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To cite this article: Laura Gasco, Gabriele Acuti, Paolo Bani, Antonella Dalle Zotte, Pier Paolo Danieli, Anna De Angelis, Riccardo Fortina, Rosaria Marino, Giuliana Parisi, Giovanni Piccolo, Luciano Pinotti, Aldo Prandini, Achille Schiavone, Genciana Terova, Francesca Tulli & Alessandra Roncarati (2020) Insect and fish by-products as sustainable alternatives to conventional animal proteins in animal nutrition, Italian Journal of Animal Science, 19:1, 360-372, DOI: [10.1080/1828051X.2020.1743209](https://doi.org/10.1080/1828051X.2020.1743209)

To link to this article: <https://doi.org/10.1080/1828051X.2020.1743209>



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Published online: 01 Apr 2020.



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Insect and fish by-products as sustainable alternatives to conventional animal proteins in animal nutrition

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ABSTRACT

This paper reviews current knowledge on two feedstuffs, that is, insect meal and fish by-products, as alternatives to conventional animal protein sources. After an introductory part that highlights the need for sustainable development of animal production, the alternative protein sources are discussed. In particular, after providing some indications on their production and supply focussing on EU, a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was performed to identify the key factors that could help or impair the development of both protein sources production sectors. Finally, future perspectives are presented. The use of processed animal proteins derived from insects in farmed fish feeding is recognised by the EU legislation that authorises the use of proteins from seven insect species and the allowed substrates to rear insects. Insects have several advantages in nutritional value and the amino acid composition of their proteins generally meet animal requirements for good growth and health. The SWOT analysis indicated that insect meals can be considered as feed functional ingredients with beneficial properties that depend on the insect species, rearing system adopted, and the substrate used for their growth. Insects are expected to be increasingly used as a replacement for conventional animal-derived proteins, especially in aquafeeds. In the section regarding fishery and aquaculture by-products, the potential use of raw materials obtained during seafood processing is discussed. Peptides and amino acids recovered from as hydrolysed proteins can be used in animal feeds to partially substitute conventional protein feedstuffs thus providing nutrients, bioactive compounds and feed additives for animals. The SWOT analysis identified opportunities and weaknesses. Both the alternative protein sources are promising alternative feed ingredients for livestock production.

HIGHLIGHTS

- The sustainable development of animal production sector needs alternative protein sources for feeds formulation.
- Insects and fishery- and aquaculture by-products represent optimal alternative protein sources.
- A SWOT analysis has identified the key factors for the development of both protein sources production sectors.

ARTICLE HISTORY

Received 27 January 2020
Revised 11 March 2020
Accepted 12 March 2020

KEYWORDS

Insects; fish by-products; protein sources; processed animal proteins

Introduction

The increase of the world population (+30% from the current 7.5 billion people expected by 2050) and changes in worldwide consumption patterns towards a higher consumption of products of animal origin are affecting the livestock production sector (FAO 2017). In 2018, the global feed production reached 1.1 billion tonnes showing an increase of 3% when compared to 2017, and an annual mean growth rate of 2.5% in the last 5 years (Alltech 2019). The protein shortage is a global matter of concern and extensive research to find new sustainable protein sources is ongoing. Sustainability of food production and processing systems based on low greenhouse gases emissions, efficient use of raw materials and waste minimisation has become a priority. As regards wastes deriving from the human consumption, about one third of food is lost or wasted worldwide (FAO 2011). International non-governmental organisations (Seas at Risk 2014; WWF 2017) are emphasising the urgency of limiting wastes and recovering valuable resources/compounds. In Europe, Article 4 of the EU Waste Framework Directive, after the revision updated in 2008, outlines a “waste hierarchy” and highlights the financial and environmental advantages of reducing, reusing and recycling materials in comparison to landfill disposal. Nowadays, according to the circular economy approach based on the “reduce, reuse, repair, and recycle” theory, waste from food can be valorised leading to the production of proteins and other valuable compounds (EU 2018; Stevens et al. 2018). This situation leads to both economic and environmental issues, such as the possibility to use wastes as substrates for insects farming or to recover valuable nutrients in case of seafood by-products.

