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Review: Recent advances in insect-based feeds: from animal farming to the acceptance of consumers and stakeholders

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ABSTRACT

The search for new, alternative and sustainable feeding sources, including insects, has become an important challenge on the feed market. In 2017, the European Union (**EU**) started to allow the use of insect meals as feeds for fish. In addition, in 2021, the EU also authorised the use of insect meal for pig and poultry farming. However, the adoption of insect meal by the European aquaculture sector is still limited, and this is mostly due to the lack of availability of insects and their higher costs than conventional feed ingredients. Thus, the insect-based feed industry is still in its infancy, and its successful development and integration in the food value chain depend on several factors. Among these, the technical feasibility and production of quality products, and acceptance by European consumers and farmers are relevant factors. To address these points, this narrative review describes the state of the art of the potential role of insect-based feeds. The stakeholders' and consumers' perspectives are investigated, along with the effects of insect-based feeds on the production and nutritional values of fish, poultry (meat and eggs), and pork. Indeed, matching the nutritional values of insect products with conventional feeds is one of the future challenges of the insect sector, as their nutritional composition is highly dependent on the rearing substrates, and thus, their use in animal feeding needs to be investigated carefully. Feeding animals with insect-based diets affects their growth performances and the chemical composition of the derived products (fish fillets, meat, and eggs). Whether these effects can be considered positive or negative seems to depend to a great extent on the percentage of insects included in their diets and the chemical composition of the ingredients. The use of insect-based feeds has also shown a potential to improve the nutritional features and values of animal products and even to add new ones. Finally, many of the acceptance studies on the use of insects in feeds have focused mostly on the consumers' perception rather than on industry stakeholders (e.g., farmers). Future research should focus more on the farmers' perceptions on and market analyses of these innovative feeds. Even though it is likely that the upscaling of the insect sector will lead to a decrease in prices and an increase in market availability, it is still critical to understand the potential barriers and drivers for the implementation of insects as feeds from a production point of view.

Implications

Nowadays, one of the greatest societal concerns is the need to increase food production, and to reduce its negative environmental effects, without increasing costs. Insects could provide positive contributions to this agricultural challenge. To take full advantage of the insect's potential, the establishment of information exchange networks, multidisciplinary research funding, and policies related to sustainable development are recommended. Insect-based feeds represent an opportunity, but it is important to consider the production yields, the nutritional value of the products, and the consumers' opinions. The present study considers all the aspects linked to the application of insect-derived products in a market context.

Introduction

The consumption of animal products is increasing, and the causes can be found in the growing global population and in

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economic growth (OECD and FAO, 2020), along with a change in consumers' preference for more animal-based products (Godfray et al., 2018). In order to satisfy this upward trend, an increment in animal farming, that is, in fish, pig, and poultry farming, is required, and this, in turn, will lead to a substantial rise in the feed demand. Thus, the search for new alternative and sustainable feeding sources has become an important challenge on the feed market and in the overall food supply chain (Sogari et al., 2019).

Today's world compound feed production has been estimated to be just over one billion tonnes annually, with a market value of over US$ 400 million (IFIF, 2022). The main ingredient used in commercial livestock feeds is feed grains, which include corn, soybeans, sorghum, oats, and barley. About one-third of all the produced cereals is used for feeds (Olugbire et al., 2021). The use of some insect species, such as black soldier fly *(Hermetia illucens* – **BSF***)* and yellow mealworm *(Tenebrio molitor* – **YM**) in feeds, has been suggested for monogastric animals and for aquafeeds, mainly to replace soy and fish meals (Makkar et al., 2014).

The impact of insect-based feeds on the global feed market is mainly focused on the animal categories that are the lowest production slices.

Although the global feed market accounts for less than 3% of pet food and only 4% of aquafeeds, these figures are much higher for the insect market: around 50 and 20%, respectively. It has been projected that the insect market will grow from 100 000 to half a million tonnes by 2030, with the share of pet food decreasing to 30%, and the share of aquafeed increasing to 40% (de Jong and Nikolik, 2021). The production of insect feeds, excluding pet food, is only 45.9% of the global feed market, which is divided into 25% for poultry, 16.7% for fish, and 4.2% for pigs (de Jong and Nikolik, 2021).

Eighty-five percent of the 350 million tonnes of soy produced in 2018 was destined for animal feeds (Ritchie and Roser, 2022), while the remaining part was used for direct human consumption (Voora et al., 2020). Although soybeans will continue to be an important commodity for the foreseeable future, the sector faces critical sustainability and social challenges: deforestation, biodiversity loss, excessive use of herbicides, and human rights violations (Voora et al., 2020). Furthermore, the inclusion of plant proteins in aquafeeds is limited by the presence of anti-nutritional factors, and thus, insects may become an interesting alternative (Dawood & Koshio, 2020).

Fishmeal is also being replaced by insects. The global production of fishmeal is around five million tonnes and that of fish oil is around 1 million tonnes (EU, 2021). About 70% of all fishmeal is used in aquafeeds, 22% in pig feeds, and 5% for poultry. Most of the produced fish oil (69%) is used in aquaculture and rarely in animal feeds (EFFOP, 2019). The share of fishmeal and fish oil obtained from fish residues – a by-product of processing – has been projected to grow above its current share of one-quarter of the overall fishmeal production (OECD and FAO, 2020). It is known that fishmeal production harms the environment, and causes eutrophication, depletion, and damage to water bodies (Ghamkhar and Hicks, 2020).

