberdeen, UK*

Abstract

Organic aquaculture has lagged behind the agriculture sector in terms of the quantities and diversity of certified organic products because of the absence of detailed accepted standards and criteria until recently. The main challenges for organic aquaculture are to improve the coordination between production and market and to achieve an appropriate framework to drive further development. Priorities for research include organic feeds and fish nutrition, consumers' needs, food safety, environmental concerns and trade issues. In organically cultured fish, differences in feeds and nutrition compared to conventional systems are likely to result in differences in the quality of the flesh, and this is a significant factor in consumer choice. The review covers aspects of current use of eco-certification, formulated feeds, feed composition, aquafeed technology, sustainable alternatives to common feed ingredients, nutritional physiology and general nutritional principles and product quality in the context of the organic aquaculture. There is a future for the development of organic aquaculture but its success depends on new knowledge and technical development to meet consumers' growing interest. The industry has to utilize the research results and update and modify the criteria and standards and thus provide high-quality products.

KEY WORDS: nutrition, organic aquaculture

Received 10 August 2010, accepted 30 November 2010

Correspondence: Dr E. Mente, School of Agricultural Sciences, Department of Ichthyology and Aquatic Environment, University of Thessaly, Fytoko Street, GR-38446 N. Ionia Magnisias, Greece. E-mails: emente@uth.gr, e.mente@abdn.ac.uk

Introduction

Many fish stocks on which capture fisheries depend are overexploited or severely depleted because of the high demand for fish production. In this context of overall resource scarcity and decreasing trend on catches, aquaculture production assumes a key importance (Tidwell & Allan 2001; FAO 2009a). Aquaculture is a rapidly growing industry (Shang & Tisdell 1997; FAO 2009a), which has experienced a significant expansion in recent decades. It represents an annual growth rate of nearly 7% from 1950s till 2006, and it is set to overtake capture fisheries as a source of food fish (FAO 2009a). Aquaculture production in 2006 was reported to be 51.7 million tonnes with a value of US$78.8 billion, showing a dramatic increase since the early 1950s, when production was <1 million tonnes per year (FAO, 2009a). Global consumption of fish as food has also been increasing fast and is reported to have doubled since 1973, from 45 million tonnes to over 90 million tonnes (Brugère & Ridler 2004). Global population growth and the raising per capita consumption of fish are the main factors contributing to this increase. Per capita consumption of fish is estimated to increase from 16 kg per year, currently, to 17.1 kg per year in 2020 (Brugère & Ridler 2004) with fish becoming more important in human's diets owing to their positive nutritional values compared to other sources of protein. Aquaculture production is estimated to continue to grow in the following decades, contributing significantly to cover the increasing demand (Delgado *et al*. 2003; Brugère & Ridler 2004; FAO 2009a).

Although much of the global growth of aquaculture is because of Asia's, and especially China's, contribution, European aquaculture has also been growing and is estimated to continue expanding in the future (Delgado *et al*. 2003; Brugère & Ridler 2004; Failler 2006; FAO 2009a). Specifically, European aquaculture production of finfish

increased from about 1 million tonnes in 1997 to 1.6 million tonnes in 2007, which corresponds to values increasing from 3.2 to 6.7 billion US$ (FAO 2009b). However, the annual growth rate of production in Europe for the period 1970–2006 is 3.4% but this growth has not been uniform as it has slowed to 1% per year since 2000 (FAO 2009a). It is apparent that, while aquaculture output will continue to grow, the rate of growth may be moderate in the near future. The main species cultured in Europe are Atlantic salmon, rainbow trout, sea bream and sea bass, followed by carps, other marine fish and flatfish. European aquaculture has diversifies to organic cultivation as it has benefited from a dynamic and cutting-edge research and technology that allows the cultivation of the main species namely Atlantic salmon, trout, carp, sea bream, sea bass and blue mussels.

Aquaculture reduces the dependency on fisheries and alleviates the economic impact of fisheries decline on coastal communities, namely by creating new jobs (Fernandes *et al.* 2000). The environmental and socio-economic sustainability of fisheries and aquaculture is a major current concern (McCausland *et al.* 2005; Subasinghe *et al.* 2009). Within the European Union, per capita consumption of seafood is increasing; there were over 400 000 jobs in the fish catching, culture and processing sectors in the European Union in 2003 (Eurostat 2007). However, many exploited fish stocks are at historically low levels. The history of fisheries suggests that supply-led management of exploitation has so far failed to deliver long-term sustainability and alternatives are needed, for example management based on consumer demand (Starkey *et al.* 2008). Organic production is an approach to agriculture with respect to sustainability. According to the definition given by the Council of the European Union:

> Organic production is an overall system of farm management and food production that combines best environmental practices, a high level of biodiversity, the preservation of natural resources, the application of high animal welfare standards and a production method in line with the preference of certain consumers for products produced using natural substances and processes (EU 2007).

Organic aquaculture has also attracted the attention of consumers, environmental advocates and entrepreneurial innovators (FAO 2009a). The growing interest in organic aquaculture has prompted governments to regulate the sector, and standards and certification procedures are being developed. Although the standards for organic production are developed recently, nutritional research has progressed slowly. This paper intends to review the state of knowledge in organic aquaculture in relation to nutrition. It reviews issues of legislation and addresses the main concerns arising from nutrition in organic aquaculture such as feeds and feeding, sourcing organic feed and nutrient resources, pigments, therapeutants and immunostimulants, probiotics/prebiotics/symbiotics. It highlights the key area for organic aquafeed research, alternatives to feedstuffs and traceability for the ingredients, development of organically certified fishmeal sources, nutritional physiology and human health benefits.

Eco-labelling and organic certification

Food safety and environmental and social standards have become key features in the trade of agro-food products in the last 15 years (Aarset *et al.* 2004; Ponte 2008), and fish products are no exception. There has been increased recognition of the importance of more sustainable and environmentally friendly fishing and aquaculture methods. Increased consumer awareness of these issues has stimulated various types of seafood eco-endorsements, such as eco-labelling, certification and branding (Ward & Phillips 2008). The growing importance of these products has resulted in increasing interest by major world retailers and, since 2002, major EU- and US-based supermarket chains have announced their commitment to sourcing all their wild fish from sustainable sources (Roheim & Sutinen 2006). This pledge has resulted in a boom in the already-increasing number of eco-endorsement schemes and will strongly impact the seafood industry in the near future.

In the current marketing of seafood products, eco-labelling and organic certifications are two common concepts (Ward & Phillips 2008; Perdikaris & Paschos 2010). Organic certification is focused on aquaculture, while eco-labelling is more oriented towards sustainability of capture fisheries and their impact on the ecosystem (FAO 2005). These eco-schemes are basically 'seals of approval' that transmit the information that the product meets ethical, environmental and good governance criteria, thus allowing consumers to make informed choices about fish products.

Organic agriculture has been growing rapidly in terms of diversity of produce, production volumes and values (Scialabba & Hattam 2002; Willer *et al.* 2008). Moreover, the acceptance and demand of organic products by the consumers has also been increasing. Since 2000, international sales of organic food increased by more than twofold, from 18 billion USD to 38.6 billion US Dollars in 2006 (Sahota 2008). Despite the rapid growth of organic production in other agricultural sectors, organic aquaculture is still in its infancy. This may be attributed to several reasons. For instance, the variety and diversification of species cultured,

and systems and methods practiced in aquaculture result in consequent complications regarding adaptation of organic practices. Moreover, and despite the regulatory development of organic agriculture, including livestock production, there has been a lack of universally accepted standards and accreditation criteria regarding organic aquaculture until recently (Tacon & Brister 2002; EU 2009). Organic certified aquaculture products include fish, crustaceans and algae (seaweed and phytoplankton).

Organic aquaculture

Limited data on the production volumes of organic aquaculture production are available. Worldwide, 16 000 tonnes of organic salmon was produced, 8800 tonnes of organic shrimp, 7200 tonnes of carp, 3000 tonnes of mussel, 2000 tonnes of trout and 1000 tonnes seabream/seabass in 2008 (Fig. 1). The estimated global production of certified organic aquaculture products in 2000 was approximately 5000 tonnes (Tacon & Brister 2002). The main organic aquaculture products produced in Europe in 2007 included mainly Atlantic salmon, rainbow and brown trout, carp with accompanying species (tench, grass carp, pike perch, eel, European catfish etc.), sea bream, sea bass, blue mussels, shrimp and Mediterranean sturgeon (Bergleiter 2001, 2008). Biao (2008) reported an estimated total production of 20 000 tonnes in 2003. Lem (2004) reported production of organic Atlantic salmon in 2003 of more than 5000 tonnes, followed by shrimp, carp, trout and other species in lower volumes. Production of organic Atlantic salmon harvest in 2008 remained to 5500 tonnes, which is approximately 4% of the total UK Atlantic salmon production (Soil Association 2009). As organic aquaculture grows, more species are produced under certified programmes and more countries contribute to the total organic production. According to Bergleiter (2008), in 2007, several species, including Atlantic salmon, trout, carp, sea bream and bass, mussels, shrimps and microalgae, were organically produced around the globe, mainly Europe, Asia, Oceania and Latin America. This growth is expected to increase further in the future, reaching 200 000 tonnes in 2015 and almost 1.2 million tonnes in 2030 equivalent to 0.6% of the total estimated aquaculture production (Tacon & Brister 2002; Lem 2004).

Despite the benefits resulting from the growth of the fish-farming industry, the increasing aquaculture production can lead to severe repercussions on at least three important factors, namely the environment, the availability of feed and the disease outbreaks (Naylor *et al.* 1998, 2000; Sapkota *et al.* 2008). Sustainable aquaculture development relates to ecological, biological, economic and institutional sustainability which, in turn, relates to social and cultural issues (Mente *et al.* 2007, 2010). Ecological sustainability refers to fundamental task of maintaining or enhancing the resilience and overall health of the ecosystem and maintaining the resource base at levels that do not foreclose future options, whereas biological sustainability is about growth, nutrition and health of farmed species. In that respect, the development of organic aquaculture could play a significant role towards sustainability, animal welfare and production of high-quality products for human consumption.