This review presents two alternatives to conventional animal protein sources, that is, insect meals and by-products deriving from fishery and aquaculture, focussing on their production and costs, safety as well as regulatory aspects of their use, and future perspectives. In order to deal rationally the whole topic, pros and cons of the entry of insect meals and fishery-aquaculture by-product in the feed production chains have been systematically evaluated.

In order to identify the key factors to be regarded as important for the development of both alternative protein meals, a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) was performed assessing: (i) the internal factors (strengths = positive attributes and weaknesses = negative attributes), purely internal to the system, and (ii) the external factors (opportunities = potentially favourable

attributes and threats = potentially unfavourable attributes) that come from outside (Kadim et al. 2014; Mancuso et al. 2019).

Insect meals

Production and supply: focus on the EU

Insects are one of the most promising protein sources for feed production. Recently, the European Commission allowed the use of insect meals in aqua-feed [Reg. (EU) 2017/893] uplifting the feed ban regarding the use of insect-derived processed animal proteins (PAPs) for farmed fish. The Regulation indicates the seven authorised insect species [black soldier fly (BSF), *Hermetia illucens*; common housefly (HF), *Musca domestica*; yellow mealworm (MW), *Tenebrio molitor*; lesser mealworm, *Alphitobius diaperinus*; house cricket, *Acheta domesticus*; banded cricket, *Gryllobates sigillatus*; field cricket, *Gryllus assimilis*], and defines the allowed rearing substrates to grow insects on. In particular, as insects are ‘farmed animals’, they can only be fed feed materials of animal origin listed in the Regulation (EU) 2017/1017 (i.e. fishmeal, blood products from not ruminants, hydrolysed proteins or gelatine and collagen from not ruminants, eggs, dietary products). Moreover, insects cannot be fed with manure, waste, former foodstuff containing meat, fish or food losses originating from restaurants or catering establishments. Among the species aforementioned, BSF, HF, and MW have the highest potential for large-scale production (Veldkamp and Bosch 2015). As far as other livestock animals are concerned (i.e. poultry or pigs), the feed ban Regulation (EC) 999/2001 (European Commission 2001) (called ‘feed ban’) still prohibits the use of insect-derived PAPs, but it is expected that within a few years certain regulatory requirements may be further reviewed.

Industrial insect production is taking off worldwide. A 24.4% growth of the quantity produced per year over the next decade is forecasted for both food and feed market with a global production of more than 730,000 tonnes in 2030 as reported in an article published on the Guardian (EAAP 2019). Recent data indicate an insect yearly production at EU level of about 6000 tonnes, corresponding to an average of 2000–3000 tonnes of insect-derived PAPs (IPIFF 2019a; Mancuso et al. 2019). They are expected to be increasingly used in Europe and around the globe as a replacement for conventional animal-derived proteins for aquaculture (Lock et al. 2018) and terrestrial livestock (Bovera et al. 2018; Khan 2018; Biasato et al. 2019a). Forecasted insect protein production to be

Table 1. SWOT analysis: Internal (Strengths and Weaknesses) and External (Opportunities and Threats) factors on the use of insects as protein source for animal feeds.

	Strengths	Weaknesses
Internal origin	Composition Shaping insect nutrient profile Content of nutrients and bioactive compounds Opportunities	Market price PUFA and minerals Research & Development Threats
External origin	Insects for organic waste valorisation Food vs Feed Lifting insects' ban Scaling up insect production Live insect larvae	Legal framework Risk related to insect uses Welfare Safety and legislation

used in both the human food and the animal feed sectors for 2025 surpasses 1.2 million tonnes (Mt) reaching about 10% of the EU share of total protein supply (IPIFF 2019a; Mancuso et al. 2019).

SWOT analysis

In the following section, pros and cons of the use of insects as protein source are assessed by using a SWOT analysis. The main factors included in the SWOT analysis as detailed hereafter are summarised in Table 1.