One of the advantages of insects is that they can grow on organic side-streams, thus contributing to a circular economy. For instance, BSF can bioconvert a large range of organic waste to produce nutrient-rich animal feeds (Surendra et al., 2020). Studies in a highly productive pilot plant have demonstrated that feeding livestock with BSF could be more beneficial than soy meal or fishmeal, if the insects are fed on unutilised side-streams intended for composting or anaerobic digestion (Smetana et al., 2019). Moreover, yellow mealworm can also be grown on agri-food side-streams and by-products that are sometimes also treated as waste (Moruzzo et al., 2021).

A great deal of research (Makkar et al., 2014; Surendra et al., 2020) has focused on how certain side-streams and their composition are able to achieve an optimal rearing substrate for highly nutritional larvae. The market and environmental-like high potential of insect-based feeds depends to a great extent on the selected diet; therefore, the following criteria need to be considered: the low price of side-stream(s), the insects' performance, the environmental impact of the entire cycle, and the final appropriate nutritional values of the insect-based feeds that are to be employed in livestock or aquatic species rearing (Sogari et al., 2019). An additional factor that should be considered is related to understanding what percentage of conventional protein sources could be replaced by insect products (van Huis et al., 2021). With regard to monetary constraints, a higher price for insect products could be justified, if there were certain health benefits associated with bioactive compounds, such as antimicrobial peptides, medium-chain fatty acids, and chitin in its derivate forms (Borrelli et al., 2021).

Another key question that needs to be answered concerns whether the by-products of insect rearing can be valorised, that is, by turning fat (obtained when an insect product is defatted), chitin, and the left-over substrates into surfactants and biodiesel, plant protection agents, and fertilisers, respectively (Zainol Abidin et al., 2020; Feng et al., 2021; Poveda, 2021). Ultimately, the type of processing will also influence the nutritional value (Meyer-Rochow et al., 2021).

The nutritional value of insects can be manipulated by intervening in the composition of the waste streams or by making sure that certain ingredients are available in the stream. For instance, the accumulation of n-3 fatty acids in the insect larvae used in aquafeeds may be achieved by utilising discarded fish or flaxseed (Barroso et al., 2019; Lawal et al., 2021).

The insect-based feed industry is still in its infancy, and its successful development and integration into the food value chain depend not only on the technical feasibility and environmental benefits but also on whether consumers are willing to accept insect-fed production animals (DiGiacomo and Leury, 2019).

An increasing number of studies have been conducted to assess the acceptability of food insects for humans (Dagevos, 2021); however, only a few of them have focused on the consumer's perception of the use of insects as a meal for pets (Sogari et al., 2022a). Although previous work (e.g., Giotis and Drichoutis, 2021) showed that the attitude towards insects as feeds is more positive than consuming insect-based foods, evaluations of the consumers' perception of insects as feeds across different pet species remain scarce.

The use of processed animal proteins in farmed animal feeds was prohibited in the European Union for almost two decades, because of the aftermath of the Bovine Spongiform Encephalopathy crisis (Regulation EC 999/2001; Regulation EU 2021/1372). Thus, this 'feed ban' has hindered the dynamics and growth of the insect sector to a great extent. However, over the past few years, the European Commission has authorised the use of insects (processed animal proteins) as feedstuff, first for aquaculture farming in 2017 and then for pigs and poultry in 2021 (Commission Regulation, 2021).

This narrative review introduces and summarises the results of the studies published during the 2019–2022 period to provide the state of the art on the potential role of insect-derived proteins as a feed source. The article focuses on the perspectives of European consumers and stakeholders, the effects of using insects on the performance of fish, pigs, and poultry, and the quality of the derived products (i.e., meat and eggs).

Insect-based feeds in aquaculture

The perception of consumers and stakeholders

There are several attributes that affect consumers' purchase decisions when buying seafood products (Ankamah-Yeboah et al.,

2018), such as the country of origin, the production method (wild or farmed), and the preservation method (chilled, frozen, canned, smoked, salted, etc.). However, among all of these attributes, the feed source is not considered to be particularly relevant for purchasing choices (Ankamah-Yeboah et al., 2018).

Because of the importance of finfish production in the southern European area (Rumbos et al., 2021), most of the recent studies on the acceptance of insect feeds for farmed fish have been conducted in Mediterranean countries, namely Spain, Greece, and Italy. Baldi et al. (2021) recruited a sample of young Italian consumers (18–25 years old) using social networks and then selected only those who consume fish on a regular basis. Their findings showed that the respondents were more open to these innovative products than millennials, and males seemed to be more in favour of insect-fed fish than females. Moreover, the informed participants showed a higher positive attitude towards eating farmed fish fed with insects than those who were not informed. In addition, using a survey distributed to a group of Greek participants in an aquaculture conference, Rumbos et al. (2021) found that the majority of participants (71% of 228) were willing to eat insect-fed fish; whereas, given the minimal information on the topic, 20% of consumers were not sure whether they would consume it or not. The positive attitude was mainly driven by the expectations that the use of insect meal would lead to beneficial aspects, in terms of a reduced burden on wild fish stocks, a lower environmental footprint impact, and – consequently – the improvement of the sustainability of the aquaculture industry.