Organic aquaculture is gaining importance in major organic food markets. The sector has experienced a growth over the last decade as a result of consumer and market reaction to concerns about poor taste and texture, contamination, animal welfare, sustainability and adverse environmental impacts of aquaculture (Table 1) (Wessells *et al.*

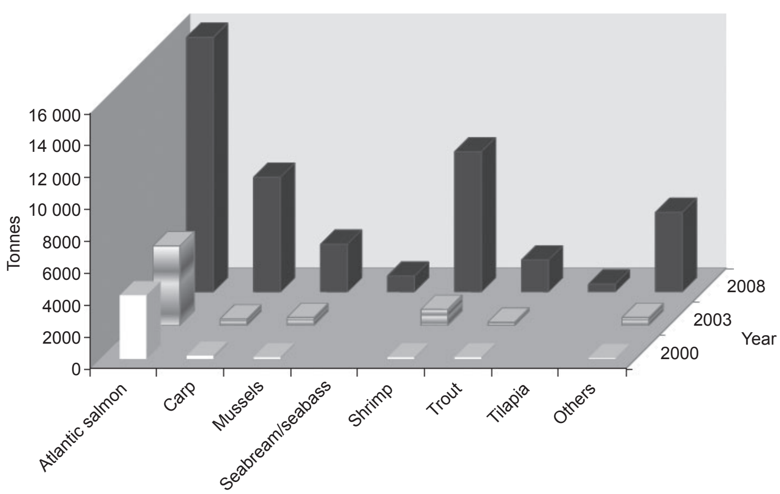

Figure 1 Organic aquaculture production (*t*) in 2000, 2003 and 2008. Sources: year 2000: Tacon & Brister (2002), year 2003: Lem (2004), year 2008: Bergleiter *et al.* (2009).

Table 1 Summary of the main current concerns arising from nutrition in organic aquaculture

	Weakness	Approaches	Challenges
Organic aquafeeds	• Increase pressure on feed grade fisheries. Wider ecosystem impacts. Increased intensive to harvest alternative sources • Understanding of functional genomics associated with growth, development and nutrition • Improve diet formulations to enhance reproductive performance • Establishment of optimal dietary requirements of amino acids and supplement diets with no synthetic amino acids • Increase growth rate and composition in tissue levels	• Substitution by alternative ingredients developing nutritionally efficient diets • Reduce feed conversion ratio. Use probiotics in feed • Examine changes in gene expression in response to alterations in feed nutrients • Evaluate nutritional eects on reproductive eciency, gonadal and larval quality • Characterization of alternative protein/amino acids sources • Determine the physiological basis which enhances expression of growth of species	• Determine the nutrient bioavailability of organic aquafeeds. Biomass maximum • Better understanding the role of eective microorganisms (EM). Gut microflora aects digestibility and nutrient utilization and excretion • Identify mechanisms by which nutrients aect or regulate genes for muscle growth • Increase knowledge of nutritional strategies and cellular functions aecting reproductive physiology • Major focus of aquatic animal nutrition research • Use models to understand tissue growth and nutrition on flesh quality and composition
Organic management techniques	• Lower stocking densities, lower production volume, longer production cycles • Regulate feed intake • Feeding strategies	• Enhancement of beneficial microfauna and Flora • Better adapted stock • Control physiological processes that regulate feeding behaviour and appetite (hypothalamic factors) • Improve feed palatability, quality and nutrient availability, inactive antinutritional factors	• Better understanding of the physiological and behavioural needs of the animals • Polyculture, sea ranching • Optimize the utilization of feed resources. Evaluate the performance of new organic diet formulations with regard to feed consumption and growth • Optimize reproductive performance, growth, nutrient retention and product quality
Immune system	• Spread of diseases • Sealice • Viruses • Anesthetization	• Fallowing • Cleaner fish (e.g. wrasse) • Use of native breeds, vaccinate, work with probiotics, prebiotics and symbiotics • Herbal treatments incorporated in the feed	• Organic diet formulation to improve fish health • Role of dietary nutrients on immune response and disease resistant • Research on novel therapeutics and immunostimulants (dosages, route of administration and duration of feeding on immune functions)
Environmental impacts	• Organic enrichment • Nutrient enrichment • Chemical release • Escapees. 'Genetic dilution'	• Biomass maximum. Genetic basis for nitrogen and phosphorus metabolism. Maximum feed limit • Restricted use of chemicals. Better water quality • Improved cage design	• Potential to manipulate intake/released relationships in nitrogen and phosphorus metabolism • Microbial species to improve water quality • Locational guidelines and Management Guidelines (inc. Codes of Practice/Conduct)

Table 1 (Continued)

	Weakness	Approaches	Challenges
Predators (cormornats, herons, seals)	• Consume and killing fish • Diculties in sourcing juveniles from another certified organic producer to replace stock	• Covering the ponds and cages. Use acoustic sounds to deter them away • Use electrical nets and equipment	• Locational guidelines • Derive regional/local Coastal Plans and integrate with national Coastal Management Plan
Legislation	• Update regularly due to recent research findings	• Monitoring and enforcement • Actively incorporate the research results	• Research and policy development
Other	• Certification costs • Higher production costs • Higher price of organic feed and labour • High investment • Prohibition of various additives for seafood processing • Costs of running nutritional experiments • Long periods (several months or years) to perform nutritional experiments	• Increase advertisement. Marketing • Lower cost for medical treatments • Improve production eciency • Reduce environmental impact • Organic alternatives for melanosis treatment • Effective experimental design • Attempt to correct potential and unexpected technical problems during the growth trials	• Marketing channels need further development • Country specific • Better quality of the final product. Processing • Sustaining growth of organic aquaculture industry • Maximum residue limit. Prohibit treatment • Fund more nutritional research experiments. Enhance the research progress

1999; Aarset *et al*. 2004; Boehmer *et al*. 2005; Hughner *et al*. 2007). Organic Atlantic salmon farming has the potential to considerably reduce social, environmental and economic risks associated with salmonids farming (Georgakopoulos & Thomson 2005). Information on the social sustainability of organic aquaculture is also essential. The IFOAM Organic World Congress conference on organic aquaculture, in June 2008, emphasized the vital need for awareness and action in relation to all three pillars of sustainability (environmental, economic and social sustainability) and questioned whether organic aquaculture can become truly sustainable without considering the social implications of operations (TOS 2008).

Organic aquaculture products have existed in Europe since the mid-1990s. These products, although relatively new when compared to other organic foods, have been growing remarkably as consumers and marketers react to concerns relating to health and environmental effects of pesticides, genetically modified organisms and food safety (Boehmer *et al*. 2005; Hughner *et al*. 2007).

There is a need to develop and harmonize standards for eco-certification and to ensure that it is applied only to well-managed fisheries and aquaculture systems, which fulfil all appropriate sustainability criteria. Various independent, national and private, standards and certification programmes for organic aquaculture (or in some cases for specific aquatic species only) have been developed since the mid-1990s (Tacon & Brister 2002; Bergleiter 2008; Biao 2008). Moreover, the International Federation of Organic Agriculture (IFOAM) has established standards for organic aquaculture production, included in the 'IFOAM norms for organic production and processing, Version 2005' (IFOAM 2009). The need for a coherent EU framework and standards for aquaculture products led to the inclusion of these products within the scope of council regulation No 834/2007 for organic production, which came into force in January 2009.

Regulation

In terms of legislative and institutional framework, though, the development has been relatively slow and progress is recent. For instance, despite including guidelines and standards for livestock and animal production, Codex Alimentarius Guidelines of the FAO/WHO's international Codex Alimentarius Commission (2009) and the US National Organic Program (NOP 2009) have not set standards for aquaculture production, yet, although the integration of policies regarding aquatic animals in the NOP's regulation is in progress (Bergleiter 2008). In 2007, the European Union's regulation (EC) No 834/2007 'on organic production and labelling of organic

products repealing regulation (EEC) No 2092/91' came into force (EU 2007). This is the first EU regulation to set organic aquaculture production standards; however, aquaculture was not included in the Commission Regulation (EC) No 889/2008 establishing detailed rules on organic production (EU 2008). In 2009, European Union has published Commission Regulation (EC) No 710/2009 laying down detailed rules on organic aquaculture animal and seaweed production. These new regulations will change the role of government regulations and institutions and will result in major changes in certification schemes in the near future.

European Union's regulations on organic agriculture, and thus aquaculture, aim at certain objectives, namely the establishment of sustainable agriculture systems that sustain and enhance the health of soil, water, plants and animals; contribute to a high level of biological diversity; make responsible use of energy and natural resources; and respect high animal welfare standards, aiming at producing high-quality products by no use of processes harmful to the environment, human, plant or animal health and animal welfare (EU 2007). Moreover, a number of fundamental principles must be followed, including the use of organically produced inputs, the exclusion of GMOs and the compliance with the principle of sustainable exploitation of fisheries, along with more specific principles focusing on the various aspects of organic production. In general, these principles are common between various certification programmes, although differences may exist. Regarding aquaculture production, Council Regulation (EC) No 834/2007 (EU 2007) and 710/2009 sets a number of guidelines and principles, on the origin of animals, husbandry practices, breeding, feeds and feeding, disease prevention and veterinary treatment. However, for the further growth of the organic aquaculture sector in Europe and globally, specific standards need to be set and there are a number of issues that should be further addressed by detailed rules and guidelines. Specifically, the stocking density shall provide for the comfort and well-being of the animals which, in particular, shall depend on the species, the age of the animals and their behavioural needs. This could affect other parameters including water quality and the impact on the environment, and consequently the animals' well-being and growth (Cottee & Petersan 2009). The low stocking densities are desirable in organic aquaculture because, as with many other disease or parasitic infections, infestation levels are host-density dependent. Stocking densities should be as close as possible to natural conditions. Some species of fish become aggressive if densities are too low and others (such as salmon) require sufficient space to allow for natural schooling to occur. Conventional sea cages of salmon farms typically stock fish at 16 kg m^{-3} for Atlantic salmon. Organic aquaculture standards have density at 10 kg m^{-3} for Atlantic salmon although lower densities will be preferable because it will reduce effluent production and the possible associated benthic impacts. The stocking density in relation to feed refers to carp and tench where it should not exceed 50% of fish yield to attain the natural feed availability. There are limits for stocking densities if a protein-rich diet is administered in carp and tench.

Feeds and feeding in organic aquaculture

In aquaculture, the nutrition highly determines the economic viability and sustainability of the business. In many conventional aquaculture operations, feed accounts for over 50% of the variable operating cost (Rana *et al*. 2009), while in organic operations a 50% surcharge is assumed for organic certified feeds, although lowering feed conversion ratios can compensate their costs (Bergleiter *et al*. 2009). Nutrition, as a broader term, involves the whole series of actions that ensure the provision of the nutrients required for vital processes to an organism (Guillaume *et al*. 1999) and includes both external, either manufactured or not, and internal nutrient sources, as well as the action of feeding and the applied feeding methods. As a general principle in nutrition of organically farmed aquatic animals, feeding shall be performed in a way that allows natural food intake and ensure that the developmental, physiological and behavioural needs of animals are met (EU 2007, 2009; KRAV 2009; Soil Association 2009). In addition, feeds must be balanced according to the nutritional requirements of the organisms, promote animal's growth and health, ensure high quality of the final edible product and cause low environmental impact (EU 2007, 2009; KRAV 2009; Soil Association 2009). However, in nutrition of aquaculture animals, differences exist according to a) the intensity of culture (e.g. extensive, semi-intensive, intensive, super intensive) and the intensity of feeding (e.g. low–high feeding rations), b) the culture media (e.g. earthen ponds, integrated agri–aquaculture systems, concrete tanks, closed recirculation systems in tanks/raceways, sea cages, net pens) and c) the feeding habits of farmed species (e.g. herbivorous, omnivorous, carnivorous), the feed formulations (e.g. diets for carnivorous species require specific amounts of marine resources such as fishmeal and fish oil) and the type of manufactured feed (e.g. pelleted or extruded feed) among others. It is therefore appropriate to lay down all nutritional considerations involved in the organic production.