Strengths

Composition - Insects are natural preys and components of the diet of many farmed animals, but their nutritional value greatly varies according to the insect species and the rearing substrate (Gasco et al. 2019a; Koutsos et al. 2019). Though being considered an interesting alternative protein source for feed, the nutritional properties of insects depend on the species, rearing system and especially on the substrate used for their growth (Veldkamp and Bosch 2015; Ottoboni et al. 2017a; Meneguz et al. 2018; Danieli et al. 2019).

Overall, insects are generally rich in proteins (30–68% on dry matter, DM) with well-balanced amino acid profiles (Finke 2015; Gasco et al. 2018a; Koutsos et al. 2019). In addition, they result promising as a fat/energy source (Wang and Shelomi 2017; Biasato et al. 2018; Schiavone et al. 2018; Gasco et al. 2019b) being rich in lipids (about 10 to 30% on DM), though their fatty acid profile is highly variable. Insects can be considered also a good source of vitamins (especially vitamin B₁₂) and bioavailable minerals, particularly iron and zinc (Finke 2015; Payne et al. 2016).

Shaping insect nutrient profile – The low level of some nutrients in insects could represent a limit in animal nutrition; however, it has been shown that the nutrient composition of insects is highly dependent on the rearing substrates (Meneguz et al. 2018; Danieli

et al. 2019). For example, using substrates naturally containing polyunsaturated fatty acids (PUFA) or rich in minerals allow to obtain enriched insect-derived materials that are more suitable for feed purposes (Liland et al. 2017; Cullere et al. 2019; Koutsos et al. 2019; Pinotti et al. 2019). Thus, the insect nutrient profile can be modulated by appropriate dietary strategies, according to specific animal dietary requirements. In addition, some deficiencies in essential amino acids or minerals can be easily compensated for by an appropriate diet supplementation with synthetic amino acids or mineral concentrates.

Content of nutrients and bioactive compounds – The use of insect-derived PAPs can significantly help to reduce the pressure and reliance on conventional protein sources, such as soybean meal or fishmeal. Insects are a natural, though minor, component of many livestock diets, thus being easily accepted and providing a valuable amount of nutrients (Biasato et al. 2019b). Insects have also been proposed as a potential source of bioactive compounds. In this respect, it has been speculated that insect's antioxidant peptides, chitin and antimicrobial peptides could stimulate the immune system (Su et al. 2017; Henry et al. 2018; Komi et al. 2018; Kvalsvik Stenberg et al. 2019), and modulate gut microbiome in animals (Bruni et al. 2018; Antonopoulou et al. 2019; Biasato et al. 2019b; Rimoldi et al. 2019), thus promoting health and welfare (Józefiak and Engberg 2017; Gasco et al. 2018b; Wu et al. 2018).

Weaknesses

Market price – Information on market price is not easy to find because the market is still limited, and companies use to tailor price based on the order size. Nevertheless, mainly due to the regulatory hurdles and the small industrial scale, in EU countries the insect-derived PAPs price is higher (from 2.0 to 10.0 €/kg) (Mancuso et al. 2019) than outside the EU (from 0.8 to about 3.5 €/kg) (Gasco, Personal communication).

An increase in the production scale and, in the EU, the use of a large range of organic substrates for insect growth can help to lower prices (ABN AMRO 2016). Estimates report that the price of insect-derived PAPs could become competitive with that of fishmeal by 2023 (Arru et al. 2019).

PUFA and minerals – Terrestrial insects contain little amounts of PUFA and this could represent a limit in animal nutrition and in derived food quality (Dalle Zotte et al. 2019). The same comment can be applied to minerals as some species have low levels of calcium or phosphorus. However, adequate nutritional intervention in insects can improve this feature (Liland et al. 2017; Pinotti et al. 2019).

Research & Development – Due to high investment costs incurred for research and development, insect companies apply strong intellectual property rights (IPR) policies. Critics of IPR protection claim that on one hand IPR system promotes innovation; on the other hand, it can limit technology transfer and the full sector development that is needed to produce the large quantities required by the feed market.

