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Factors affecting the decision-making process of using insect-based products in animal feed formulations

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REVIEW ARTICLE

Abstract

Insect meals are promising alternative feed ingredients although their application is still not commonplace. Their inclusion requires the consideration of various factors to optimise growth, animal welfare, and feed costs. The insect meal form (whole or defatted) impacts the level of inclusion, in particular in feeds where low amount of lipids is needed (e.g. poultry). From a nutritional point of view, the factors that influence the insect meal characteristics include insect species, rearing substrates and production processes. Processing (drying, defatting) can dramatically influence the nutrient digestibility and availability that requires assessment through *in vivo* or *in vitro* trials, with differences being observed in relation to the entity of the defatting process as well. The inclusion of full-fat or defatted meal may impact the final product quality (fatty acid profile). Low digestibility of chitin is also a limiting factor. Studies to increase the digestibility of insect meals using additives are ongoing. For these reasons, when different insect protein suppliers are used for feed production, chemical analyses need to be performed. In addition to the nutritional aspect, in some species (i.e. fish), a physical evaluation of the feed is necessary. In particular, the high fat content of whole larvae meal may increase the mixture viscosity and decrease the pellet stability, resulting in nutrient loss. Palatability affects feed ingestion; though insect meals seem well accepted, some palatability issues have been reported at high inclusion levels. It is however not clear if these issues are due to the level of inclusion or to some intrinsic characteristics of the meal used. Finally, the crucial factor for the future practical incorporation of insect meals in animal feeds is the availability and consistency of the supply. Without large and consistent quantities, it will be difficult for feed producers to incorporate these alternative ingredients within their production processes.

Keywords: feed formula, inclusion, insects, nutritional value, processing

1. Introduction

Over the last 25 years, the consumption of products of animal origin increased by over 55%, driven by the population and income growth, and, according to the OECD-FAO Agricultural Outlook 2021-2030, the global meat supply is expected to reach 374 million metric tonnes by 2030, with a further increase in meat consumption of about 14% (OECD-FAO, 2022). To meet the increasing demand for meat, the global feed production has, in turn, increased at a rate of about 2% over the past 20 years, reaching over 1.23 billion metric tonnes in 2021. The largest producing countries are China (21.2%), USA (18.7%), Brazil (6.5%) and India (3.6%), while all the European countries account for about 21.5% In relation to the feed productions recorded in 2020, the sectors that registered the highest increase in 2021 were pet (+8.2%), pig (+6.6%), aquaculture (+3.7%), and broilers (+2.3%) (Alltech, 2022).

Apart from production issues, socio-economical and environmental aspects must also be considered. First of all, the global COVID-19 pandemic, the worsening in the climate change faced in the last years, food-feed competition for resources, and the recent uncertainties related to the

Ukraine crisis, caused huge supply challenges and a sharp increase and volatility of conventional feed ingredients prices. As a second aspect to consider, greenhouse gas (GHG) emissions are actively responsible for climate change, and it is estimated that about 1/4th of all GHG emissions may be caused by the agri-food system (Mrówczyńska-Kamińska *et al.*, 2021). Furthermore, the doubling of animal-based protein demand expected by 2050, as well as the increasing food-feed competition (especially for grains), will further exacerbate GHG emissions, as a consequence of intensified land pressure to produce more animal feed. Thirdly, the already mentioned increase in consumption trends will also determine a parallel increase in food loss and waste, thus further exacerbating the environmental pressure (Ojha *et al.*, 2020). Last but not least, consumers have a critical, key role in food-non feed strategies development, as a result of their increasing awareness of the impact of food production and consumption on health and environment (Henchion *et al.*, 2017), as well as increasing demand for potentially healthier, more natural, and better-tasting products (Van Loo *et al.*, 2014). Great efforts are, therefore, demanded to improve feed efficiency and animal nutrition, and the feed industry is exploring alternative feed ingredients and additives that are able to sustain animal growth, health and welfare, as well as guarantee affordable feed costs.