Giotis and Drichoutis (2021) performed another study on Greek consumers (no = 451), by recruiting participants using a survey distributed on social media and emailed to a list of subjects from the general population. Their findings suggested that individuals showed higher acceptance rates for the indirect consumption of insects – i.e., a farmed gilt-head (sea) bream that had been fed on an insect-based feed – than for direct entomophagy – i.e., an energy bar with insect protein or a biscuit made with insect flour. Their results showed that 56% of their participants would be willing to pay a premium to purchase gilt-head bream fed with insect-based feeds.

In another survey, Ferrer Llagostera et al. (2019) recruited a sample of Spanish consumers from the Centre for Agro-food Economy and Development. Their findings showed that most of the consumers in their study (no = 215) were willing to pay a premium for gilt-head seabream fed with insect meal as they considered it a more sustainable alternative than fish from conventional aquaculture. However, they also found that the consumers indicated a lower perception of the taste of the gilt-head sea bream fed with insects, which was considered to be worse than that of fish fed with traditional feeding systems. This implies that improving the taste of insect-fed fish might have positive effects on the acceptance of consumers.

In France, Bazoche and Poret (2020) investigated the acceptability of farmed trout fed with insect meal instead of fishmeal among a group of consumers (no = 327) recruited by a market research company to quota sample for gender and age. In their study, half of the participants received information on the environmentally negative effects of obtaining fishmeal from the by-catch of marine fishing (e.g., according to FAO, a quarter of all fish captured is used to produce feeds) and on the positive impact of insect meal as a viable alternative to fishmeal. Their results suggest that providing this information encouraged the acceptance of this new type of feed to a great extent, compared to the control group (no information). They also reported that males were far readier than females to accept insect-fed fish.

Although the EU authorised the use of insects in fish diets in 2017 (European Commission, 2017), its adoption by the European aquaculture sector is still limited. A few studies have investigated the reasons for not adopting this new type of alternative feed. For instance, during an aquaculture conference in Greece, a survey was conducted among stakeholders in the aquafeed and aquaculture industry to understand the acceptance of integrating insect meal in farmed fish feeds (Rumbos et al., 2021). The results indicated that six companies out of the nine that were interviewed were willing to include insects in aquafeeds, whereas another two companies did not indicate a preference. Only one company reported that more information was needed to make a choice. Interestingly, none of the stakeholders answered negatively. Moreover, four out of the nine companies indicated that they would be interested in producing or using insect-based feeds in their plants/on their farms. The most important factors identified for this positive attitude were the reduced environmental footprint and the innovation challenge. On the other hand, the issues that affected the decision-making process - albeit to a lesser extent – were a possible effect of the quality of the products and production costs (Rumbos et al., 2021).

In an Italian study (Mulazzani et al., 2021), insect meal producers, fish feed producers, and fish farmers – who reared trout and seabass - were interviewed. According to the feed producers, insect meals produced in Europe can be considered to have a good and standardised quality; nevertheless, the cost of such products is still not competitive. The sales price of insect meals is influenced by different factors, such as the production system, the employed substrate, and the country in which the farm is located (Niyonsaba et al. 2021). Moreover, in some cases, the economic data have not yet been disclosed. A recent review by Niyonsaba et al. (2021), which considered the meals that included YM and BSF larvae, showed that only the sales prices for BSF products were available and that – in Europe – they ranged from €2 000 to €5 000 per ton in 2019 and 2020.

The International Platform of Insects for Food and Feeds acknowledges, as an aspirational target, that the total production capacity of the European insect sector could even reach 260 000 tonnes by 2030 (i.e., as feeds for food-producing animals, but also including other applications) (IPIFF, 2020a). Moreover, building on the total expected investment of 2.5 billion EUR that will be invested by the mid-2020s, the sector may reach a total turnover of €2 billion per year (IPIFF, 2020b). Aquafeeds could thus represent the largest market, with a demand of 40% of all the insect meal produced for feeds. By 2030, more than 10% of the fish consumed in the EU (the equivalent of approximately 30 servings for each European) would be derived from fish farms that used insect proteins in their feed formulations (IPIFF, 2021).

Insect meals in fish diets

The scientific literature on the use of insect meals in aquaculture is wide and varied, and the most frequently tested aquatic species are carnivorous, both for freshwater and saltwater species (e.g., trout, salmon, seabass, tilapia, and largemouth bass). Moreover, most insect meals originate from BSFs, YMs, and – albeit to a lesser extent – houseflies.