Nutrition in organic extensive production systems

The nutrition of aquatic animals such as carps, tilapias, catfish, perch, pike, coregonids, sturgeon, milkfish, penaeid shrimps and freshwater prawns that are cultured in inland waters such as ponds, net cages (hapas) and lakes should be provided by food material, such as aquatic plants, algae, plankton, small invertebrates and detritus that are naturally available in the culture media (EU 2009). In such systems, areas of natural vegetation should be maintained around inland water units as a buffer zone for external land areas not involved in the farming operation (EU 2009).

Nutrition in organic semi-intensive production systems

Natural foods are highly nutritious but quantitatively limited, which can support extensive production systems with low yields per unit area. When higher yields are targeted, as in semi-intensive production systems, then higher nutrient availability is required. The natural food productivity of the cultivated water can be enhanced by external inputs in the form of fertilisers, both of inorganic and of organic nature, such as livestock manures, plant material and inorganic phosphate, nitrogen and potassium products. The authorization of fertilisers in organic aquaculture production has not yet been fully clarified in European Commission, and its necessity for sustained production, the specific conditions for use and application rates should be elaborated in future. In agreement with the overall principles of organic production, fertilisers, as external inputs, can be used if only are sourced from certified organic farming operations, are natural or naturally derived substances and are consistent with the principle of maintaining or enhancing the quality of the water and water resources (EU 2007; Naturland 2009; Soil Association 2009). In agreement with organic plant production, livestock manures and any organic material used for ecosystem's fertility should be coming from organic livestock production and should be preferably composted (EU 2007). They should not consist of, be developed from, or contain traces of genetically modified organism (KRAV 2009), while mineral nitrogen fertilisers are not allowed (EU 2007). In addition, fertiliser applications should not lead to a concentration of heavy metals or other environmentally dangerous or infectious substances (KRAV 2009).

Some private certification bodies have incorporated standards for fertilisers in organic aquaculture, concerning their origin and species-specific application rates (Bioland 2009; Naturland 2009; Soil Association 2009). As such, the fertilisers used must originate, insofar as is available, from certified organic farming operations and where these are not available, conventionally produced organic fertilisers preferably from extensive operations can be applied. Some common fertilisers that are acceptable for organic aquaculture include organically produced manure, compost and plant waste as well as mineral fertilisers of natural origin (Soil Association 2009). At a management plan, details for the fertilization rates and times must be recorded (Soil Association 2009). For species like carp, tench and pike, organic fertiliser that can be applied to the pond should not extend 20 kg N ha^{-1} (EU 2009) or 40 kg N ha^{-1} (Naturland 2009). For carp pond farming, natural productivity should be at a level that provides at least 50% of carp's feed (Soil Association 2009). Shrimp ponds can also be fertilised with locally produced nutrients that are acceptable for use in organic farming (Soil Association 2009). This should include products and waste from the organic land around the shrimp farm. In addition, supplementary doses of phosphate, originated from natural sources, are permitted in shrimp pond culture, and the overall quantity of fertilisers should be limited in first order by the effluent water quality (Naturland 2009). The natural productivity of shrimp ponds should be maintained at such a level so as to provide at least 50% of feed, and for that the levels of phytoplankton and zooplankton should be measured (Soil Association 2009).

One way of providing manures and plant material as fertilisers to the pond system is through the integration with terrestrial agriculture, thereby making use of the terrestrial agricultural by-products more directly and efficiently (Jauncey 1998). Thus, common semi-intensive aquaculture systems are integrated with terrestrial livestock production systems, like those of pigs, ducks, chickens, water fowls, cattle and goats, which are adjacent to or above the pond. Aquaculture can also be integrated with crop production (e.g. rice and water hyacinths) where the latter can be benefited from the waste water of the former, while the former can be benefited from the inputs of harvested yield of the latter. Such integrated agriculture–aquaculture systems should be encouraged as suit to the basic principle of organic production where wastes and by-products of the operations are recycled returning nutrients to the production systems. In the case of organic integrated aquaculture–agriculture production systems, all terrestrial inputs to the aquaculture systems should be originated from organic operations. However, the use of animal excreta in aquaculture systems may lead to potential concerns regarding human health, product quality and food safety issues and should be further looked into. Organic

aquaculture regulations shall include standards regarding integrated aquaculture–agriculture production systems.

The soil of the pond bottom is the primary nutrient source of the pond ecosystem and as such plays a vital role in the maintenance of pond productivity (Jauncey 1998). Therefore, a common practice in pond farming is the pond drying and liming with quicklime (CaO) or limestone ($CaCO_3$) in order to alkalify the water environment. In agreement with European Union's authorized chemical fertilisers, calcium carbonate such as chalk, marl, ground limestone, Breton ameliorant and phosphate chalk should be only of natural origin (EU 2008), while the use of quicklime is prohibited (Bioland 2009).

The combination in the same aquaculture system of species that occupy different trophic levels or ecological niches is encouraged in organic production (Soil Association 2009). Polyculture can fully exploit the space of the culture media, can lead to more effective utilization of available natural food and can create additional income. Organic aquaculture standards typically include recommendations, but no binding standards regarding polyculture (Bergleiter *et al.* 2009). European Commission should also attempt to elaborate standards for polyculture in future regulations.

At semi-intensive production systems, where the even stimulated by fertilization natural food productivity is insufficient to sustain higher yields, external feed inputs are required to supplement dietary nutrients. As supplementary feeds farmers can use a range of feedstuffs from simple, unprocessed, agriculture or industry by-products to formulated, pelleted feeds (Table 2). In organic aquaculture, supplementary feeds must be also of organic origin, and specifically of organic plant origin, preferably grown on the farm itself (EU 2009). Alternatively, organically produced seaweed may be fed as supplements. In any case, the external inputs should be natural or naturally derived substances (EU 2007), and the operator should keep documentary evidence of the need to use supplementary feeds (EU 2009). In the case of omnivorous–carnivorous species cultured in inland waters, such as penaeid shrimps, freshwater prawns (*Macrobrachium* spp.) and siamese catfish (*Pangasius* spp.), the EU production rule for organic aquaculture has set that their ration of supplementary organic feed may comprise a maximum of 10% of fishmeal and fish oil derived from sustainable fisheries (EU 2009). The latter is assumed to refer to a 10% maximum of each of fishmeal and fish oil; however, this is not clear, as it could be taken either as a combined total or a maximum of each, and hence should be clarified.

Nutrition in organic intensive production systems

At intensive systems, where very high levels of production are required and/or clear water systems (tanks, cages etc.) are used, natural feeding becomes insignificant and all nutrient requirements of cultured species must be met by exogenous complete feeds (Jauncey 1998). In Table 2, several acceptable and non-acceptable materials for organic feeds are listed. In the case of herbivorous and omnivorous species, complete organic feeds can be formulated by plant feed ingredients. Plant feed ingredients, and generally all feed ingredients, should be traceable to organic standards, except where a feed material is not available on the market in organic form but has been authorized for use in organic aquaculture (EU 2007). Genetically modified organisms (GMOs) and products produced from or by GMOs, growth-enhancing substances and synthetic feed additives such as synthetic amino acids and chemo-synthetic pigments are not allowed (EU 2007; KRAV 2009; Naturland 2009; Soil Association 2009). Hormones and hormone derivatives in the feed is incompatible with the concept of organic production. Organic cultivated seaweed or sustainably harvested wild seaweed, including all multicellular marine algae or phytoplankton and microalgae, may be used as feed ingredient. Organic yeast shall not be present in organic feed together with non-organic yeast. Terrestrial animal-based feed ingredients (including poultry/mammalian derived material) are not allowed, except milk products that are of organic origin. Synthetic feed ingredients are not allowed, except feed additives, such as vitamin and mineral supplements, that are identical to natural and essential for nutritional purposes. The use of such additives should be used to a minimum extent and should not exceed requirements of the specific species. Synthetic antioxidants are not allowed and only natural antioxidant substances should be used.

In the case of carnivorous species, organic aquafeeds shall consist of fishmeal and fish oil to maintain animal's health, satisfy their nutritional requirements for specific amino acids and fatty acids and to suit to their carnivorous feeding habits. The use of fishmeal and fish oil contradicts the organic principle of sustainability owing to the decline of fisheries and overexploitation of wild stocks; though, it is now possible for salmon farming to be a net producer of fish protein and oil (Crampton *et al.* 2010). Organic aquafeeds feeds may consist of marine feed ingredients coming from sustainable use of fisheries and of plant feed ingredients originated from organic production (EU 2008, 2009). Regulation on organic fish certification permits fishmeal and oil from certified

Table 2 Acceptable and non-acceptable materials in feeds for organic aquaculture (adopted and modified from EU 2008)

Acceptable materials
1. Feed materials of animal origin
1.1. Fish, other marine animals, their products and by-products
Under the following restrictions: Products origin only from sustainable exploitation of fisheries resources under Common Fisheries Policy and to be used only for species other than herbivores
Fish
Fish oil and cod-liver oil not refined
Fish molluscan or crustacean autolysates
Hydrolysate and proteolysates obtained by an enzyme action, whether or not in soluble form, solely provided to aquaculture animals
Fishmeal
Crustacean meal
Under the following restrictions: produced under organic principles and intended only for feeds of other farmed species or taxa
Fishmeal, crustacean meal, shrimp shell or other processed ingredients of aquaculture origin
Zooplankton, microcrustaceans, rotifers, worms and other aquatic feed animals
Fishmeal and fish oil from non-organic aquaculture trimmings, or trimmings of fish caught for human consumption may be used for a transitional period until 31 December 2014. Such feed material should not exceed 30% of the daily ration
1.2. Milk and milk products
Produced under organic principles or non-organic materials that have been authorized for use in organic production under the following restrictions: the use of a limited proportion of non-organic feed of animal origin is allowed where farmers are unable to obtain feed exclusively from organic production. The maximum percentage of non-organic feed authorized per period of 12 months for species other than herbivores should be 5% during the period from 1 January 2010 to 31 December 2011
Raw milk
Milk powder
Skimmed milk, skimmed-milk powder
Buttermilk, buttermilk powder
Whey, whey powder, whey powder low in sugar, whey protein powder (extracted by physical treatment)
Casein powder
Lactose powder
Curd and sour milk
2. Feed materials of plant origin
2.1. Aquatic origin
Produced under the organic principles
Seaweed
Multicellular marine algae or phytoplankton
Microalgae
2.2. Land origin
Produced under the organic principles or non-organic materials that have been authorized for use in organic production under the following restrictions: the use of a limited proportion of non-organic feed of plant origin is allowed where farmers are unable to obtain feed exclusively from organic production. The maximum percentage of non-organic feed authorized per period of 12 months for species other than herbivores should be 5% during the period from 1 January 2010 to 31 December 2011
2.1. Cereals, grains, their products and by-products
Oats as grains, flakes, middlings, hulls and bran
Barley as grains, protein and middlings
Rice germ expeller
Millet as grains
Rye as grains and middlings
Sorghum as grains
Wheat as grains, middlings, bran, gluten feed, gluten and germ
Spelt as grains
Triticale as grains
Maize as grains, bran, middlings, germ expeller and gluten
Malt culms
Brewers' grains
2.2. Oil seeds, oil fruits, their products and by-products
Rape seed, expeller and hulls
Soya bean as bean, toasted, expeller and hulls
Sunflower seed as seed and expeller
Cotton as seed and seed expeller
Linseed as seed and expeller
Sesame seed as expeller