Within this challenging scenario, the use of insects represents one of the most promising alternative feed strategies, because of the low emission of GHG, the small land area needed to produce 1 kg protein, their remarkable feed conversion efficiencies, and their ability to convert organic side streams into high-value protein products (Gasco *et al.*, 2020). Within the huge number of insect species existing, about 5.5 million of which only 1 million has been named so far (Stork, 2018), only a few have been considered for feed application: *Tenebrio molitor* (TM), *Alphitobius diaperinus* (AD), *Zophobas morio*, *Hermetia illucens* (HI), *Musca domestica* (MD), *Bombyx mori*, and several crickets such as *Acheta domesticus* and *Gryllus bimaculatus* (Gasco *et al.*, 2020). However, even if the scientific research regarding the suitability as feed ingredients has increased substantially over the last 10 years, their use in animal nutrition is still not a common practice, and their inclusion requires the consideration of various factors to optimise nutrients use, animal production, health and welfare, and feed costs. They include: (1) insect species and composition; (2) variability and processing methods; (3) availability and consistency of supply; (4) nutrient digestibility; (5) anti-nutritional factors; (6) physical properties of pellets; (7) palatability; (8) safety risks; (9) stability; (10) cost; (11) impact on product quality; and (12) legislation.

2. Insect species and composition

Feed formulation and production require the selection of different ingredients that, combined with each other, are able to cover the animal's nutritional requirements. Therefore, in order to include an insect-based product into a feed formula, the assessment of its chemical composition is mandatory.

Insect composition depends on the insect species (Hawkey *et al.*, 2021). Insect groups such as Diptera (HI and MD) and Coleoptera (TM) are holometabolous (complete metamorphosis), while hemimetabolous (partial metamorphosis) includes Orthoptera, Blattodea, and Hemiptera. The first category presents different active and feeding larval stages, a non-feeding pupae stage and adults with different feeding patterns. For instance, while the adult of MD has a clear and compulsory feeding behaviour, HI adults do not necessarily have to eat, as they can survive several days without consuming any food and devoting all their energy to the mating behavior (Kortsmit *et al.*, in press). In hemimetabolous, nymphs look like smaller versions of adults and do not go through a pupae stage. After several moults, nymphs develop to the adult stage and they are ready to reproduce. All the hemimetabolous stages present a feeding pattern. Insects that undergo a complete metamorphosis contain a higher lipid content when compared to the hemimetabolous ones, as lipids accumulated during larval stages and are used to complete the metamorphosis during the non-feeding pupal stage, and, in the case of HI, to sustain reproductive activity and increase survival (Li *et al.*, 2021).

The nutritional value of insects can greatly vary depending on species, development stage, or processing method (Oonincx and Finke, 2021). Overall, insect protein content can vary between 25-75% on a DM basis, having a more balanced amino acid profile than plant feedstuffs, and providing higher levels of essential amino acids (Oonincx and Finke, 2021). Lipid levels can also fluctuate between 10 to 70% DM, being mainly characterised by linoleic acid (with the only exception of HI, in which the main fatty acid (FA) is represented by lauric acid) (Oonincx and Finke, 2021). Moreover, depending on the species and feed substrates, insect larvae show a variable FA profile, which can be modulated through the rearing substrate to increase useful FA such as n-3 FA (Danieli *et al.*, 2019; Gasco *et al.*, 2020).

The analysis of the insect-based product for its proximate composition in terms of DM, crude protein (CP), ether extract (EE), crude fibre (CF) and ash is compulsory. When assessing CP using the Kjeldahl method, which implies the conversion of total nitrogen extracted using a nitrogen-to-protein conversion factor (Kp), the appropriate parameters (that varies according to insect species and type of product, whole insects or insect protein isolates) should be used instead of the more conventional Kp value of 6.25. Otherwise, an overestimation of 10-15% in the true CP content is made (Boulos *et al.*, 2020; Janssen *et al.*, 2017; Ritvanen *et al.*, 2020). In particular, a specific Kp of 4.76±0.09 was calculated for TM, AD and HI larvae, while, after protein extraction and purification, a Kp factor of 5.60±0.39 was found for the corresponding meals (Janssen *et al.*, 2017). Moreover, to proper formulate a feed and not to incur in nutritional deficiencies, analyses of amino acid (AA), FA, minerals and vitamins must be included as well. The gross energy content, easily determined by bomb calorimetry, is also a valuable parameter. However, according to the different animal species (poultry, pigs, aquaculture species), the determination of the digestible or the metabolise energy is always recommended.