Along with the differences in fish and insect species, other important elements could affect the growth performance results and therefore need to be considered – such as the insect development stage, the type of meal (whole or defatted), and the applied treatment method (the inactivation and/or transformation of larvae). All the considered scientific publications tested iso-lipidic and iso-proteic diets, with the exception of a trial conducted on Nile tilapia, in which the diets were only iso-proteic. The use of whole BSF and YM meals with an inclusion level of 18% generated a difference in the performance of rainbow trout and seabass. In other words, given the higher protein use and the more active digestive function, fish fed on YM performed better, in terms of

final BW, specific growth rate (**SGR**), and feed conversion ratio (**FCR**), than those fed on BSFs (Reyes et al., 2020; Melenchón et al., 2022). The lowest BSF inclusion level (12%) in largemouth bass generated a reduced growth performance, compared to the control diet (Fischer et al., 2022). Conversely, the inclusion of 20 and 17% of full-fat BSF larva meal in the diets of Atlantic salmon and Nile tilapia, respectively, increased the final BW and kept the FCR equal, when compared to the control diet (Wachira et al., 2021; Weththasinghe et al., 2021). As reviewed by Tran et al. (2022), in the period covered by their review, HF meal had only been tested in seabass diets and it showed an equal final BW but a higher FCR than YM-based feeds (both included at 20%). Furthermore, the defatted BSF meal seemed to yield a better growth performance in rainbow trout and seabass than the whole one. Specifically, the FCR, feed intake, final BW, and SGR of rainbow trout did not differ for the BSF and YM dietary treatments, in which the insect meal was included at levels of up to 15 and 20%, respectively (Caimi et al., 2021; Tran et al., 2022). With regard to seabass, meals with 20% of defatted BSF can be employed without any growth performance reduction (Tran et al., 2022).

In addition to the BSF larval meals, prepupa and pupa meals have been evaluated, although the literature on this topic is still scarce. Rainbow trout fed with 30% of BSF prepupa meals showed lower final BW and SGR values, and equal FCR rates to the control, whereas the inclusion of 45% of partially defatted pupa meal in a feed did not affect these parameters (Hoc et al., 2021; Cardinaletti et al., 2022). As for BSF larva meals in largemouth bass, the growth and the FCR were negatively affected by the use of prepupa meal (10% inclusion), due to the high chitin content (Fischer et al., 2022).

Considering the results highlighted so far, the growth performance of the considered aquatic species does not appear to be affected negatively by the inclusion of YM meal, while the effect of BSF seems to vary, depending on the fish species. Nevertheless, it is possible to observe variable results within the same species, due to the different compositions of insect meals derived from breeding substrates and the effects of the processing treatments. The variability of the results could be reduced by a greater standardisation of the insect-based products, and this condition could be profitable for practical applications.

Finally, the studies conducted heretofore represent a solid starting point to understand the feasibility of using insect meals, and to open new research lines on how to improve their application in aquaculture.

Quality of the products

Aquaculture products are appreciated by consumers throughout the world because of their nutritional benefits, which are mostly related to their richness in n-3 polyunsaturated fatty acids (n-3 **PUFA**s), and because of their sensory attributes. n-3 PUFAs are mainly accumulated in the fillets of fish as a result of their diet and, in specific species, are partly synthesised through an endogenous production (especially in freshwater species). Therefore, the use of feeds with a high n-3 PUFA content is mandatory to maintain this nutritional characteristic, although for some species more than for others.

Fish meal and fish oil are commonly used in the diets of carnivorous fish to provide them with a high n-3 PUFA content. Although the nutritional composition of insects depends to a great extent on the rearing substrates, insect lipids are primarily composed of saturated fatty acids (**SFA**s) and monounsaturated fatty acids (**MUFA**s), while PUFAs – especially, n-3 PUFAs – are scarce (Aguilar, 2021). Therefore, even though insects are considered valuable alternative sources of proteins, the nutritional value of fish products could be affected by the employed feed, if not (completely) defatted. Caimi et al. (2021) reported that the use of partially defatted BSF larva meals in rainbow trout feeds led to a larger amount of SFAs and MUFAs in the fillets, whereas the PUFAs (particularly n-3) decreased as the BSF meal inclusion increased. Similarly, Mastoraki et al. (2020) found an altered fatty acid profile in European seabass fed on YM and housefly meals, as a substitution for 30% of fish meal. Specifically, since n-6 PUFAs were abundant in the diet, the fish fillets had higher contents of these fatty acids. Conversely, the substitution of fish meal with BSF larvae did not affect the n-3 PUFAs, when compared with the control diet. The discrepancy in the results pertaining to the employment of BFS meals in rainbow trout and European seabass could be related to the type of BSF meals that were employed, as well as the differences in the two species of fish, the basal diets, and environmental factors (Mastoraki et al., 2020). Indeed, the chemical composition of the fatty acids in the two BSF meals differed. These variations can be ascribed to both the substrates fed to the insects and to the lipid processing and extraction methods (Mastoraki et al., 2020). Furthermore, Pulido et al. (2022) showed that, in fillets of gilt-head sea bream fed on BSF meals, the n-3 PUFAs decreased in favour of SFAs, but the overall amount of n-3 PUFAs positioned in the middle position (sn-2) of the triglycerides did not reduce.

Several studies have reported a lack of variation in the physical properties, such as the colour, of the fillets from fish fed on insect meals (Pulido et al., 2022).

Insect-based feeds in poultry

The perception of consumers and stakeholders

Poultry farming is the second most important agricultural subsectors in many countries, after the fish sector (Shaviklo, 2023). This has led to a growing interest in finding sustainable alternative sources to traditional soybean meals for laying hens, due to the need to reduce costs and overcome animal feed shortages (Shaviklo, 2023). In recent years, insects used as feed ingredient in poultry farming have become a valuable solution as they introduce nutritional, environmental, and animal welfare benefits (Spartano and Grasso, 2021a).