Opportunities

Insects for organic waste valorisation - Some insect species can efficiently convert low value organic substrate (wastes from industry or agriculture) into high value products exalting the concept of Circular Economy and Zero Waste (Verbeke et al. 2015; Bosch et al. 2019; Pinotti et al. 2019). In addition, they seem to have a low environmental impact in terms of land use and water consumption (Dobermann et al. 2017; van Huis and Oonincx 2017), even though available environmental studies and Life Cycle Assessments (LCAs) are still limited (Mertenat et al. 2019).

Feed vs Food – Some issues of neophobia exist when consumers are faced with the direct insect consumption (insects as food) (Sogari et al. 2019a). However, they responded positively to the question if they would eat meat products from livestock fed insect meals (insects as feed), when properly informed about current animal feed issues (Verbeke et al. 2015; Mancuso et al. 2016; Ferrer Llagostera et al. 2019; Macombe et al. 2019; Sogari et al. 2019b). Moreover, in this case, insect-based feeds and animal food from livestock fed with them are considered to have a better nutritional value and to be more sustainable than the conventional feed/food counterparts (Verbeke et al. 2015; Ferrer Llagostera et al. 2019).

Lifting insects' ban – Decoupling the use of insect meals from other banned animal proteins in livestock feeding could decrease the EU dependence on

conventional protein sources and, particularly, on the most imported ones such as (in 2018/2019): oilseed meals (27.2Mt), oilseeds (19.8Mt) soybean and sunflower meals (respectively 18Mt and 3.5 Mt) and other food industry co-products (European Commission 2019). As a conceivable further benefit, it can lead to a reduction/valorisation of the organic waste produced at EU level.

Scaling up insect production – Since the beginning of the century, several companies that farm insects for feed purposes have been founded. Nevertheless, currently the insect industry is not able to deliver large quantities or to compete with conventional feed commodities, even though the sector is growing very fast and many companies are scaling up their R&D small-scale facilities going for automation and large-scale productions. The current global insect production is estimated at 50,000 tonnes/year, but the potential for increase is large (IPIFF 2019a; Mancuso et al. 2019). For example, by considering a dietary inclusion level of insect-derived PAPs of 5% and the global feed production for the aquaculture, poultry and pig sectors of about 790 Mt (Alltech 2019), the global insect meal demand today could be about 40 Mt.

The willingness of consumers to pay a premium for insect meal-fed fish compared to conventionally fed fish (Ferrer Llagostera et al. 2019) can help the development of the insect industry.

Live insect larvae - Live insect larvae can be used as environmental and nutritional enhancers in poultry (broiler chickens or laying hens) in order to reduce feather pecking and improve animal welfare (Bellezza Oddon et al. 2019; Veldkamp and van Niekerk 2019). At present, organic livestock systems seem to be the most appropriate for the use of live insect larvae because of the higher sale price of organic food that is able to cover larvae costs and the favourable attitude of consumer of organic products towards animal welfare issues.

Threat

Legal framework – Under the current EU legislation framework, the short list of allowed substrates for mass rearing is a bottleneck for the development of the insect industry. In the EU, in the light of the 'precautionary' principle applied to the food safety policy, substrates such as catering or animal wastes are forbidden, even though in other parts of the world the scenario is quite different and sometimes with less restrictions in the use of wastes and other poor substrates (Pinotti et al. 2019; Sogari et al. 2019b; Fowles and Nansen 2020). The limitations imposed at EU scale

Table 2. Insect and fish animal protein main exemptions and derogations.

	Intended For				
	Ruminants	Un-weaned Ruminants	Non Ruminants	Fish	Pet and Fur Animals
Insect PAP	NA	NA	NA	A	A
Fish meal	NA	A	A	A	A

A: authorised; PAP: processed animal protein; NA: not authorised.

have several implications because the available data on the environmental and economic sustainability of the insects as feedstuff indicate that insect meals are more sustainable when insects are grown on poor substrates, often not authorised in the EU (Bosch et al. 2019; Smetana et al. 2019). More research aimed at assessing the safety risks deriving from chemicals, mycotoxins, heavy metals, pesticides and other residues (Charlton et al. 2015; EFSA 2015; Purschke et al. 2017; Camenzuli et al. 2018; Leni et al. 2019) in poor substrates intended for insect rearing is needed before enabling their use.