Even if the insect producers deliver the product with the information on its composition, it would be advisable to always confirm it with own laboratory analyses.

3. Variability and processing methods

The insect meal form (full-fat or defatted) directly affects the level of inclusion in a feed formula, in particular in diets where a low amount of lipids is needed (i.e. poultry). From a nutritional point of view, the factors that influence the insect-based products composition, apart from the differences related to the insect species, are the rearing substrates and the production processes (Oonincx and Finke, 2021).

Concerning the impact of the rearing substrates, the insect fractions mainly affected are lipids, minerals and vitamins (Oonincx and Finke, 2021). Apart from the already mentioned ability of insects to accumulate n-3 FA from the rearing substrate, the available information about the impact of vitamins and minerals are quite limited, with variations in vitamin E and A, and calcium, iron zinc and manganese being mainly reported in HI (Oonincx and Finke, 2021). On the contrary, proteins, and in particular the AA profile, seem to be more linked to insect species (Hawkey *et al.*, 2021; Liland *et al.*, 2017; Proc *et al.*, 2020). However, some recent studies on HI have pointed out that the rearing substrate is able to modulate both the CP content (with values ranging between 35 and 49%) (Barragan-Fonseca *et al.*, 2017, 2021; Fuso *et al.*, 2021) and the AA profile (mainly lysine, valine and leucine (Fuso *et al.*, 2021)) as well. These findings open up to the possibility of manipulating the insect composition profile, in order to obtain derived products that are more suitable for feed production.

Insects can be processed in different ways. The most used by industry rely on devitalisation techniques (blanching, boiling, drying, cooling, freezing, freeze drying), mechanical processes (grinding, pressing, milling), and fractionation methods (extraction, purification, separation, centrifugation) (Mishyna *et al.*, 2021; Ojha *et al.*, 2021; Parniakov *et al.*, 2022; Ravi *et al.*, 2021). The different devitalisation techniques may significantly affect the nutrient quality parameters of HI larvae in terms of protein solubility, dispersibility, lipid class composition, degree of hydrolysis-protein hydrolysates, and antioxidant fractions (Ravi *et al.*, 2020), while the different fractionation methods (dry vs wet) display a greater influence on the nutrient content (different fractions with high yields in proteins, lipids and chitin) (Ravi *et al.*, 2021).

Even if recently there has been an increasing interest in the use of insects in animal feed, and research is very active, the insect sector is still in its early stages, particularly when compared to other feed commodities (FAO, 2021). Only few manufacturers of insect products have fixed their production processes, while the majority are still defining them. Therefore, even starting from the same batch, the resulting products can present huge differences in terms of composition. When supplying insect-based products from the same producer, random analyses of batches could be advisable. Moreover, low levels of inclusion in the feed formulation should allow reducing the impact of such variability. A future solution to avoid variability due to different suppliers could be to gather the different productions to deliver the feed industry with constant products.

4. Availability and consistency of supply

A crucial factor for the future practical incorporation of insect meals in animal feeds is the availability and consistency of the supply, which, in turn, is strictly related to the different rearing substrates used and processing methods adopted previously described.

To enter as 'constant' ingredient in animal feed, an ingredient must be available in adequate quantities. The definition of 'adequate quantities' is mainly related to the level of inclusion of the ingredient in the feed formulations, which, in turn, is linked to the different animal species to be fed. Aquaculture species, in particular carnivorous ones, require high levels of proteins (about 35 to 45%), and insect meals have been proven to appropriately sustain growth and animal heath up to levels of about 50% (Hua, 2021; Tran *et al.*, 2022; Weththasinghe *et al.*, 2022). On the contrary, terrestrial monogastrics require lower levels of proteins. Depending on the different feeding phases, poultry is fed CP levels from 16 to 24%, while pig diets include CP from 18 to 23%. In both species, levels up to 5-10% of insect meals have been reported to not impair productive performance or health status of the animals (Biasato *et al.*, 2018, 2019; Dabbou *et al.*, 2018; Dörper *et al.*, 2021; Moula and Detilleux, 2019; Veldkamp and Vernooij, 2021).