Table 2 (Continued)

Palm kernels as expeller
Pumpkin seed as expeller
Olives, olive pulp
Vegetable oils (from physical extraction)
2.3. Legume seeds, their product and by-products
Chickpeas as seeds, middlings and bran
Ervil as seeds, middlings and bran
Chickling vetch as seeds submitted to heat treatment, middlings and bran
Peas as seeds, middlings and bran
Broad beans as seeds, middlings and bran
Horse beans as seeds middlings and bran
Vetches as seeds, middlings and bran
Lupin as seeds, middlings and bran
2.4. Tuber, roots, their products and by-products
Sugar beet pulp
Potato
Sweet potato as tuber
Potato pulp (by-product of the extraction of potato starch)
Potato starch
Potato protein
Manioc
2.5. Other seeds and fruits, their products and by-products
Carob
Carob pods and meals thereof
Pumpkins
Citrus pulp
Apples, quinces, pears, peaches, figs, grapes and pulps thereof
Chestnuts
Walnut expeller
Hazelnut expeller
Cocoa husks and expeller
Acorns
2.6. Forages and roughages
Lucerne
Lucerne meal
Clover
Clover meal
Grass (obtained from forage plants)
Grass meal
Hay
Silage
Straw of cereals
Root vegetables for foraging
2.7. Other plants, their products and by-products
Molasses
Seaweed meal (obtained by drying and crushing seaweed and washed to reduce iodine content)
Powders and extracts of plants
Plant protein extracts (solely provided to young animals)
Spices
Herbs
3. Feed materials of mineral origin
Of natural origin or non-organic materials of mineral origin that have been authorized for use in organic production
3.1. Sodium
Unrefined sea salt
Coarse rock salt
Sodium sulphate
Sodium carbonate
Sodium bicarbonate
Sodium chloride

Table 2 (Continued)

3.2. Potassium
Potassium chloride
3.3. Calcium
Lithotamnion and maerl
Shells of aquatic animals (including cuttlefish bones)
Calcium carbonate
Calcium lactate
Calcium gluconate
3.4. Phosphorus
Defluorinated dicalcium phosphate
Defluorinated monocalcium phosphate
Monosodium phosphate
Calcium-magnesium phosphate
Calcium-sodium phosphate
3.5. Magnesium
Magnesium oxide (anhydrous magnesia)
Magnesium sulphate
Magnesium chloride
Magnesium carbonate
Magnesium phosphate
3.6. Sulphur
Sodium sulphate
4. Feed additives
4.1. Nutritional additives
4.1.1. *Vitamins*
Vitamins derived from raw materials occurring naturally in feedingstuffs
Synthetic vitamins identical to natural vitamins for aquaculture animals
4.1.2. *Trace elements*
E1 Iron: ferrous (II) carbonate, ferrous (II) sulphate monohydrate and/or heptahydrate ferric (III) oxide
E2 Iodine: calcium iodate, anhydrous calcium iodate, hexahydrate sodium iodide
E3 Cobalt: cobaltous (II) sulphate monohydrate and/or heptahydrate, basic cobaltous (II) carbonate, monohydrate
E4 Copper: copper (II) oxide, basic copper (II) carbonate, monohydrate copper (II) sulphate, pentahydrate
E5 Manganese: manganous (II) carbonate, manganous oxide and manganic oxide, manganous (II) sulphate, mono- and/or tetrahydrate
E6 Zinc: zinc carbonate, zinc oxide, zinc sulphate mono- and/or heptahydrate
E7 Molybdenum: ammonium molybdate, sodium molybdate
E8 Selenium: sodium selenate, sodium selenite
4.2. Zoo-technical additives
Enzymes and microorganisms
4.3. Technological additives
4.3.1. *Preservatives*
E 200 Sorbic acid
E 236 Formic acid (*)
E 260 Acetic acid (*)
E 270 Lactic acid (*)
E 280 Propionic acid (*)
E 330 Citric acid
(*) For silage: only when weather conditions do not allow for adequate fermentation
4.3.2. *Antioxidant substances*
E 306 – Tocopherol-rich extracts of natural origin used as an antioxidant
Natural antioxidant substances
4.3.3. *Binders and anticaking agents*
E 470 Calcium stearate of natural origin
E 551b Colloidal silica
E 551c Kieselgur
E 558 Bentonite
E 559 Kaolinitic clays
E 560 Natural mixtures of stearites and chlorite
E 561 Vermiculite
E 562 Sepiolite
E 599 Perlite
Conventional molasses

Table 2 (Continued)

4.3.4. *Silage additives*
Enzymes, yeasts and bacteria can be used as silage additives
The use of lactic, formic, propionic and acetic acid in the production of silage is only be permitted when weather conditions do not allow for adequate fermentation
Emulsifying and stabilizing agents
Lecithin of organic sources
4.2. Certain substances used in animal nutrition
Substance listed must have been approved under Council Directive 82/471/EEC concerning certain products used in animal nutrition
Organic yeast
Yeasts: *Saccharomyces cerevisiae*, *Saccharomyces carlsbergiensis*
Phaffia yeast (as a source of astaxanthin – limitation not to exceed 10 ppm in fish) (not permitted for shrimp feed)
4.3. Substances for silage production
Sea salt
Coarse rock salt
Whey
Sugar
Sugar beet pulp
Cereal flour
Molasses
Not acceptable
1. Feed materials of animal origin
Fishmeal and fish oil from dedicated operations that are not independently certified as sustainable
Fishmeal or other processed ingredients from the same taxa
Meal and other processed ingredients from terrestrial animals
2. Feed materials of plant origin
Non-organic feed materials of plant origin, not listed here, that they have not been authorized for use in organic production
Feedingstuffs that have been solvent extracted (except those extracted using ethanol and water)
Genetically modified organisms or products and ingredients delivered from them
3. Artificial, synthetic or nature-identical pigments
4. Growth regulators, hormones and appetite stimulants
5. Synthetic binders

sustainable fishery areas or from by-products and trimmings from seafood-processing fishery or from certified organic aquaculture, but of a different species or from by-catches from food fisheries. The feed ration may comprise a maximum of 60% of organic plant products (EU 2009).

The production of fishmeal has remained relatively stable over the past 15 years, and this situation is unlikely to improve (Tacon & Metian 2008). Indeed, it has been suggested that the availability of fishmeal will decline in the future, such that fishmeal no longer can be considered a sustainable protein source for aquafeeds (Craig & McLean 2006). Accordingly, alternate proteins are needed to replace fishmeal, especially for diets of carnivorous species. Plant proteins can replace fishmeal up to 25–35% (Tidwell & Allan 2001; Pereira & Oliva-Teles 2003; Chou *et al*. 2004; Hardy 2010; Enami 2011). Plant proteins are probably the most widely used alternative to fishmeal, but they pose problems, including lower crude protein levels, palatability issues, amino acid deficiencies and the occurrence of antinutritional factors such as trypsin inhibitors and phosphorus and nitrogen release to the environment (Francis *et al*. 2001; Hardy & Tacon 2002).

There are a limited number of studies investigating partial replacement of fishmeal with organic diets (Craig & McLean 2005, 2006; Li *et al*. 2006; Lunger *et al*. 2007). Lunger *et al*. (2006) fed cobia fish (*Rachycentron canadum*) for 6 weeks, an organically certifiable yeast-based protein source diet as a fishmeal replacement and showed that up to 25% fishmeal could be replaced without affecting growth rates, feed efficiency or biological indices. Substitution levels above this resulted in decreased performance in all measured parameters. Further dietary inclusion rates for this protein might be problematic, however, because of amino acid imbalances and limitations by added amino acids (Craig & McLean 2006). Craig & McLean (2005) replaced fishmeal and soybean meal with an organic diet (yeast), and there was no difference in growth rates in tilapia. Browdy *et al*. (2006) conducted a nutritional study by replacing fishmeal with a plant-based diet (algal fermentation), in shrimps *Litopenaeus vannamei*, and showed that there were no significant difference in final production, survival and FCR. However, fishmeal diet deposited more DHA in shrimp's tissues in comparison with the plant-protein diet. A growth study on cobia fish (*Rachycentron canadum*), by Lunger *et al*. (2007), showed

that there were no differences in fish weight gain, feed efficiency, muscle tissue ratio, visceral somatic index and packed cell volume when they fed a 40% replacement of fishmeal by an organic diet containing yeast, soya and plant seeds. Li *et al*. (2006) studied the effect of organic fertilization and organic diets on production of channel catfish *Ictalurus punctatus*, in earthern ponds. Their results showed that the slightly higher body fat observed in organic fish resulted from the slightly higher fat content in the organic diet; however, the amount of deposited fat was within the range typically found in channel catfish. Thus, research has not determined clearly the proportions of aquatic and plant origin that should be used in organic feed. This aspect is of great importance especially for the culture of carnivorous species that dominate European aquaculture (Tacon & Brister 2002; Cottee & Petersan 2009). Research on enteroproteins, an Ento-protein from insects, is developing to replace fishmeal in the future (Bergleiter *et al*. 2009).

Plant ingredients can be used in organic aquaculture up to percentage but consideration on the final product quality and taste is important. The proportion and quality of the plant ingredients that can be used in the organic diets can have an effect to the final product quality like fat content, colour and texture (de Francesco *et al*. 2004; Lunger *et al*. 2007). Given, that in some cases, differences in the nutritional characteristics between conventional and organic plant products may exist (Woese *et al*. 1997; Bourn & Prescott 2002), or the reported animals' preference on organic feeds (Mäder *et al*. 2007), the potential use of such commodities in feeds for organic aquatic animals should be further investigated. Thus, more research is needed on plant proteins used for organic aquaculture on growth and final product quality.