Risk related to insect uses – In 2015, EFSA released a risk profile related to production and consumption of insects as food and feed (EFSA 2015) pointing out the importance to deliver new data on the full assessment of unconventional substrates, production and processing methodologies, to better understand and control all possible hazards that could threaten the development of this promising sector.

While there is no evidence of risks related to allergens for humans consuming meat products from livestock fed insect-derived PAPs, allergy risks for the insect-sector workers mainly due to contact or inhalation have been documented (EFSA 2015; Macombe et al. 2019).

Infections and diseases caused by bacteria, viruses, and fungi can affect insects and be a threat in insect rearing facilities in which heavy losses may occur. A proper knowledge of insect pathologies and control coupled with good farming practices, hygiene, environmental control, and proper Hazard Analysis and Critical Control Points plans can help to prevent and mitigate these issues.

Welfare - Insects' welfare has received little attention, and no specific legislation exists. So far, scientific evidence on whether insects feel pain is not conclusive (Goumperis 2019). Nevertheless, in the EU the animal welfare is considered a crucial issue; the International Platform of Insects for Food and Feed (IPIFF) encourages producers to embrace good welfare practices and asks for more research to fill the knowledge gaps on insect welfare (IPIFF 2019b).

Safety and legislation - With regard to insects as feedstuff, some additional aspects must be considered. Since insect-based feeds are feeds of animal origin, an

extra-set of requirements following the ban on the use of PAPs such as the compliance with the legislation for eradicating transmissible spongiform encephalopathy, which limits or prohibits the use of PAPs, needs to be considered. This last point is crucial: insects as PAPs are subject to a few general bans (the same as their substrates), for which there are ranges of exemptions and derogations. Specifically, in the EU, as for the other farmed animals, authorised insect species may only be fed with 'authorised substrates'; the insect material obtained is allowed in EU only for aquafeed. A complete overview of the feed ban in the EU is reported in Table 2 [Reg. (EU) 2017/893; European Commission 2017].

Thus far, the research carried out to evaluate the effects of dietary inclusion of insect-derived PAPs or dried larvae on *in vivo* performance, health status, and food product quality of fish and terrestrial monogastric species (poultry, swine) is promising. However, as for the other feed ingredients, well-defined protocols and controls of insect material productive chain must be implemented and regulated to protect animal and human safety (Ottoboni et al. 2017b; van Raamsdonk et al. 2017; Veys and Baeten 2018).

The rules for insects as feed greatly vary among countries (Sogari et al. 2019b). For instance, while in the EU the insect-derived PAPs are only authorised in aquaculture and specific authorizations are needed in USA, in Canada *Hermetia illucens* products are allowed in poultry and fish, and no authorisation is required in China or South Korea.

Future perspectives

Insects are animal-source foods, and the amino acids compositions of their protein generally meet human and animal requirements. Moreover, insect meals hold potential as functional ingredients. All these properties might open new markets in the near future such as the pharmaceutical industry. Cultural barriers regarding insects as food are still quite strong in the western part of the World but, in the medium term, consumers could potentially accept insect ingredients in food products, starting with 'hybrid products', for example, meat-, dairy- or plant-based products which include insects (as a meal, protein, or fat). To achieve this

Table 3. SWOT analysis: Internal (Strengths and Weaknesses) and External (Opportunities and Threats) factors on the use of by-products deriving from fishery and aquaculture as protein source for animal feeds.

	Strengths	Weaknesses
Internal origin	Composition Protein and nutrients source Bioactive compounds and feed additives	Low exploitation Nuisances Processing techniques and product quality Management of seafood by-products
External origin	Opportunities Waste reduction Bioactive compounds Novel food & feed ingredients Safety & legislation	Threats Short shelf-life

goal, research in food technology and targeted advertisement (*e.g.* showing advantages, cooking sessions, early adopters) are fundamental. One of the future challenges for the insect sector will be to deliver to the market not only large volumes of insect-derived PAPs but also insect meals having good and consistent quality.