Spartano and Grasso (2021a) conducted one of the first studies on eggs produced from insect-fed hens. They found that the type of feed is not one of the main attributes that consumers from the United Kingdom focused on when buying eggs; free-range labels, price, and organic production were the most important attributes. In addition, when providing information about the environmental, food waste, and animal welfare benefits, the intention of the consumers to purchase and consume eggs from insect-fed hens increased.

Spartano and Grasso (2021b) recruited a UK sample (no = 294) using a market company to obtain gender, age, and geographic area representativeness. Their results showed a limited consumer awareness of the use of insects as feed ingredient. However, they found that most participants were willing to try and pay a premium price for such products, with an average willingness to pay all the respondents of £1.36, i.e., on average 18% more than the price of conventional free-range eggs on the UK market.

Lippi et al. (2021), through an online survey, investigated the willingness to buy and eat eggs from hens fed with insects by recruiting a sample of Italian consumers (no = 510). The participants were recruited on a national basis via advertisements posted on websites and social networks. The obtained results showed that 40% of the participants would buy and eat eggs laid by hens fed on insect-derived meals as "hens already eat insects as part of their natural diet". However, as in previous studies, the participants also highlighted that food neophobia is an important aspect that can influence the use of insects for human consumption.

Altmann et al., 2022, considering poultry meat, recruited a representative sample (no = 1197) of participants who were selected on the basis of their gender and the age quotas of the German population. In this discrete choice experiment, the consumers stated a preference for poultry breasts from insect-fed chickens (Altmann et al., 2022). In this study, an information statement (i.e., "Insect-based feeds can increase the flavour of poultry meat") was provided to a group of respondents prior to the choice experiment. The supply of such information led to an increase in the acceptance and the willingness to pay for insect-fed chicken breasts. The authors suggested that informing consumers about the link between feedstuff and meat colour could strengthen the consumers' trust in product attributes, without decreasing their quality expectations.

Menozzi et al. (2021) investigated the willingness of Italian consumers (no = 565) to purchase, eat, and pay for meat obtained from farmed duck fed on insects. The sample was recruited online, and participants were excluded if they were vegetarian/vegan. The provision of information about the environmental, safety, nutritional, and taste-related aspects of insect-based feeds led to a significant increase in the intention of the participants to eat such products. This result helps to confirm that increasing the knowledge of consumers about insect-based diets reduces their fear of using insects in animal feeds, which, in the specific case, they believed could lead to less tastier final products. In addition, most of the respondents reported that they would like information about the use of insect meal to be provided on the label. Interestingly, when the participants were asked about their opinion on eating duck fed on insect-based diets, most of the respondents reported either curiosity or indifference, followed by a pleasant sense of surprise.

Providing information on the benefits of insects in feeds, including the fact that insects are eaten in nature by poultry, has been shown to increase consumers' interest in animal welfare. This latter aspect has been shown to be a direct determinant of the purchasing intention of consumers to buy duck meat from ducks fed with either insect-based meal or live insects (Sogari et al., 2022b). The possibility of using live insects in feeds is important, considering the growing attention that has been demonstrated towards animal welfare when purchasing meat. This is in line with what many consumers reported as one of the main reasons for consuming farmed duck fed on an insect-based diet, i.e., poultry already feeding on insects in their natural environment (Menozzi et al., 2021).

Unlike in the fish sector, no research on the perception of stakeholders on the use of insect feeds in poultry and egg production in EU countries has been conducted. The few studies on this topic are from Africa and South America.

According to the global market forecasts, the number of insect protein meals sold to the poultry sector in 2030 will be 70 000 tonnes/year for layers and 50 000 tonnes/year for broilers, that is, 14 and 10% of the total insect protein meals of 500 000 tonnes/year, respectively (de Jong and Nikolik, 2021). In Europe, 20–30% of the produced insect meal will be used in the poultry sector, of which 60% will be destined for laying hens and 40% for broiler production. By 2030, 1 in 40 eggs consumed in the EU will be derived from insect-fed laying hens and 1 in 50 chicken meat servings will be derived from insect-fed broilers (IPIFF, 2021).