The substitution of fish oil with plant alternatives has been thoroughly studied in the last decades (Bell & Waagbø 2008; Glencross 2009; Turchini *et al*. 2009; Sales & Glencross 2011); however, data on organic approaches is scarce. Torstensen *et al*. (2008) found a growth depression when simultaneously replacing both fishmeal and fish oil. Rainbow trout showed growth reduction occurred when all fishmeal was replaced by plant proteins with no replacement of oil (Overturf & Gaylord 2009). Fish oil provides the fish with essential fatty acids while it is also a very significant energy source. In general, the replacement of fish oil with plant oils causes no negative effects on growth, while the fatty acid composition of the fish tissues is affected, reflecting the fatty acid composition of the diet (Bell & Waagbø 2008, Glencross 2009; Turchini *et al*. 2009). Hence, the use of organically produced plant oils to substitute fish oil in aquafeeds could be challenging and should also be examined, given especially the effects that such feed formulations may have on fish muscle fatty acid compositions, including reductions in long chain fatty acids such as EPA and DHA, and ultimately on the quality of the final product.

The development of nutritionally efficient diets using organic sources of ingredients in organic aquaculture diets is a challenge. Research is still needed to evaluate the biophysical and biochemical characteristics of new alternative sustainable proteins and lipids as replacements for fishmeal and fish oil, to determine their nutrient availability, to assess their efficiency for various life stages of organic aquaculture species, to reduce their environmental impacts and to supply them with low cost.

As in intensive production systems, feed rations are intense, and in compliance with organic production principles feeding practices should ensure that the environmental impact from the fish production units is minimal and that overfeeding that leads to feed wastage should be avoided. Thus, for aquaculture animal production in fish ponds, tanks or raceways, farms should be equipped with natural filter beds, settlement ponds, biological filters or mechanical filters to collect waste nutrients or use seaweeds and/or animals (bivalves and algae) that contribute to improving the quality of the effluent (EU 2009). Uneaten fish feed, where appropriate, should be removed promptly to avoid any risk of significant environmental damage as regards water status quality, to minimize disease risks and to avoid attracting insects or rodents (EU 2009). When automatic feeding systems are used, these should be kept in good working order. Moreover, fish could be trained in feeding and could come to the boat or a platform for organic food at an acoustic signal (Lindell *et al*. 2008). Furthermore, fish can be trained to catch themselves by swimming into a net when they hear a tone that signals feeding time, acoustic fish ranching.

Other nutritive feed ingredients

Vitamins and minerals are essential for fish growth, development, health and well-being (NRC 1993). These nutrients are found in a plethora of feed ingredients. However, the content of vitamins and minerals may vary dramatically among different commodities, and hence, diet mixtures may not always fulfil fish dietary requirements. Therefore, diet formulations for aquatic organisms typically include vitamin and mineral premixes, so that intake is sufficient and nutritional requirements are met (Hardy & Barrows 2002). In that respect, the use of such additives is permitted in organic fish diets while the use of synthetic compounds, such as 'synthetic vitamins identical to natural vitamins for aquaculture

animals', may also be allowed (EU 2007, 2008, 2009). It should be mentioned, though, that specific rules and constrains are applied, and in general the necessity for their use must be shown and the use of natural sources is encouraged, while additional approval for their use may also be needed (EU 2008, 2009). Nevertheless, the rational use of these additives is of importance for the sustainability of fish nutrition to be maintained. Thus, research data for specific vitamin and mineral requirements for different species and diet formulations and manufacturing that follow the physiological needs and maximize the diets and additives efficiency and bioavailability could play a significant role. Phytogenics, which are plant-derived products, originated from leaves, roots, herbs, spices available in dried or ground form or as extracts or essential oils added to the feed to improve performance in agriculture (Steiner 2006). Research on their application in some aquaculture species is on progress.

Pigments

Skin and flesh coloration comes in great variety in fish and is a complex feature affected by various factors (Leclercq *et al.* 2010). It could also be a significant factor affecting customer preference and marketing acceptance of the final product (Torrissen 1995). Carotenoids are the main group of pigments responsible for the colour of skin and flesh of various cultured fish, while their role as antioxidants has also been reported (Breithaupt 2007). Carotenoids cannot be synthesized *de novo* by the fish, which therefore depend on the dietary supply to obtain these pigments (Choubert & Storebakken 1989; Torrissen 1995). Wild fish obtain carotenoids through the feed chain, while in aquaculture pigments (e.g. astaxanthin and canthaxanthin) are commonly used in diet formulations for the desired flesh and skin colour to be obtained (Breithaupt 2007). Pigments for aquafeeds include both natural and synthetic carotenoids. However, organic certification programmes reject the use of synthetic additives while, in the case of astaxanthin for Atlantic salmon and trout, permit the use of pigments from organic or natural sources instance (EU 2009). Clarifications and details may be needed, though, in terms of the use of other pigments and carotenoids apart from astaxanthin and/or for other species.

Several natural feeds, such as algae (e.g. *Haematococcus pluvialis* and *Chlorella vulgaris*), yeasts (e.g. genera *Phaffia*, *Rhodotorula*, *Rhodosporidium* and *Sporobolomyces*), krill, crustaceans and plants, are carotenoid sources and some have been successfully used in aquafeeds as alternatives to synthetic pigments (Gouveia *et al.* 1998; Gomes *et al.* 2002; Breithaupt 2007; Kop & Durmaz 2008; Erdem *et al.* 2009; Frengova & Beshkova 2009; Pan & Chien 2009). This is in line with the organic principles and regulations; however, further research is needed to develop organic production of these sources and expand their use, to elucidate their effects in fish coloration, growth, health, welfare and quality of the final product, to estimate the required and/or maximum dosages of pigments for specific species and to suggest effective feeding strategies for providing the pigments without compromising the environmental and economic sustainability of the system. Regarding extensive or semi-intensive aquaculture systems, natural carotenoid sources could be produced within the systems and comprise part of the feed ration of the cultured fish. Such practices comply with the organic principles and should be further developed.

Therapeutants and immunostimulants

Antibiotics are often included in conventional aquaculture diet formulations for prophylactic and therapeutic purposes. Although there is a decline in antibiotic use in highly developed fish-farming countries like Norway, aquaculture worldwide still relies heavily on these compounds (Naylor & Burke 2005; Sapkota *et al.* 2008). However, the extensive use of antibiotics may have serious implications to animal and human health and to the environment (Naylor & Burke 2005; Cabello 2006; Sapkota *et al.* 2008; Burridge *et al.* 2010). Therefore, its use is opposite to organic principles, and most certification programmes prohibit the prophylactic use of antibiotics. Instead, alternative methods and farming practices for disease prevention are promoted. The use of antibiotics may be permitted in organic aquaculture in cases where despite the prevention measures diseases occur (EU 2009). The European Union limits allopathic treatments in organic aquaculture to a maximum of 2 per year; however, it suggests the use of alternative veterinary treatments such as the use of natural substances in homoeopathic dilutions, plant extracts, minerals, natural immunostimulants and probiotics (EU 2009).

It is well documented that various stress conditions, including high stocking densities and daily handling, can depress dramatically the immune system of the fish, and hence, the elimination of these stress factors could prevent diseases (Boshra *et al.* 2006; Magnadóttir 2006). Nutrition has also been linked to fish health, and stimulating effects on disease and stress resistance have been reported for several nutrients and feed substances (Sakai 1999; Boshra *et al.* 2006). Moreover, herbal compounds have been shown to be successful alternatives to antibiotics and other synthetic compounds (Citarasu 2010). Diet formulations including

such ingredients could play a significant role in disease prevention and cure in sustainable aquaculture. Such practices, including reduction of stress factors, good farming conditions and nutrition, have been reported to work well in organic aquaculture in terms of health (Bergleiter 2008). Further research on the specific effects, treatments, dosages, etc. on different species and/or production system and even potential side effects on animals, humans and the environment will benefit organic aquaculture.

Probiotics incorporated in the aquafeed can also enhance fish and crustaceans health by increasing their resistance to disease, while they can lead to improved feed conversion and growth rates, too. Probiotic bacteria improve the health of the fish by controlling pathogenes by modifying the microbial community composition in the intestine, thus stimulating fish immune system (Verschuere *et al.* 2000). Vine *et al.* (2006) showed that some bacteria may participate in the digestion processes of aquatic animals especially by supplying fatty acids and vitamins. Probiotics are effective for use in organic aquaculture, which could be benefitted by the use of probiotics for immunity enhancement, disease control and feed conversion improvements through microbial colonization of the digestive tract. However, there are practical problems in their application such as their supplementation form, the dosage level and their duration of application (Merrifield *et al.* 2010). The future application for probiotics in aquaculture deals with a better understanding of the microbial ecology of the cultured species as well as restricting the probiotic screens to the bacterial species that share the immediate environment with the cultured species. Prebiotics are non-living indigestible carbohydrates that can be added to the diet to improve feed conversion and stimulate immune response (Merrifield *et al.* 2010). However, more research is needed for prebiotics and their benefits on fish and their potential to increase the efficiency and sustainability of aquaculture (Ringø *et al.* 2010). Synbiotics are a mixture of probiotics and prebiotics that beneficially affects the host's survival and welfare. Studies on prebiotics and synbiotics should be given high priority in the future to assess their effects on fish health. Organic aquaculture should further investigate microbial interventions and interactions of feeds and microflora in the gastrointestinal tract of the cultured species.

Organic aquafeed technology

For the manufacturing of organic aquafeeds, several control requirements and regulations have been set and recommended by certification bodies concerning facilities, processing aids and production methods. As a general principle, additives, processing aids and other substances and ingredients used for processing feed should respect the principles of good manufacturing practice (EU 2008). Operators producing processed feed should establish and update appropriate procedures based on a systematic identification of critical processing steps (EU 2008). This must guarantee at all times that the produced processed feeds comply with the organic production rules (EU 2008). In particular, operators should take precautionary measures to avoid the risk of contamination by unauthorized substances or products. Thus, regarding the preparation unit, there should be an indication about the facilities that are used for reception, preparation and storage of the products intended for processing organic aquafeed. The unit should also indicate the facilities that are used for the storage of other products used to prepare feedingstuffs and the facilities used to store products for cleaning and disinfection. Furthermore, the operator should indicate the name of the feed materials that intends to prepare and keep in the unit documentary accounts regarding the information on the origin, nature, and quantities of feed materials, additives, sales and finished products (EU 2008).