By-products deriving from fishery and aquaculture

Production and supply: focus on the EU

Fishery and aquaculture by-products include all parts of farmed and captured fish (head, fins, scales, skin, bones, and viscera) and shellfish crustaceans (carapax, exoskeleton, shell, debris) removed during processing (filleting, canning, and packaging) for human consumption. These by-products are rich of macro- and micronutrients and their use can result in the production of fishmeal and fish oil to use in animal nutrition. Nevertheless, these products are still underused (Olsen et al. 2014) resulting in economic and environmental issues (Li et al. 2019).

The FAO estimated discards from the world's fisheries to exceed 20Mt/year and recommended reconsidering their use (FAOSTAT 2014). In the EU, the by-products generated by the fishing sector represent 5.2Mt/year (Lopes et al. 2015). To reduce the unwanted catches, the EU imposed the landing obligation [Reg. (EU) No 1380/2013; European Commission, 2013]. The prohibition of discarding and the obligation to hold all catches of species has fully entered into force in January 2019. According to the Common Fisheries Policy, this measure will reduce the by-catch, defined as 'non target' fish. However, in a recent review on implications of the landing obligation for fisheries the authors recognise the difficulties to predict the potential impact of the banning discards due to significant gaps and high variability of discard data collected from all the areas in the Mediterranean and

Black Sea (Guillen et al. 2018). In the fisheries and aquaculture sectors, the processed products are increasing with large amounts of solid waste generated from fish filleting and shell removal from shrimps and shellfish.

SWOT analysis

Similarly to what was done in the insect meal section, the pros and cons on the use of by-products deriving from fishery and aquaculture are assessed through a SWOT analysis and the main points are summarised in Table 3.

Strengths

Composition - The nutritional composition of fish by-products exhibits a wide range in relation to the aquatic species and the tissue considered in terms of proteins. In yellowfin tuna (*Thunnus albacares*), the skin shows the protein content ranging around 32% (on dry matter, DM), the fat level is about at 3% (DM) and ash rate is around 63% (DM). In Atlantic salmon (*Salmo salar*), in the head region, the protein content amounts at 13% (DM) whereas the lipid level is about at 22% (DM) and ash content stays at 4% (DM). In the viscera of the same species, the protein level varies around 8% (DM) whereas the lipid level was about at 44% (DM) and ash content ranges around 1% (DM). In the skeleton of tilapia (*Oreochromis niloticus*), the protein content reaches 50% (DM), the lipid fraction exceeds 30% (DM) and ash is around 15% (Sierra Lopera et al. 2018). In anchovies, the protein and fat contents (% DM) of by-products are 46% and 34% for head, 41% and 25% for frame, and 31% and 62% for viscera, respectively (Gencbay and Turhan 2016).

Different reviews paid attention to the contribution of by-products to the whole fish, because they can range from 30 to 80% in un-processed fish body weight and are composed of muscle cuts (15–20%), skin and fins (1–3%), bones (9–15%), heads (9–12%), viscera (12–18%) and scales (5%) (Pinotti et al. 2016;

Villamil et al. 2017). The physical form of these discards can be liquid (silage), where hygienic risks can arise especially during storage and transportation, or solid.

Enzymatic hydrolysis of fish by-products is one of the most important techniques used to produce short chain peptides and amino acids known as fish protein hydrolysates (FPH). FPH show a well-balanced amino acid profile with high levels of essential amino acids. Recent studies have focussed on the improvement of the process to break by-product proteins from discards, with the pre-treatment as an essential step to recover peptides and amino acids in FPH. The high efficiency possible with innovative processes may increase functionality and oxidative stability in respect to conventional proteins (Halim et al. 2016). FPH, extracted from different fish species, demonstrate a possible replacement for fishmeal in aquaculture feeds without compromising productive performances of farmed species. In European sea bass, FPH, manufactured from by-products of different farmed species (tilapia, shrimp) was included in practical diets as fishmeal replacer (5% dry matter) without compromising fish metabolism and performances (Leduc et al. 2018). In gilthead sea bream, FPH was tested as partial replacement of fishmeal in growing feed without affecting zoo technical parameters and gut morphology (Fronte et al. 2019). In white shrimp, diets supplemented with 10% FPH, represented by cooked (heads, fins, skin, dark muscle meat) and fresh (viscera) by-products obtained from tuna processing, improved the protein digestibility and performances in the juveniles (Hernandez et al. 2011). In abalone, a low FPH inclusion, amounting to 6g/kg protein in the final diet, improved cellular immunity and growth (Goosen et al. 2014). In young pigs, FPH, derived from farmed salmon and added to diet fulfilling all the nutrient recommendations for young stage, gave equal growth results and greater feed intake in comparison to soy protein concentrate (Norgaard et al. 2012).