Considering the global feed production of 1.23 billion metric tonnes (Alltech, 2022), the inclusion of 5-10% of insect-based proteins into poultry, pig or aquafeed would require 43.6 to 87.1 million metric tonnes, which are levels far above the current insect production, estimated in Europe of about 10,000 tonnes. Even if the insect production capacity is expected to grow rapidly – reaching, only at European level, a volume of 1 million metric tons (IPIFF, 2021) – and, to this quantity, production from other region of the world can be added, the global volume is still low. For a feed manufacturer, the certainty of having a constant availability not only in terms of quantity, but also of quality, is a fundamental requirement for deciding to enter the market (and, therefore, to invest in marketing actions) with new feed containing insect-based products.

5. Nutrient digestibility

Apparent digestibility coefficient (ADC) of a nutrient refers to the extent to which the nutrient is digested by an animal. In particular, the ADC is a parameter of fundamental importance in animal nutrition, as it allows to properly formulate diets avoiding nutritional unbalances that could result to poor growth and welfare, as well as pollution issues due to excess of nutrients released in the environment (Abbasi *et al.*, 2019). There are internationally recognised protocols to assess the digestibility of an ingredient in fish (Bureau *et al.*, 1999), poultry (Ravindran *et al.*, 1999, 2017) and pigs (Zhang and Adeola, 2017). Even if several studies using insect-based products also assessed diet digestibility, data regarding the ADC of the single insect-based products are quite limited (fish: Basto *et al.*, 2020; Fontes *et al.*, 2019; Gasco *et al.*, 2022; Mo *et al.*, 2019; poultry: De Marco *et al.*, 2015; Mwaniki *et al.*, 2020; Schiavone *et al.*, 2017; pigs: Tan *et al.*, 2020). *In vitro* protocols have also been assessed (Kovitvadhi *et al.*, 2019; Rodríguez-Rodríguez *et al.*, 2022). Overall, the insect meals have been reported to display good to high nutrient digestibility in all monogastric animals, with ADCs for DM ranging from 61.7 to 95.8 in fish, 53.0 to 77.6 in poultry, and 78.8 to 95.9 in pigs, CP from 58.3 to 92.4, 51.0 to 84.8, and 77.3 to 89.6, respectively, and EE from 82.4 to 98.8, 88.0 to 99.0, and 78.0 to 89.8, respectively (Lee *et al.*, 2022).

Studies on the possibility of increasing the digestibility of insect meals using additives (mainly enzymes) are ongoing, and include both the enzymatic proteolysis of insect proteins during larval processing (Liceaga, 2021) and the addition of chitinases or proteases to the insect-based diets to increase ADC values (Bolton *et al.*, 2021). Processing methods involving the larvae (drying or defatting) or the insect-based diets (pelleting or extrusion) can also influence the nutrient ADC (Ottoboni *et al.*, 2018), and, due to the importance of these parameters, further research is highly recommended.

6. Anti-nutritional factors

Anti-nutritional factors (ANFs) are components present in raw materials that interfere with animal metabolism, digestion, and health. Depending on their nature, they can have different impacts such as reduced digestibility and growth, and gastrointestinal problems (Samtiya *et al.*, 2020). Ingredients used in animal nutrition may contain ANFs, and there are methods to deactivate them to reduce their negative effects (Saadi *et al.*, 2022). Do insects contain ANFs? The question is still open.

Meals from HI larvae have been reported to possess antiprotease activity; significant *in vitro* protease inhibition using intestinal homogenates from rainbow trout and tilapia was demonstrated to be related to larval age (Vandenberg *et al.*, 2018). Heating of the meals to temperatures typically employed during primary processing (i.e. scalding and/or drying) or during feed production (steam pelleting or extrusion) significantly reduces this antiprotease activity (Diarra, 2020), thus for typical animal feed applications, this ANF should not significantly impact nutrient digestibility. Recent work has demonstrated feeding live HI larvae to turkey poults (Veldkamp and van Niekerk, 2019) and older laying hens (Star *et al.*, 2020) altered animal behaviour of birds fed live larvae showing reduced aggression/feather pecking. In these studies, production performance was not negatively impacted, but live HI replacement was limited to 10% of the diet; higher inclusion levels may result in negative impacts on nutrient digestibility.