At a parallel production and storage of organic and non-organic feeds in a preparation unit, the operators should carry the organic operations continuously until the complete run has been dealt with, separated by place or time from similar operations performed on non-organic products (EU 2007, 2008; KRAV 2009). In addition, they should store organic feeds and feedingstuffs, before and after the operations, separate by place or time from non-organic products. Moreover, operators should inform the control authority or control body thereof and keep available an updated register of all operations and quantities processed. They should also take the necessary measures to ensure identification of lots and to avoid mixtures or exchanges with non-organic products. Furthermore, operations on organic feeds should be carried out only after suitable cleaning of the production equipment, while their effectiveness should be monitored and recorded (EU 2008).

No solvent-extracted processes should be used in organic production methods. Also, any feedingstuffs used or processed in organic production should not have been processed with the aid of chemically synthesized solvents (EU 2007, KRAV 2009). Only water, ethanol or fats may be used as solvents (KRAV 2009). Production processes should be carried out with care, preferably with the use of biological (e.g. fermentation and brewing), mechanical and physical methods (EU 2007, KRAV). Any techniques that reconstitute properties that are lost in the processing and storage of

organic feed, that correct the results of negligence in the processing or that otherwise may be misleading as to the true nature of these products shall not be used (EU 2007).

For labelling, organic aquafeed should indicate the percentage (by weight or on dry matter basis) of feed materials from organic production method and the percentage of feed materials from products in conversion to organic farming. Labelling of 'organic' aquafeed may be used only if at least 95% of the product's dry matter is organic (EU 2008, KRAV 2009). Any remaining product ingredients must be organically produced, unless not commercially available in organic form. At the label, the names of feed materials from the organic production method and from products in conversion to organic farming should be indicated. Furthermore, operators should guarantee that non-organic products are not placed on the market with an indication referring to the organic production method (EU 2008). Processing methods that might be misleading as to the true nature of the product should be excluded.

Nutritional physiology

Nutritional requirements of many aquatic species are still not completely understood (Kaushik & Seiliez 2010). Dietary protein is the major and most expensive component of formulated aquafeeds (Wilson 2002). Amino acids play important and versatile roles in aquatic animal nutrition and metabolism; e.g. appetite stimulation, growth and development regulation, energy utilization, immunity, osmoregulation, stress responses, ammonia detoxification, antioxidative defence, pigmentation, gut development, neuronal development, reproduction, influence taste, texture, and even postmortem and seafood quality (Peng 2009). The challenge of obtaining the right fatty acid and amino acids profile as close to the wild fish as possible is necessary for good aquatic animal health (Kaushik 1998; Jobling 2001; Grigorakis 2007; Mente *et al*. 2010). Many amino acids, termed 'functional AA', regulate key metabolic pathways that are crucial to maintenance, growth, reproduction and immune responses (Peng *et al*. 2009). Identification and dietary supplementation of those AA or their biologically active metabolites is expected to offset adverse effects of replacement of fishmeal from aquafeeds, therefore restoring food intake and growth. However, organic aquaculture prohibits the use of supplementation with synthetic amino acids. Aquafeed formulation in recent years has led to the concepts of 'functional aquafeeds' and 'environmentally oriented aquafeeds' (Peng *et al*. 2009). Functional aquafeeds are defined as feeds supplemented with specific ingredient(s) to achieve desirable efficiency of metabolic transformation, growth performance, health and/or compositional traits of aquacultured animals at various developmental stages. Environmentally oriented aquafeeds are defined as feeds modified to minimize negative impacts of environmental changes (including salinity, ammonia, extreme temperatures and stressors imposed by husbandry handling) on growth, health and reproduction of aquacultured animals. Research on new dietary factors to improve the immune status of the animal, leading to better disease resistance, will help us to understand the mechanisms of modulation of the immune functions (Trichet 2010). Future research will continue to study AA nutrition technologies increased nutrient utilization efficiency and their application to formulate functional and environmentally oriented aquafeeds using natural feed additives. This is a challenge for organic aquaculture to produce organic aquafeed, and more research needs to be conducted on this aspect.

In fish, protein growth is a balance between protein synthesis and protein degradation (Houlihan 1991; Houlihan *et al*. 1993, 1995a,b). Protein growth is negatively correlated with rates of protein degradation when variation in food consumption is allowed for, thus we may conclude protein turnover may be responsible for growth efficiency in fish and crustaceans (Mente *et al*. 2003; Fraser & Rogers 2007). An understanding of protein metabolism in organic aquacultured fish will help identify genes that may lead to more efficient utilization of dietary protein (Martin *et al*. 2008). Research focus is on the genes controlling synthesis of highly unsaturated fatty acids (HUFA). The ability of fish to synthesize HUFA is of increasing importance as the supply of fish oils comes under greater pressure, because of the decline in fish stocks that supply the oils. If the molecular genetic control of HUFA synthesis could be elucidated, it may be possible to improve their ability to synthesize HUFAs from non-fish sources (Martin *et al*. 2007).

Human health benefits

There are no studies and there is a substantial lack of data on benefits on human health from the consumption of organic aquaculture products. A review by Dangour *et al*. (2009) indicated that there is currently no evidence to support the selection of organically overconventionally produced foods on the basis of nutritional superiority. However, the study did not compare the taste of the products nor it addressed contaminant content (such as herbicide, pesticide and fungicide residues) of organically and conventionally produced foodstuffs or the environmental impacts of organic and conventional agricultural practices. Studies in rats showed that organically

grown feed may have some benefit for animal health and performance, especially improvements in reproductive health (Bourn & Prescott 2002). There was also evidence that organic food consumption affects human fertility (Bourn & Prescott 2002). Studies need to be carried out investigating the effect of organic feed in animal and human health. More controlled research is needed to evaluate the nutritional value of the organically grown aquaculture products.

Conclusion

Organic aquaculture has experienced a remarkable growth over the last decade. However, certification of organic aquaculture is recognized as a vital consideration in improving organic aquaculture standards in Europe and internationally. Organic aquafeed price is the biggest share of production costs in organic aquaculture. As ingredient prices are rising, cost reductions in the formulations are needed by maximizing the efficiency of digestive and metabolic process that converts nutrients into growth. Research on nutrition and on the effects of the organic diets on fish health and final product quality is urgently needed to provide a sound development of organic aquaculture and effective guidelines to assure the quality of the final product. Organic aquafeeds have to be designed as functional and environmental. Further research is needed on using amino acids, feed additives or pigments or supplements available in a natural form. Probiotics are effective for use in organic aquaculture but research on their application and their duration of application is still needed. Research on organic nutrition and aquafeeds needs to focus on feeds that have a better utilization of dietary nutrients to improve the efficiency of nutrient utilization or optimizing gut health, fish health, optimize growth and performance and disease resistance.

Acknowledgements

The authors thank Professor D.F. Houlihan and Dr Sam Martin for useful discussions. This study was co-funded by the European Commission and the Hellenic Ministry of Rural Development and Food, Directorate Fisheries and Aquaculture (EPAL 2000–2006).

References

Aarset, B., Beckmann, S., Bigne, J. *et al.* (2004) The European Consumers' understanding and perceptions of the 'organic' food regime: the case of aquaculture. *Br. Food J.*, **106,** 93–105.

Bell, J.G. & Waagbø, R. (2008) Safe and Nutritious Aquaculture Produce: Benefits and Risks of Alternative Sustainable Aquafeeds. In *Aquaculture in the Ecosystem* (Holmer, M., *et al.* eds.), pp. 185–225. Springer, Netherlands.

Bergleiter, S. (2001) Organic products as high quality niche products: background and prospects for organic freshwater aquaculture in Europe. *Paper Presented at the ad hoc EIFAC/EU Working Party on Market Perspectives for European Freshwater Aquaculture*, Brussels (Belgium), 12–14 May 2001.

Bergleiter, S. (2008) Organic aquaculture. In: *The World of Organic Agriculture. Statistics and Emerging Trends 2008* (Willer, H., Yussefi-Menzler, M. & Sorensen, N. eds), pp. 83–87. International Federation of Organic Agriculture Movements (IFOAM), Bonn, Germany and Research Institute of Organic Agriculture (FiBL), Frick, Switzerland.

Bergleiter, S., Berner, U., Censkowsky, U. & Julia-Camprodon, G. (2009) Organic aquaculture 2009. Production and markets. Naturland e.V. and Organic Services GmbH. Report, 120 p.

Biao, X. (2008) The development of and prospects for organic aquaculture worldwide. *Outlook Agric.*, **37,** 255–260.

Bioland (2009) Bioland standards. http://www.bioland.de/bioland/biolandqualitaet/standards.html.

Boehmer, S., Gold, M., Hauser, S., Thomas, B. & Young, A. (2005) Organic Aquaculture. In: *AFSIC Notes #5, Vol. 2009. Alternative Farming Systems Information Center, National Agricultural Library, U.S. Department of Agriculture*. Retrieved from http://www.nal.usda.gov/afsic/AFSIC_pubs/afnotes5.htm.

Boshra, H., Li, J. & Sunyer, J.O. (2006) Recent advances on the complement system of teleost fish. *Fish Shellfish Immunol.*, **20,** 239–262.

Bourn, D. & Prescott, J. (2002) A comparison of the nutritional value, sensory qualities, and food safety of organically and conventionally produced foods. *Crit. Rev. Food Sci. Nutr.*, **42,** 1–34.

Breithaupt, D.E. (2007) Modern application of xanthophylls in animal feeding – a review. *Trends Food Sci. Technol.*, **18,** 501–506.

Browdy, C., Seaborn, G., Atwood, H., Davis, D.A., Bullis, R.A., Samocha, T.M., Wirth, E. & Leffler, J.W. (2006) Comparison of Pond Production Efficiency, Fatty Acid Profiles, and Contaminants in *Litopenaeus vannamei* Fed Organic Plant-based and Fish-meal-based Diets. *J. World Aquac. Soc.*, **37,** 4.

Brugère, C. & Ridler, N. (2004) Global aquaculture outlook in the next decades: an analysis of national aquaculture production forecasts to 2030. In: *FAO Fisheries Circular No. 1001* (FAO ed.), pp. 47. FAO, Rome.

Burridge, L., Weis, J.S., Cabello, F., Pizarro, J. & Bostick, K. (2010) Chemical use in salmon aquaculture: a review of current practices and possible environmental effects. *Aquaculture*, **306,** 7–23.

Cabello, F.C. (2006) Heavy use of prophylactic antibiotics in aquaculture: a growing problem for human and animal health and for the environment. *Environ. Microbiol.*, **8,** 1137–1144.

Chou, R.L., Her, B.Y., Su, M.S., Hwang, G., Wu, Y.H. & Chen, H.Y. (2004) Substituting fishmeal with soybean meal in diets of juvenile cobia, *Rachycentron canadum*. *Aquaculture*, **229,** 325–333.

Choubert, G. & Storebakken, T. (1989) Dose response to astaxanthin and canthaxanthin pigmentation of rainbow trout fed various dietary carotenoid concentrations. *Aquaculture*, **81,** 69–77.