Protein and nutrients source – In aquaculture, the use of discarded by-products may significantly reduce pressure on fish stocks destined for fishmeal production and is associated with a sustainable farming of aquatic animals. Positive results on performances were obtained in both fish and crustaceans when fishery and aquaculture by-products were included as fishmeal substitute in diets containing high levels of plant proteins (Uyan et al. 2006; Hernandez et al. 2011; García-Romero et al. 2014; Kim et al. 2014; Gisbert et al. 2018). Moreover, numerous FPH seemed to improve the protein digestibility, particularly due to

the high content of short peptides and free amino acids which are palatable and more readily absorbed (Chalamaiah et al. 2012).

Bioactive compounds and feed additives – Previous studies have shown that, after processing, fishery and aquaculture discards can have beneficial biological effects on the fish immune system (Kotzamanis et al. 2007). In hydrolysates obtained from shrimp shell discard, significant antioxidant activity was found, showing their potential application in aquafeeds (Ambigaipalan and Shahidi 2017).

As feed additives, enhanced flesh colour and sensory properties were obtained in red porgy (*Pagrus pagrus*) using crab meal (García-Romero et al. 2014). Shrimp shell meal included in feed (12-24%) for yellow croaker (*Larimichthys croceus*) significantly improved skin colouration and skin carotenoids without negatively affecting growth performance and feed conversion ratio (Yi et al. 2015).

Weaknesses

Low exploitation – The FAO and the EU recommend the reduction of wastes from fisheries and aquaculture through the application of adequate processing techniques. While in some countries such as Norway and Iceland they are largely adopted, in Mediterranean regions this is still not a common practice (Šimat et al. 2019).

Nuisances – Researchers are studying a sustainable reuse of fish by-products by means of innovative solutions aimed at reducing the consumption of large volumes of water, energy and pollution problems caused by the onset of unpleasant odours. Impacts associated with fish discard processing and the potential adverse impacts associated with waste management are considered by new methodologies, as the Ecological Footprint (EF) and LCA (Samuel-Fitwi et al. 2013; Lopes et al. 2015).

Processing techniques and product quality – Techniques used for the processing of different kinds of by-products can lead to important modifications of the amino acid profile and to a reduction of protein recovery (42–90%) (Gehring et al. 2011). The inclusion of new ingredients, derived from the processing of fish by-products, could affect the quality of fish produced for human consumption (*i.e.* easy oxidation or strong odour) with consequent possible alterations of the market value, based on the current appreciation by the market itself (sensory properties, nutritional value and fish health status) (Iriundo-DeHond et al. 2019).

Management of seafood by-products – From a logistic point of view, the management of seafood by-products requires particular care due to their high perishability. As good practice management, freezing and separation from the marketable aquatic species must be guaranteed throughout the whole production chain. As consequence of the EC Regulation of landing obligation, if by-products come from fisheries, boat factories are organised to process by-products on board by grinding, steaming, cooking, and pressing to separate cake and liquid phase containing fish solubles (Ween et al. 2017). In the aquaculture sector, to avoid fermentation and spoilage, the logistic supply chain of discards has to be arranged in accordance with sanitary and environmental certification.

Opportunities

Waste reduction - The increase in seafood products demand is going to increase the volume of by-products, especially those derived from canning (Garrido Gamarro et al. 2013) and mechanic separation (Secci et al. 2016). Among the interesting benefits derived from the use of fishery and aquaculture by-products, the possibility to reduce waste and to increase the recovery of precious nutrients for animals is of high value. The development of new technologies, in the perspective of the circular economy, can help to reduce waste production throughout the production chain.