Insect meals in poultry diets

Since insects are a food source for many bird species, their introduction into poultry farming is being studied intensively. The scientific research in this field has covered different types of insect meals, species, and stages of development. Furthermore, these studies have focused on both broiler chickens and laying hens. Recently, broiler chicken trials have been carried out using whole meals from different insect species, such as BSF, housefly, YM, silkworm (*Bombyx mori*), and superworm (*Zophobas morio*). All the aforementioned references tested iso-proteic and iso-energetic diets. Murawska et al. (2021), starting from BSF, tested high full-fat meal inclusion levels (starter: 20–30 and 40%; grower: 20–25 and 35%; finisher: 10–20 and 30%) and reported a lower growth performance (BW, feed intake, and average daily gain (**ADG**)) in the insect-treatments than in the control, except for the ADG of the 10% group during the finisher phase. As far as FCR is concerned, no differences were observed between the control and the two diets with the lowest inclusion levels, whereas the dietary treatment with the highest insect-content yielded the lowest value (Murawska et al., 2021). On the other hand, the use of BSF prepupa (5% of inclusion), YM (2, 2.5, 4, 5, and 8% of inclusion), and housefly (4 and 8% of inclusion) larva full-fat meals determined equal results, in terms of BW, feed intake, ADG and FCR, to the control group (Elangovan et al., 2021; Elahi et al., 2022). Broiler chickens fed on diets containing 17% of YM whole meals displayed the same BW and ADG values as silkworm and control dietary treatments, while *Zophobas morio* values were the lowest (Pietras et al., 2021). The feed intake decreased for insect-based diets, compared to the control, and the YM-fed birds ate less than those fed with silkworms. This led the silkworm and *Zophobas morio* groups to perform similar FCRs to the control, while the FCR for YM was the lowest (Pietras et al., 2021). As highlighted by Benzertiha et al. (2020), the use of low *Zophobas morio* inclusion levels (2–3%) did not affect the growth performance of broilers. As far as defatted meal is concerned, only BSF was tested, at 4 and 10% inclusion levels, and no difference between the dietary treatments was observed in terms of feed intake or FCR. Nevertheless, the highest inclusion level led to a reduced BW value (Hartinger et al., 2021).

The research on laying hens has recently focused above all on the use of BSF meals, whether full-fat or defatted. According to the review of Elahi et al. (2022), the inclusion of full-fat BSF larva meals affected both the growth and production of laying hens. All the laying pullets fed on insect diets (3, 6, and 9% of inclusion), from 1 to 42 days old, showed higher BW and ADG values than the control. Moreover, the numbers recorded for the 3% treatment were higher than those for the 6%, 9%, and control groups (Elahi et al., 2022). The same outcome was found for the feed/gain ratio, where insect-based diets led to lower values than the control, with the 3% group equalling the 6% one, and both showing higher values than the 9% group (Elahi et al., 2022). The 3% full-fat BSF meal inclusion also generated positive effects on the production performance. The egg weight of laying hens fed on the 3% insect diets was higher than the 1–5% and control groups, while the egg production was comparable with the 5% and control ones (Elahi et al., 2022). Heuel et al., 2021, with regard to the defatted meal, tested two products derived from different insect companies (A: industrial scale; B: small-scale) at 15% of inclusion. The authors observed similar feed intakes, laying percentages, and FCR between the hens fed on insect diets and the control, while the egg weight and mass were lower for diet B than for both diet A and the control (Heuel et al., 2021). This result confirmed that the breeding systems and the substrates of the insects can influence the chemical composition of meals and, consequently, the growth performance of the animals fed on such meals. For this reason, standardised insect products (regarding the protein and lipid contents) would ensure the possibility of conducting comparisons between experimental trials.

Quality of the final products

The quality of poultry meat and eggs is notoriously affected by various factors, from the genetics of the bird, the farming system,

and the age of the animal, to the slaughtering method. The diet of the animals could also play a major role when all the other factors are fixed. Shaviklo et al. (2021) analysed raw and cooked meat samples of Ross 308 male broilers fed on YM meal and found negative sensory attributes (especially for the 3% inclusion level of YM meal). The raw samples showed an impaired odour and flavour, with reduced yellowness and pinkness on the leg and breast skin, increased darkness of the carcass skin, and of the skinless leg and breast. Similar results were also found for cooked samples, where YM inclusion was found to impair the juiciness and acceptance of the meat, while it increased the perception of the odour and flavour of chickpeas. Thus, an increment in the YM levels corresponded to a reduction in meat quality (in 24-day-old broilers). However, when the feeds containing the insect meal were suspended and the animals were fed the control feed for 18 days, no differences were detected in the sensory parameters between the control and the YM groups.

Colour changes were also found in broilers fed on BSF meals, with a linear increment and a reduction in the redness and yellowness of the breast, respectively (Schiavone et al., 2019). BSF meals also affected the fatty acid profile of the meat, with increased SFA and MUFA contents, to the detriment of the PUFA fraction (Schiavone et al., 2019). Dabbou et al. (2020) reported significant modifications in the fatty acid profile of free-range chickens fed on YM meals. On one hand, the inclusion of YM meals significantly reduced the number of SFAs, as well as the atherogenicity and thrombogenicity indexes, but increased the MUFAs in the breast. On the other hand, the effects of the dietary insect meals on the fatty acid profile of the thigh meat were negligible and the atherogenicity and thrombogenicity indexes were not influenced by insect inclusion.

Heuel et al. (2021) tested BSF meals and oil in feeds for laying hens and noted an absence of differences in most of the egg quality characteristics. Indeed, no significant effects were detected in shell stability, egg composition, or in the albumen and yolk physiochemical composition (proximate composition, colour, and Haugh units). Bejaei and Cheng (2020) fed laying hens on full-fat dried BSF larvae, in replacement of soybean meals and soybean oil. This switch led to an inferior egg quality and to appearance and taste concerns. Minor modifications were detected in the yolk fat content when a linear increasing amount of insect inclusion was employed in the feed; however, the perceptions of odour, flavour, and texture were not affected. A higher proportion of yolk was detected in the eggs of Lohmann Brown Classic laying hens fed on BSF meal as a replacement for soya bean (100%, Secci et al., 2018). The yolks derived from the hens fed on BSF meals also showed a higher redness index and were richer in γ-tocopherol, lutein, β-carotene, and total carotenoids. Moreover, despite the fatty acid profiles of the yolks being similar between the diets, the eggs derived from the hens fed with insect meals showed decreased yolk cholesterol levels (11%).