Citarasu, T. (2010) Herbal biomedicines: a new opportunity for aquaculture industry. *Aquacult. Int.*, **18,** 403–414.

Codex Alimentarius Commission (2009) Guidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods. Retrieved on 15 July 2009 from http://www.codexalimentarius.net/web/more_info.jsp?id_sta = 360.

Cottee, S.Y. & Petersan, P. (2009) Animal welfare and organic aquaculture in open systems. *J. Agric. Environ. Ethics*, **22,** 437–461.

Craig, S.R. & McLean, E. (2005) The organic aquaculture movement: a role for NuPro as an alternative protein source. In: *Nutritional Biotechnology in the Food and Feed Industry* (Jacques, K. & Lyons, P. eds.), pp. 285–293. Nottingham University Press, UK.

Craig, S.R. & McLean, E. (2006) Nutrigenomics in aquaculture research: a key in the 'Aquanomic' revolution. In: *Nutritional Biotechnology in the Food and Feed Industry* (Jacques, K. & Lyons, P. eds.), pp. 433–444. Nottingham University Press, UK.

Crampton, V.O., Nanton, D.A., Ruohonen, K., Skjervold, P.-O. & EL-Mowafi, A. (2010) Demonstration of salmon farming as a net producer of fish protein and oil. *Aquacult. Nutr.*, **16,** 437–446.

Dangour, A., Dodhia, S., Hayter, A., Aikenhead, A., Allen, E., Lock, K. & Uauy, R. (2009) Comparison of composition (nutrients and other substances) of organically and conventionally produced foodstuffs: a systematic review of the available literature. *Report for the Food Standards Agency (FSA), Nutrition and Public Health Intervention Research Unit London School of Hygiene & Tropical Medicine*, 35 pp.

Delgado, C.L., Wada, N., Rosegrant, M.W., Meijer, S. & Ahmed, M. (2003) *Fish to 2020: Supply and Demand in Changing Global Markets*, 236 pp. International Food Policy Research Institute, Washington, DC and WorldFish Center, Penang, Malaysia.

Enami, H.R. (2011) A review of using canola/rapeseed meal in aquaculture feeding. *J. Fish. Aquat. Sci.*, **6,** 22–36.

Erdem, M.E., Yesilayer, N. & Kaba, N. (2009) Effects of Organic and Synthetic Carotenoids on the Sensory Quality and Chemical Composition of Rainbow Trout (*Oncorhynchus mykiss*, W. 1792). *J. Anim. Vet. Adv.*, **8,** 33–38.

EU (2007) *Council Regulation (EC) No 834/2007 of 28 June 2007 on Organic Production and Labelling of Organic Products and Repealing Regulation (EEC) No 2092/91*. Official Journal of the European Union, Luxembourg.

EU (2008) *Commission Regulation (EC) No 889/2008 of 5 September 2008 Laying Down Detailed Rules for the Implementation of Council Regulation (EC) No 834/2007 on Organic Production and Labelling of Organic Products with Regard to Organic Production, Labelling and Control*. Official Journal of the European Union, Luxembourg.

EU (2009) *Commission Regulation (EC) No 710/2009 of 5 August 2009 Amending Regulation (EC) No 889/2008 Laying Down Detailed Rules for the Implementation of Council Regulation (EC) No 834/2007, as Regards Laying Down Detailed Rules on Organic Aquaculture Animal and Seaweed Production*. Official Journal of the European Union, Luxembourg.

Eurostat (2007) *Fishery Statistics: Data 1990–2006*. Eurostat, European Commission, Luxembourg.

Failler, P. (2006) *Future Prospects for Fish and Fishery Products. Fish Consumption in the European Union in 2015 and 2030 – Part 1. European Overview & Part 2*. Country projections, FAO Fisheries Circular. No. 972/4. FAO, Rome.

FAO (2005) Guidelines for the ecolabelling of fish and fishery products from marine capture fisheries. Food and Agriculture Organization of the United Nations, Rome.

FAO (2009a) *The State of World Fisheries and Aquaculture 2008*, pp. 176. SOFIA, Rome.

FAO (2009b) Fishery Statistical Collections. Retrieved on 15 July 2009 from http://www.fao.org/fishery/statistics/global-aquaculture-production/query/en.

Fernandes, T., Miller, K. & Read, P. (2000) Monitoring and regulation of marine aquaculture in Europe. *J. Appl. Ichthyol.*, **16,** 138–143.

de Francesco, M., Parisi, G., Médale, F., Lupi, P., Kaushik, S.J. & Poli, B.M. (2004) Effect of long-term feeding with a plant protein mixture based diet on growth and body/fillet quality traits of large rainbow trout (*Oncorhynchus mykiss*). *Aquaculture*, **236,** , 413–429.

Francis, G., Makkar, H.P.S. & Becker, K. (2001) Antinutritional factors present in plant-derived alternate fish feed ingredients and their effects in fish. *Aquaculture*, **199,** 197–227.

Fraser, K.P.P. & Rogers, A.D. (2007) Protein metabolism in marine animals: the underlying mechanisms of growth. *Adv. Mar. Biol.*, **52,** 267–362.

Frengova, G. & Beshkova, D. (2009) Carotenoids from *Rhodotorula* and *Phaffia*: yeasts of biotechnological importance. *J. Ind. Microbiol. Biotechnol.*, **36,** 163–180.

Georgakopoulos, G. & Thomson, I. (2005) Organic salmon farming: risk perceptions, decision heuristics and the absence of environmental accounting. *Account. Forum*, **29,** 49–75.

Glencross, B.D. (2009) Exploring the nutritional demand for essential fatty acids by aquaculture species. *Rev. Aquac.*, **1,** 71–124.

Gomes, E., Dias, J., Silva, P., Valente, L., Empis, J., Gouveia, L., Bowen, J. & Young, A. (2002) Utilization of natural and synthetic sources of carotenoids in the skin pigmentation of gilthead seabream (*Sparus aurata*). *Eur. Food Res. Technol.*, **214,** 287–293.

Gouveia, L., Choubert, G., Gomes, E., Rema, P. & Empis, J. (1998) Use of Chlorella vulgaris as a carotenoid source for rainbow trout: effect of dietary lipid content on pigmentation, digestibility and retention in the muscle tissue. *Aquacult. Int.*, **6,** 269–279.

Grigorakis, K. (2007) Compositional and organoleptic quality of farmed and wild gilthead sea bream (*Sparus aurata*) and sea bass (*Dicentranchus labrax*) and factors affecting it: a review. *Aquaculture*, **272,** 55–75.

Guillaume, J., Kaushik, S., Bergot, P. & Metailler, R. (1999) *Nutrition and Feeding of Fish and Crustaceans*, 408 p. INRA-IFREMER and Springer-Praxis Publishing, UK.

Hardy, R.W. (2010) Utilization of plant proteins in fish diets: effects of global demand and supplies of fishmeal. Review article. *Aquacult. Res.*, **41,** 770–776.

Hardy, R.W. & Barrows, F.T. (2002) Diet formulation and manufacture. In: *Fish Nutrition* (Halver, J.E. & Hardy, R.W. eds.), 3rd edn, pp. 505–600. Academic Press, Elsevier Science, San Diego, CA, USA.

Hardy, R.W. & Tacon, A.G.J. (2002) Fishmeal: historical uses, production trends and future outlook for sustainable supplies. In: *Responsible Marine Aquaculture* (Stickney, R.R. & McVey, J.P. eds), pp. 311–325. CAB International, Oxon, UK.

Houlihan, D.F. (1991) Protein turnover in ectotherms and its relationship to energetics. In: *Advances in Comparative and Environmental Physiology*, Vol. 7 (Gilles, R. ed.), pp. 1–43. Springer-Verlag, Berlin.

Houlihan, D.F., Mathers, E. & Foster, A.R. (1993) Biochemical correlates of growth rate in fish. In: *Fish Ecophysiology* (Rankin, J.C. & Jensen, F.B. eds), pp. 45–70. Chapman & Hall, London.

Houlihan, D.F., Carter, C.G. & McCarthy, I.D. (1995a) Protein turnover in animals. In: *Nitrogen Metabolism and Excretion* (Walsh, P.J. & Wright, P. eds), pp. 1–32. CRC Press, Boca Raton.

Houlihan, D.F., McCarthy, I.D., Carter, C.G. & Marthy, F. (1995b) Protein turnover and amino acid flux in fish larvae. *ICES Mar. Sci. Symp.*, **201,** 87–99.

Hughner, R., McDonagh, P., Prothero, A., Shultz, C. & Stanton, J. (2007) Who are organic food consumers? A compilation and review of why people purchase organic food. *J. Consumer Behav.*, **6,** 94–110.

IFOAM (2009) *The IFOAM Norms for Organic Production and Processing, Version 2005*, 136 pp. IFOAM, Germany.

Jauncey, K. (1998) *Tilapia Feeds and Feeding*, 241 p. Pisces Press Ltd., Bridge of Allan, Scotland.

Jobling, M. (2001) Nutrient Partitioning and the influence of feed composition on body composition. In: *Food Intake in Fish* (Houlihan, D., Boujard, T. & Jobling, M. eds), pp. 366. Blackwell Science, Oxford, UK.

Kaushik, S.J. (1998) Whole body amino acid composition of European sea bass (*Dicentrarchus labrax*), gilthead seabream (*Sparus aurata*) and turbot (*Psetta maxima*) with an estimation of their IAA requirement profiles. *Aquat. Living Resour.*, **11,** 355–358.

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

Kop, A. & Durmaz, Y. (2008) The effect of synthetic and natural pigments on the colour of the cichlids (*Cichlasoma severum* sp., Heckel 1840). *Aquacult. Int.*, **16,** 117–122.

KRAV (2009) Standards for KRAV-certified production – January 2009. http://www.krav.se.

Leclercq, E., Taylor, J.F. & Migaud, H. (2010) Morphological skin colour changes in teleosts. *Fish Fish.*, **11,** 159–193.

Lem, A. (2004) An overview of the present market and trade situation in the aquaculture sector – The current and potential role of organic products, Ho Chi Minh City, Vietnam 15–17 June 2004.

Li, M.H., Robinson, E.H., Mischke, C.C., Eugene, L., Torrans, E.L. & Bosworth, B.J. (2006) Effects of Organic Fertilization and Organic Diets on Production of Channel Catfish in Earthen Ponds. *N. Am. J. Aquac.*, **68,** 53–62.

Lindell, S., Miner, S., Goudey, C. & Page, S. (2008) Acoustic conditioning and ranching of black sea bass Centropristis striata. 2008 Northeast Aquaculture Conference & Exposition, Looking to the future farming the waters, NACE 2008. Portland Maine 3–5 December.