Insects contain chitin, which is a major component of their exoskeleton and helps in protecting their soft tissues. The chitin content depends on the insect species, the stage (larvae, nymph, pupae, adult) and the process applied. It is still questionable if chitin is a good or worse component for animal feed (Hawkey *et al.*, 2021). Some authors attributed the decrease in diet digestibility – and, when identified, retarded animal performance – after the administration of insect-based diets to the chitin (Biasato *et al.*, 2018; Caimi *et al.*, 2020; Dabbou *et al.*, 2018; Guerreiro *et al.*, 2021; Håkenåsen *et al.*, 2021). On the other hand, chitin has been reported to have immunostimulating, antimicrobial and/or anti-inflammatory properties, being also able to exert a prebiotic effect by selecting potentially positive bacteria the gut of monogastric animals (Gasco *et al.*, 2021)

Plants have different chemical defence mechanisms to protect themselves against surrounding environment, including ANFs. Phytate is an ANF that reduces the absorption of minerals by chelating them, and makes the addition of phytases to the animal feed (for poultry and pigs) necessary to decrease its negative effect (Walk and Rama Rao, 2020). Tannins are also ANFs present in grapes and other plants, which are able to bind and precipitate proteins. To our knowledge, only one paper reported these two ANFs in insects, likely accumulated from the rearing substrate (Ekop *et al.*, 2010). Levels assessed resulted in low and far below toxic levels in humans. It has to be said that, with the only exception of chitin, ANFs are compounds not usually investigated in insect-based products. Therefore, it would be advisable to perform analyses for these compounds as well. However, considering the recommended moderate inclusion levels of insect-based products in feed formulation (10-20%), the presence of ANFs should not represent a relevant issue.

7. Physical pellet properties

Another parameter that can influence the inclusion of insect-based products in feed is how they 'behave' during the pelletising or extrusion processes.

Indeed, even if for some livestock species (i.e. pigs or poultry) feed can be distributed in mash form, for others – especially aquaculture species – a pellet is compulsory. Furthermore, even in animal species where the pelletising process is not compulsory, there is a consensus on the fact that the distribution of feed in the form of pellets leads to better results in terms of animal growth and production parameters (Evans *et al.*, 2021; Jafarnejad *et al.*, 2011). Several reasons can explain this effect. Firstly, the feedstuff results to be more digestible due to the starch structure modification (gelatinisation) that occurs during the heating process (Samuelsen *et al.*, 2014). As a second aspect to consider, there is a decrease in feed spilling during feed consumption as the animal is not able to select the preferred ingredients (Amerah *et al.*, 2007). Finally, the high temperatures and pressures applied during the pelleting/extrusion process can inactivate some of the ANFs in (plant) raw materials such as protease inhibitors and lectins (Kumar *et al.*, 2022; Saadi *et al.*, 2022). Avoiding feed losses has also a positive economic and environmental impact.

The pelleting process consists of passing a mash of raw materials through holes in a metal dies plate (of a specific diameter) to produce compacted pellets. When aquaculture species are concerned, the most common procedure to produce feed is the extrusion process, which combines humidity and pressure. Pelleting/extrusion also enable to regulate the pellet floatability and, in turn, to produce pellets with different sinking speed adapted to the different fish feeding habits.

Even if an increasing number of publications supports the effectiveness of insect-based products in animal nutrition, only few researches investigated the impact of these innovative products on the physical and technological properties of feed (Alcaraz *et al.*, 2021; Irungu *et al.*, 2018; Rawski *et al.*, 2020). Irangu *et al.* (2018) showed how the interaction between the quantity of insect meal inclusion and the moisture level used during the extrusion process impacted pellet floatability, expansion rate and stability. Moreover, the viscosity effect that a full-fat meal confers to an extruder die can decrease pellet stability, thus resulting in nutrient loss (Rawski *et al.*, 2020). The extrusion process can also impact the final quality of the product. Indeed, Irungu *et al.* (2018) reported higher CP and nitrogen free extract, as well as lower ether extract and crude fibre contents, in extruded feeds when compared to the non-extruded ones. Recently, Mishya *et al.* (2021) demonstrated how processing treatments affect properties of insect proteins and insect-containing products, with repercussions on their techno-functional properties (solubility, foaming, emulsifying and gelling).