Bioactive compounds – The possibility to extract bioactive peptides for pharmaceutical, nutraceutical and cosmeceutical industries is promising, adding great value to this under-used waste. Indeed, anti-inflammatory, immunomodulatory, antimicrobial, antiviral, anticarcinogenic, antioxidant and cardioprotective peptides have been identified in fish by-products (Najafian and Babji 2012; Ahn et al. 2015; Chi et al. 2015; Nurdiani et al. 2017; Pangestuti and Kim 2017) and several companies are interested in investing in this sector (Cheung et al. 2015).

Novel food & feed ingredients - In the last years, fish waste has been submitted to modern extraction techniques, applied after the conventional treatment consisting of freezing, grinding, pressing and cooking. Due to innovative bioprocesses, discards can provide precious nutrients, such as protein, fatty acids, peptides, chitin, collagen, carotenoids, and minerals, useful in animal nutrition and in human well-being (pharmaceuticals, cosmetics, nutraceuticals) (Shabani et al. 2018; Bruno et al. 2019). For recovering lipids, long chain n-3 polyunsaturated fatty acids can be extracted from rich oil by-products of different aquatic origin (Dave

and Routray 2018; Šimat et al. 2019) and can find uses in the food industry (Iriundo-DeHond et al. 2019).

Safety and legislation – According to Regulation 1069/2009, the majority of animal by-products of aquatic origin are classified as Category 3. Fish and aquaculture by-products originate from establishments or plants manufacturing products for human consumption, and shells from shellfish with soft tissue or flesh. The European legislation states that Category 3 by-products can be transformed for animal consumption to contribute responsibly to the environment and public health. From this prospective, fish by-products are the animal by-products with the smallest limitations imposed by the EU legislation. These by-products are indeed allowed for most of the farmed species, including young ruminants.

Threat

Short shelf life - One of the main problems is the sanitary aspect due the short shelf life of these compounds at both the liquid and solid state. This problem could be solved by implementing a stable and continuous cold chain on the entire processing line. Another point to remark is the ban, in force in the EU, to feed fish products to farmed fish of the same species [Reg. (EC) No 1069/2009; European Commission 2009].

Future perspectives

The use of fishery and aquaculture by-products as protein source is possible in replacement to conventional ones. Fishery and aquaculture by-products can also be used for rearing insects. Despite this, in the EU these materials are not allowed for growing insects for food and feed. Some studies (Liland et al. 2017; Pinotti et al. 2019) clearly indicate that insect meal composition can be modulated by adding these by-products to the substrate used for rearing larvae, thus highlighting the great potential of fish by-products for designing innovative feed ingredients. In addition to high-value bio-compounds, fish by-products have arisen great interest in the evaluation of suitability as an alternative to fossil fuels (Singh and Singh 2010; Rodrigues et al. 2017; Kara et al. 2018).

Conclusions

The increasing global need to find alternative and sustainable protein sources has promoted research in the field of non-conventional feed ingredients, such as insects, and in the new processing of well-known

biomasses such as fish and aquaculture by-products. Insects and fishery and aquaculture by-products are characterised by adequate protein content and their composition varies according to their production/harvest systems and processing. Therefore, they can be both considered as promising alternative feed ingredients for fish farming and livestock production. In addition to their nutritional and dietetics features, they also represent a way of transforming food waste biomasses/streams into valuable feed materials. Waste streams are often an important environment and economic issue. However, an essential pre-requisite for the use of these alternatives feed ingredients in animal feeding is their safety. Researchers and authorities must address this dispute properly in order to avoid possible public concern about these materials and increase the acceptance of their use. Such approaches will create new opportunities in terms of economic development and job opportunities.

Acknowledgments

This review has been produced as part of the activity of the "Use of innovative feed proteins in animal feed" Study Commission of the Italian Association for Animal Science and Production (ASPA). The authors thank the scientific organisation of the ASPA that appointed this Commission.

Disclosure statement

The authors of this review declare no conflict of interest.

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