Lunger, A.N., Craig, S. & McLean, E. (2006) Replacement of fishmeal in cobia (*Rachycentron canadum*) diets using an organically certified protein. *Aquaculture*, **257,** 393–399.

Lunger, A.N., McLean, E. & Craig, S.R. (2007) The effects of organic protein supplementation upon growth feed conversion and texture quality parameters in juvenile cobia (*Rachycentron canadum*). *Aquaculture*, **264,** 342–352.

Mäder, P., Hahn, D., Dubois, D. *et al.* (2007) Wheat quality in organic and conventional farming: results of a 21 year field experiment. *J. Sci. Food Agric.*, **87,** 1826–1835.

Magnadóttir, B. (2006) Innate immunity of fish (overview). *Fish Shellfish Immunol.*, **20,** 137–151.

Martin, S.A.M., Mohanty, B., Cash, P., Houlihan, D.F. & Secombes, C.J. (2007) Proteome analysis of Atlantic salmon (*Salmo salar*) SHK-1 cells following recombinant interferon gamma stimulation. *Proteomics*, **13,** 2275–2286.

Martin, S.A.M., Collet, B., MacKenzie, S., Evensen, O. & Secombes, C.J. (2008) Genomic tools for examining immune gene function in salmonid fish. *Rev. Fish. Sci.*, **16**(Suppl 1)**,** 155–164.

McCausland, W.D., Mente, E., Pierce, G.J. & Theodossiou, I. (2005) A simulation model of sustainability of coastal communities: aquaculture, fishing, environment and labour markets. *Ecol. Modell.*, **193,** 271–294.

Mente, E., Legeay, A., Houlihan, D.F. & Massabuau, J.C. (2003) Influence of oxygen partial pressures on protein synthesis in feeding crabs. *Am. J. Physiol. Regul. Integr. Comp. Physiol.*, **284,** 500–510.

Mente, E., Pantazis, P., Neofitou, C., Aifanti, S., Santos, M.B., Oxouzi, E., Bagiatis, V., Papapanagiotou, E., Kourkouta, V. & Soutsas, K. (2007) Socioeconomic interactions of fisheries and aquaculture in Greece: a case study of south Evoikos gulf. *Aquac. Econ. Manage.*, **11,** 313–334.

Mente, E., Stratakos, A., Boziaris, I.S., Kormas, K.A., Karalazos, V., Karapanagiotidis, I.T., Catsiki, V.A. & Leondiadis, L. (2010) Sustainable aquaculture development: a case of organic sea bream production. Final Report. Hellenic Ministry of Rural Development and Food, (EPAL 2000–2006), pp. 85.

Merrifield, D.L., Dimitroglou, A., Foey, A., Davies, S.J., Baker, R.T.M., Bøgwald, J., Castex, M. & Ringø, E. (2010) The current status and future focus of probiotic and prebiotic applications for salmonids. *Aquaculture*, **302,** 1–18.

Naturland (2009) Naturland standards for organic aquaculture. http://www.naturland.de/standards.html.

Naylor, R. & Burke, M. (2005) Aquaculture and ocean resources: raising tigers of the sea. *Ann. Rev. Environ. Resour.*, **30,** 185–218.

Naylor, R.L., Goldburg, R.J., Mooney, H., Beveridge, M., Clay, J., Folke, C., Kautsky, N., Lubchenco, J., Primavera, J. & Williams, M. (1998) Nature's subsidies to shrimp and salmon farming. *Science*, **282,** 883.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Mooney, H. & Troell, M. (2000) Effect of aquaculture on world fish supplies. *Nature*, **405,** 1017–1024.

NOP (2009) USDA, National Organic Program (NOP) – Regulation. Retrieved on 15 July 2009 from http://www.ams.usda.gov/AMSv1.0/nop.

NRC (1993) *Nutrient Requirements of Fish*. National Academy Press, Washington, DC.

Overturf, K. & Gaylord, T.G. (2009) Determination of relative protein degradation activity at different life stages in rainbow trout (*Oncorhynchus mykiss*). *Comp. Biochem. Physiol. B*, **152,** 150–160.

Pan, C.-H. & Chien, Y.-H. (2009) Effects of dietary supplementation of alga *Haematococcus pluvialis* (Flotow), synthetic astaxanthin and β-carotene on survival, growth, and pigment distribution of red devil, *Cichlasoma citrinellum* (Günther). *Aquacult. Res.*, **40,** 871–879.

Peng, L., Kangsen, M., Jesse, T. & Guoyao, W. (2009) New developments in fish amino acid nutrition: towards functional and environmentally oriented aquafeeds. *Amino acids*, **37,** 43–53.

Perdikaris, C. & Paschos, I. (2010) Organic aquaculture in Greece: a brief review. *Rev. Aquac.*, **2,** 102–105.

Pereira, T.G. & Oliva-Teles, A. (2003) Evaluation of corn gluten meal as a protein source in diets for gilthead sea bream (*Sparus aurata* L.) juveniles. *Aquac. Res.*, **34,** 1111–1117.

Ponte, S. (2008) Greener than thou: the political economy of fish ecolabeling and its local manifestations in South Africa. *World Dev.*, **36,** 159–175.

Rana, K.J., Siriwardena, S. & Hasan, M.R. (2009) Impact of rising feed ingredient prices on aquafeeds and aquaculture production. *FAO Fisheries and Aquaculture Technical Paper*, No. 541, ISSN 2070-7010. Food and Agriculture Organization of the United Nations, Rome.

Ringø, E., Olsen, R.E., Gifstad, T.Ø., Dalmo, R.A., Amlund, H., Hemre, G.I. & Bakke, A.M. (2010) Prebiotics in aquaculture: a review. *Aquacult. Nutr.*, **16,** 117–136.

Roheim, C. & Sutinen, J. (2006) Measures to promote sustainable fishing practices. *Natural Resources, International Trade and Sustainable Development*, Issue Paper 3. ICTSD & HSTF, 58 p.

Sahota, A. (2008) The global market of organic food and drink. In: *The World of Organic Agriculture. Statistics and Emerging Trends 2008* (Willer, H., Yussefi-Menzler, M. & Sorensen, N. eds), pp. 53–57. International Federation of Organic Agriculture Movements (IFOAM), Bonn, Germany and Research Institute of Organic Agriculture (FiBL), Frick, Switzerland.

Sakai, M. (1999) Current research status of fish immunostimulants. *Aquaculture*, **172,** 63–92.

Sales, J. & Glencross, B. (2011) A meta-analysis of the effects of dietary marine oil replacement with vegetable oils on growth, feed conversion and muscle fatty acid composition of fish species. *Aquacult. Nutr.*, **17,** e271–e287.

Sapkota, A., Sapkota, A.R., Kucharski, M., Burke, J., McKenzie, S., Walker, P. & Lawrence, R. (2008) Aquaculture practices and potential human health risks: current knowledge and future priorities. *Environ. Int.*, **34,** 1215–1226.

Scialabba, N.E.-H. & Hattam, C. (2002) *Organic Agriculture, Environment and Food Security*, 258 pp. Food and Agriculture Organization of the United Nations (FAO), Rome.

Shang, Y. & Tisdell, C. (1997) Economic decision making in the sustainable aquacultural development. In: *Sustainable Aquaculture* (Bardach, J.E. ed.), pp. 127–148. John Wiley and Sons, Inc, New York.

Soil Association (2009) Organic market report 2009. Retrieved on 15 July 2009 from http://www.soilassociation.org/Businesses/Marketinformation/tabid/116/Default.aspx.

Starkey, D.J., Holm, P. & Barnard, M. (2008) *Oceans Past: Management Insights from the History of Marine Animal Populations*. Earthscan Research Editions.

Steiner, T. (2006) *Managing Gut Health. Natural Growth Promoters as a Key to Animal Performance*, 98 pp. Nottingham University Press, Nottingham, UK.

Subasinghe, R., Soto, D. & Jia, J. (2009) Global aquaculture and its role in sustainable development. *Rev. Aquac.*, **1,** 2–9.

Tacon, A.G.J. & Brister, D. (2002) Organic aquaculture: current standards and future prospects. In: *Organic Agriculture, Environment and Food Security* (Scialabba, N.E.-H. & Hattam, C. eds.), pp. 163–175. Food and Agriculture Organization of the United Nations (FAO), Rome.

Tacon, A.G.J. & Metian, M. (2008) Global overview on the use of fishmeal and fish oil in industrially compounded aquafeeds: trends and future prospects. *Aquaculture*, **285,** 146–158.

Tidwell, J.H. & Allan, G.L. (2001) Fish as food: aquaculture's contribution. *EMBO*, **2,** 958–963.

Torrissen, O.J. (1995) Strategies for salmonid pigmentation. *J. Appl. Ichthyol.*, **11,** 276–281.

Torstensen, B.E., Espe, M., Sanden, M. *et al.* (2008) Novel production of Atlantic salmon (*Salmo salar*) protein based on combined replacement of fish meal and fish oil with plant meal and vegetable oil blends. *Aquaculture*, **285,** 193–200.

TOS (2008) Organic aquaculture. *Organ. Stand.*, **91,** 3–9.

Trichet, V.V. (2010) Nutrition and immunity: an update. *Aquacult. Res.*, **41,** 356–372.

Turchini, G.M., Torstensen, B.E. & Ng, W.-K. (2009) Fish oil replacement in finfish nutrition. *Rev. Aquac.*, **1,** 10–57.

Verschuere, L., Rombaut, G., Sorgeloos, P. & Verstraete, W. (2000) Probiotic bacteria as biological control agents in aquaculture. *Microbiol. Mol. Biol. Rev.*, **64,** 655–671.

Vine, N.G., Leukes, W.D. & Kaiser, H. (2006) Probiotics in marine larviculture. *FEMS Microbiol. Rev.*, **30,** 404–427.

Ward, T. & Phillips, B. (2008) *Saefood Ecolabelling*. Wiley-Blackwell Publishing, Oxford, UK.

Wessells, C., Johnston, R. & Donath, H. (1999) Assessing consumer preferences for ecolabeled seafood: the influence of species, certifier and household attributes. *Am. J. Agric. Econ.*, **81,** 1084–1089.

Willer, H., Yussefi-Menzler, M. & Sorensen, N. (2008) *The World of Organic Agriculture. Statistics and Emerging Trends 2008*. International Federation of Organic Agriculture Movements (IFOAM), Bonn, Germany and Research Institute of Organic Agriculture (FiBL), Frick, Switzerland.

Wilson, R.P. (2002) Protein and amino acids. In: *Fish Nutrition, 3rd version* (Halver, J.E. & Hardy, R.W. eds), pp. 144–179. Elsevier Science, San Diego, USA.

Woese, K., Lange, D., Boess, C. & Bögl, K.W. (1997) A comparison of organically and conventionally grown foods – results of a review of the relevant literature. *J. Sci. Food Agric.*, **74,** 281–293.