Insect-based feeds in pig

The perception of consumers and stakeholders

Compared to the previously discussed animal species, few studies have been performed on the acceptance of consumers and stakeholders concerning the use of insects as feeds ingredient for pigs. This could be due to the fact that the EU has only recently authorised the use of insects as an ingredient in pig diets (Commission Regulation, 2021).

Verbeke et al. (2015) conducted the first study that investigated the perception of consumers on the use of insects in feeds for farmed pigs, compared to other species. The research involved a group (no = 415) of farmers, agriculture sector stakeholders, and citizens who were recruited from among the visitors to an agricultural fair (Agriflanders) in Flanders, Belgium. The study mainly focused on the attitudes towards the idea of including insects in feeds and the willingness to eat different products obtained from insect-fed animals, including eggs, poultry meat, fish, pork, beef, and milk. The results showed that the consumers' acceptance of pork was lower than that of eggs, poultry, and fish, but higher than that of beef and milk. One possible explanation for these results could be that insects were perceived as a more 'natural' or even 'naturally preferred' food source for fish and poultry than for other animal species, especially ruminants (Verbeke et al., 2015).

Weinrich and Busch (2021), in a recent study conducted on a German sample (no = 618) recruited online by a professional panel provider, found that consumers, in general, did not consider they were well-informed about animal nutrition. In addition, the participants had less knowledge of the practices of feeding pigs than those of feeding poultry. However, even though uninformed, the consumers' willingness to purchase meat obtained using alternative protein sources was high. The participants' willingness to buy insect-fed poultry was in fact higher than their willingness to buy insect-fed pork.

Finally, nowadays, there is a higher acceptance for using insects as feed ingredient to produce fish and poultry meat than to produce pork (Verbeke et al., 2015). However, due to the low number of consumer studies that have focused on pigs fed with insects and their derived products (e.g., pork chops, sausages), there is still a great deal of room for researchers to investigate the potential of this market in more detail. Today, the pig sector is still a niche for insect feeds but, according to the global market forecasts, the quantity of insect protein meals should increase and reach a quantity of 30 000 tonnes/year (for piglets) by 2030, thus, representing 6% of the total demand for insect protein meals, that is, 500 000 tonnes/year (de Jong and Nikolik, 2021). In Europe, 5–15% of such insect meals will go to the pig sector. By 2030, 1 in 100 pig meat servings consumed in the EU will be derived from insect-fed pigs (IPIFF, 2021).

Insect meals in pig diets

The information on the use of insects in swine feeds is limited, compared to poultry and aquaculture. This gap may be due to the number of insects required for an experimental trial, which is higher for swine than for other species, and the size of the insect-rearing companies, which does not allow them to produce a sufficient number of products (Hong and Kim, 2022); therefore, most studies have focused on the evaluation of insect meal effects on the growth of weaned piglets (in trials lasting about 4 weeks). Furthermore, despite the research on this growth phase being scarce, these studies have covered several insect species, development stages, and types of meals. Moreover, all the cited references in this section tested iso-proteic and iso-energetic diets.

As far as full-fat meal is concerned, BSF and cricket (*Gryllus bimaculatus*) products were tested at higher inclusion levels than YM (10–20%, 4.2–5–6%, and 1–2–3%, respectively). No difference, in terms of the average daily feed intake, average daily gain (ADG), and gain-to-feed ratio, was identified for the above-mentioned species, when compared to control diets formulated with conventional animal proteins (Ao et al., 2020; Håkenåsen et al., 2021; Boontiam et al., 2022; Cho et al., 2022). In the same growing period, Tang et al., 2021 evaluated BSF full-fat prepupa meal in an enterotoxigenic *Escherichia coli* environment, considering an inclusion level of 3%. The growth performance, even in this scenario, was not affected by the dietary treatments (Tang et al., 2021). The 2.5% inclusion of defatted YM meals generated a higher ADG than the 5% inclusion level; however, both levels were equal

to the control for the ADG, average daily feed intake, and gain-to-feed ratio parameters (Ko et al., 2020). The same outcome was confirmed by Cho et al. (2022), who tested the 3% inclusion level of hydrolysate YM meals and did not observe any differences from the control.

As reviewed by Hong and Kim (2022), only one trial with increasing inclusion levels of BSF full-fat meals (6, 9, 12, and 14%) has been conducted during the finishing phase. In this feeding phase, inclusion levels equal to or higher than 9% led to a reduced FCR and higher ADG parameters than the control, whereas the parameters of the 6% dietary treatment were comparable (Hong and Kim, 2022).

Considering the above-reported background, insect meals do not seem to generate negative effects in the weaning phase. Nevertheless, studies are still necessary to assess the maximum inclusion percentage. Finally, during the finishing phase, the inclusion of percentages of between 9 and 14% of BSF meals seems to positively affect the growth performance of pigs.