Therefore, when including insect-based products in a feed formulation, physical evaluation of the feed is necessary.

8. Palatability

Palatability affects feed ingestion. In particular, when aquafeeds are concerned, the increasing replacement of fish meal with plant proteins has led to palatability issues. Therefore, palatability enhancers (i.e. squid or krill meals) are often added to 'mask' unwanted tastes.

Even though insects, as part of the natural diets of fish and birds, seem to be well accepted, some palatability issues have been reported with high inclusion levels in fish. For example, a decrease in diet acceptability and feed intake with diets having more than 33% of HI meal inclusion has been reported by Kroeckel *et al.* (2012) in juvenile turbots. The lower feed intake induced a decrease in CP and energy intake, with an overall worsening in the performance parameters (Kroeckel *et al.*, 2012). However, literature is not consistent in this regard, and numerous reports have not demonstrated significant palatability issues even with high inclusion levels up to 40% (Renna *et al.*, 2017; Biasato *et al.*, 2022). Interestingly, Terry *et al.* (2021) even reported enhanced properties and increased feed acceptance when including insect-based products in shrimp diets. The authors investigated the inclusion of 1 and 2% of HI protein hydrolysate (when compared to a control diet without any enhancer and a diet having both the squid meal and the krill oil) and experienced an improved palatability of diets containing the insect-based products (Terry *et al.*, 2021).

It is, therefore, not clear if the above mentioned palatability issues were due to the level of inclusion or to some intrinsic characteristics of the meal used. Indeed, if not properly conducted, processing methodology can lead to the production of unpleasant flavours or Maillard reactions, which can, in turn, decrease the overall palatability of the feed (Kim *et al.*, 2016; Tran *et al.*, 2008). Moreover, it is important to recall that insects can uptake unpleasant flavours from the rearing substrate. Therefore, particular care has to be taken when processing the insect meal, and palatability trials are highly recommended.

9. Safety risks

Feed ingredients may contain compounds that may be considered as dangerous for animal consumption, such as heavy metals, dioxins, mycotoxins, veterinary drugs and pesticides. As already stated, the insect nutrient profile can be positively modulated through the rearing substrate, but insects are also able to accumulate undesired molecules if the substrates are contaminated (Meyer *et al.*, 2021). Transfer and accumulation of contaminants depend on many factors: the chemical, the insect species and life stage, the source of contaminants, and the rearing substrate conditions. In particular, insects are able to uptake heavy metals (lead, arsenic, mercury, and cadmium (Biancarosa *et al.*, 2018; Van der Fels-Klerx *et al.*, 2016), while mycotoxins and polycyclic aromatic hydrocarbons seem not to represent a relevant issue (Meyer *et al.*, 2021). Furthermore, mycotoxins and veterinary drugs could be degraded by insects, even if the involved metabolic routes are still not well known. More research is, therefore, warranted, as safety is a pre-requisite in the entire food chain.

It has to be said that, under EU regulations, insects reared for the production of feed, food or other products are considered as farmed animals (European Commission, 2009), and, as a consequence, they must be fed only with authorised raw materials (European Commission, 2022), respecting the limits of undesirable substances in animal feed (European Commission, 2002) and pesticides (EC, 2005). Taking into account that insects can act as bio accumulators, the same legislation also applies to the insect-based products to be included into a feed.

However, not all the countries have the same regulations. Therefore, as uptake of unwanted compounds could happen, hazard analyses on insect-based products should be compulsory.