Quality of the final products

As previously mentioned, only a few research studies have investigated the practice of feeding insects to swine. Altmann et al. (2019) replaced 50, 75, or 100% of soybean meals with partially defatted BSF meals in the diet of barrows. The insect diet did not modify the physio-chemical characteristics, such as the proximate composition, the colour, the cooking loss, or the lipid oxidation, of the pork. Partially defatted BSF meals induced only slight variations in the meat odour, although the overall odour was stronger; however, no off-odour or off-flavour were detected by the panellists. Furthermore, the inclusion of the BSF meal increased the juiciness of the meat, compared to the control meat, while the remaining characteristics were rated similarly (i.e., the hardness, adhesiveness, malleability, moistness, crumbliness, tenderness, and the number of chews necessary before swallowing).

The modifications in the fatty acid composition of the backfat were mostly related to the lauric acid (C12:0) content of the partially defatted BSF meal. Since lauric acid represents one of the richest fatty acids in the pupae, this modification is quite normal in monogastric animal tissues when non-totally defatted BSF meal is employed.

Other alterations were identified, that is, increased γ-linolenic acid (C18:3n-6) and linoleic acid (C18:2n-6) contents. Therefore, as previously reported, other changes in products from animals fed on insect meals could be related to both the substrates employed in the insect rearing and the processing of the insect products (Meyer-Rochow et al., 2021). Nevertheless, Altmann et al. (2019) did not report any differences in lipid oxidation in steaks from the control and from BSF-fed pigs when packed under MAP (modified atmosphere packaging).

Yu et al. (2019) tested two dietary inclusion levels of dried BSF larva powder (4 and 8%) in finishing pigs, at the expense of soybean meals, and reported an increased marbling of the loins (*longissimus thoracis*), but no effect on the pH, the colour, the drip loss, or the tenderness were observed. The inclusion of BSF powder also induced changes in the fatty acid profile of the loins. Animals fed on the insect diet showed increased concentrations of lauric acid (C12:0), myristic acid (C14:0), palmitoleic acid (C16:1), arachidonic acid (C20:4), eicosapentaenoic acid (C20:5), and docosahexaenoic acid (C22:6) in their muscles, whereas the α-linoleic acid (C18:3n-3) concentration decreased. Nevertheless, no differences were detected between the SFA, MUFA, and PUFA concentrations of the different dietary groups. Chia et al. (2021) reported variations in the liver of animals related to the inclusion of BSF in pig diets. The organ was richer in CPs when the total amount of fish meal was replaced with BSF meals. Furthermore, the loins presented percentages of crude fat that were around five times higher than the control ones. Feeding insect meal to the pigs also induced increased Fe and Zn concentration levels in the loins and increased K levels in both the loins and livers.

Discussion

This narrative review article is aimed at providing valuable insights for scientists and animal industry stakeholders who are interested in investigating the potential role of employing insect meals in animal diets as a sustainable alternative to conventional feeds.

Because of the recent advancements in the EU authorisations on the use of insect feeds, only a few studies have been conducted on the potential interest of adopting this innovation. Therefore, future research should focus more on the stakeholder's perception of this promising feed and on understanding the barriers to (e.g., high costs) and drivers of (e.g., better product quality) the adoption of insect meals. The upscaling of the insect sector will assumedly lead to a decrease in prices and an increase in market availability (Rumbos et al., 2021).

Furthermore, even though most of the consumer studies have suggested that individuals are interested in this type of innovation (i.e., insect-fed animals), certain limitations, such as social biases in the responses, should be considered due to the hypothetical scenario and online nature of the conducted studies (e.g., no real products or actual prices). If society is interested in undertaking this change, it will be facilitated by a further understanding of the main factors that influence the perceptions of consumers, which will also provide support to policy makers and producers in the development of strategies that could successfully support this sector. For example, the strategic provision of information through public campaigns and general communication on the production methods of farm animals, including environmental and sustainability aspects of the feed source, could increase the awareness and acceptance of consumers of farmed animals fed on insects. In addition, a part of the literature (e.g., Spartano and Grasso, 2021b) suggests that insect-fed animals should be marketed under enhanced animal welfare standards (e.g., using free-range labelling). Thus, a critical role for the success of this emerging alternative feedstuff hinges on the provision of appropriate information at the point of sales, including the use of a labelling system, accredited by reliable sources, on the product packaging.

Conclusions

Despite the large number of research studies conducted on the effects of insect-based feeds on the growth performance of conventional livestock animals, the results in some cases appear to be conflicting. A qualitative standardisation of insect products would allow defined inclusion levels to be determined for the different livestock species.

Studies on the sensory evaluation of insect-fed animals are rather limited and future research should thus focus on consumer and sensory studies to investigate whether and how the product attributes and the overall liking can favour the acceptance of insect-fed animals. In addition, considering that the type of feed is not the main decisional factor when purchasing meat products, future studies should measure the trade-off between this attribute and other elements, such as the origin of a product and the farming methods.

Ethics approval

Not applicable.

Data and model availability statement

None of the data was deposited in an official repository. Information can be made available from the authors upon request.

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Declaration of interest

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