10. Stability

Stability is an important parameter for all the feed ingredients. A raw material that is not stable due to high humidity or lipid levels could be prone to degradative processes such as fermentation, spoilage, mould development or oxidation during the storage. Considering the insect sector, it can be seen that the majority of producers delivers the market with defatted products, as the decrease in lipid levels is able to increase, in turn, the product stability, the protein level in the insect meal (with the possibility of selling the product at a higher price), and the possibility to include the insect meal at higher rates in animal diets (as high lipid levels are associated with high gross energy contents) (Hawkey *et al.*, 2021).

11. Cost

The feed represents the most significant operating cost in an animal farm. When formulating a feed, producers combine different feedstuffs to have a feed matching the animal requirements at the lowest cost. Changing the proportion of ingredients or including new raw materials could have a huge impact on farm profitability.

Due to low produced quantities and high production costs, the price of insect-based proteins is still high (2,500 and 5,500 €/t) and not competitive when compared to fishmeal (1,200-1,600 €/t) or soybean meal (450-700 €/t) (Mancuso *et al.*, 2019; Pippinato *et al.*, 2020). Global efforts are required to scale up production. According to recent projections, the price is expected to remain similar throughout the scale-up phase, before dropping by €1,000 per tonne, and by another €1000 per tonne, when the sector will reach its maturity (De Jong and Nikolik, 2021). Considering the dramatic increase of price faced in 2022, it is clear that any opportunity to optimise or reduce the feed costs should be carefully examined and capitalised.

However, the 'sustainability benefits' that insects can offer – such as the waste bioconversion, the decrease in dependency on less sustainable ingredients (fish meal, soybean meal), or the health benefits associated with the use of insect-based products (Gasco *et al.*, 2021) –, in combination with a proper marketing of the final product, can justify relatively high prices.

12. Impact on product quality

When using alternative ingredients, particular attention must be paid to their impact on the product quality. An ingredient can be nutritionally valid, being also able to guarantee optimal animal performance and no negative health issues, but it can confer to the final product unwanted colour, flavour, or odour, thus resulting in a rejection by the consumer. However, in the case of the insect-based products, the choice of the proper inclusion levels in animal diets efficiently minimises such risks. Indeed, no significant influence on product quality traits has been highlighted when low inclusion levels of insect meal (i.e. 10-20%) in the animal diets are considered (Renna *et al.*, 2017; Schiavone *et al.*, 2019; Yu *et al.*, 2019). On the contrary, increasing inclusion levels have been associated to detrimental effects on the FA profile (increase in SFA and MUFA at the expense of the n-3 PUFA) (Renna *et al.*, 2017; Schiavone *et al.*, 2019).

13. Legislation

The recent authorisation of insect-derived processed animal proteins in poultry and pig nutrition opened the market for insect-based products (Commission Regulation 2021/1372; EC, 2021) – which, since September 2021, can be legally used across the EU in pet animals, fish, poultry and pigs. However, as already mentioned before, the EU legislation imposes general obligations and/or restrictions applying to insect producers, such as registration or approval of their activities before national competent authorities, compliance with hygiene standards at the different stages of production, and allowance of raw materials authorised for farmed animals as rearing substrates for insects (IPIFF, 2020). However, the latter aspect is one of the most critical factors that has prevented the insect sector to scale-up so far. Indeed, the adoption of new by-products as rearing substrates (i.e. former foodstuffs containing meat and fish, and catering waste) will play a key role in enhancing the circularity of insect production, helping European insect farms to reach their full potential (IPIFF, 2019).

14. Conclusions

Insect meals hold much promise as novel and sustainable feed ingredients for livestock, aquaculture and companion animals. Despite numerous advantages of insect meals over traditional feed ingredients, in terms of fulfilling nutrient requirements, many challenges remain. Despite a large number of large-scale players entering the market, a large supply of consistent quality product remains a major issue for the animal feed industry. Continued efforts to upscale production will increase product availability and quality/consistency and reduce costs. Expanding authorisations for raw materials as rearing substrates will promote the circularity of insects as animal feed ingredients. The present review aimed to resume all the essential aspects that cannot be excluded when an insect meal is included in a feed formula. Moreover, in literature, different research gaps were highlighted, and for this reason, future research will be needed to have a clear framework to maximise the use of these sustainable proteins.

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Conflict of interest

The authors declare no conflict of interest.

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