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REVIEW

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Effects of alternative feed ingredients on red meat quality: a review of algae, insects, agro-industrial by-products and former food products

Luciano Pinotti[a,b], Sharon Mazzoleni[a], Andrea Moradei[a], Peng Lin[a] and Alice Luciano[a]

[a]Dipartimento di Medicina Veterinaria e Scienze Animali (DIVAS), Università degli Studi di Milano, Lodi, Italy; [b]CRC I-WE (Coordinating Research Centre: Innovation for Well-Being and Environment), Università degli Studi di Milano, Milan, Italy

ABSTRACT

Following the promotion of animal welfare awareness, modern meat production should be applied ethically and sustainably. Alternative circular feeds such as algae, insects, agro-industrial by-products (AIBPs) and former food products (FFPs) play a key role to re-define the current meat production system. This review highlights the effects of feed ingredients mentioned above on red meat quality, from a blue-bio/circular economy point of view. The results show that when algae are added in adequate amounts, they can improve nutritional and sensory quality of meat. Insects, and AIBPs, can affect meat quality mainly in terms of selected components like fat content and quality, while the effects of FFPs as feed ingredients on meat quality are still limited. These alternative feedingstuffs are regarded as interesting protein/energy sources for animal diets and are expected to be increasingly used globally as a replacement for conventional feedstuffs. The inclusion level of insects, AIBPs and FFPs is often higher than that of algae, because algae are considered more as feed supplements instead of ingredients that mainly provide macronutrients to the animals. However, more research is needed for a comprehensive evaluation of these materials, especially in terms of: (i) feed formulation and processing methods (inclusion level of such materials and technology used for feed production); (ii) their potential impacts on animal growth and health status and on environmental footprint; (iii) carcass quality; and (iv) final meat product quality, safety and wholesomeness.

HIGHLIGHTS

- Algae, insects, agro-industrial by-products (AIBPs) and former food products (FFPs) can affect meat quality.
- The inclusion level of insects and FFPs is often higher than algae, while that of AIBPs could be variable.
- These materials can affect meat quality mainly in terms of selected components like fat content and quality.
- These feed materials have been linked to improved sustainability, feed/food circularity and consumer perception.

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Introduction

The rapid-growing global population and the increased income will double the overall demand for animal products by 2050 (FAO 2007). Such a rise in demand will be particularly critical for livestock agriculture (FAO 2011). In this scenario, there is a lot of discussion about two major feeds, namely corn and soy food crops, in terms of their sustainability in animal diets, which is closely linked to the issues of land use, water footprint, climate change and food-feed competition (Madeira et al. 2017; Govoni et al. 2021). Thus, seeking alternative feed ingredients is of interest to address the challenges in livestock production system. Importantly, while improving sustainability of produced red meat by using alternative feed ingredients, their impacts on meat quality should be taken into account as well. The present review will discuss some selected alternative feed ingredients and their implications on red meat quality.

Meat quality is a complex topic (Hartung et al. 2009). The FAO (1990) defined quality meat as one of the most important aspects in animal production and health, and is critical for the meat industry. Generally, meat quality is based on a combination of chemical

CONTACT Luciano Pinotti luciano.pinotti@unimi.it

characteristics and sensory perceptions, which determine the suitability of meat for human consumption. From a consumer's perspective, some of these parameters are objective and extrinsic, and others are subjective and intrinsic (Joo et al. 2013). The extrinsic parameters refer to those that cannot immediately be detected by physical or sensory examination of the meat itself, but which are associated with the way that the meat is produced. These parameters focus more on animal welfare, nutritional values and ecological sustainability of the production systems (Salami et al. 2019; Beauchemin et al. 2022). On the other hand, the intrinsic parameters that associated with sensory perception such as appearance, colour, flavour, texture, tenderness, juiciness and aroma are the most important factors used to judge meat quality (Joo et al. 2013; Liu et al. 2022) and largely influence consumer's purchase decision (Purslow 2022). Meat colour is affected by the level of myoglobin in muscle fibre and its oxidative state (Miller 2002). Depending on different cultural background, meat colour is judged diversely but is always associated with freshness. The 'freshness' and 'wholesomeness' of meat refer to the perception that meat is safe for human consumption and free from pathogens, parasites, infectious agents and toxins (Purslow 2017). Meat tenderness and juiciness are a result of the muscle structural integrity and the ability of muscle proteins to bind water (Guerrero et al. 2013).

Meat is fundamentally defined by the composition of muscle such as lean, fat and connective tissues (Costa, Cardoso, et al. 2021). Fat can be deposited intramuscularly as marbling, intermuscularly as seam fat, or externally as subcutaneous fat. Particularly, intramuscular fat (IMF) content has been shown to affect flavour, marbling, tenderness, juiciness and visual characteristics of meat. Although a higher fat content is related to an increased palatability, the acceptable range is considered to be between 3 and 7.3% (Miller 2002; Vasta et al. 2008). Moreover, too much visible fat in meat products is not appreciated by consumers due to health concerns and negative association to increased risk of cardiovascular disease, obesity and cancer (Miller 2002). Still, the optimal marbling level of meat depends on cultural tradition and individual preference (Ngapo et al. 2007; Font-i-Furnols et al. 2013; Cheng et al. 2015).

In order for animals to produce superior quality meat, nutrition obviously plays a fundamental role. Thus, the role of nutrition in meat quality has been extensively studied in different species (Jiang and Xiong 2016). Several studies have described the effects of providing alternative feed ingredients to animals on fat content, fatty acid (FA) composition and other quality parameters (Resconi et al. 2009; Eiras et al. 2014). In general, as the energy density of the diet increases, the growth rate of animals also increases. Animals may thus reach the slaughter weight at a younger age, and the carcass may be heavier and greater in overall fatness and marbling (Vestergaard et al. 2000; Greenwood and Bell 2019). The increased marbling or IMF content will then render the increased juiciness and tenderness as well as enhanced species-specific flavour due to different combinations and amounts of FAs (Sami et al. 2004; Arshad et al. 2018). On the other hand, when ruminants are fed on forage, they tend to have slower growth rate. Thus, the animals may be slaughtered later, yielding carcass with less fat and leaner meat, which is nevertheless considered as a positive attribute for human diet and health-conscious consumers (Sami et al. 2004; Dunne et al. 2009). Additionally, forage-fed ruminants can retain β-carotene and lutein derived from the grass, resulting in more yellow fat (Moloney et al. 2022). However, some forage contains compounds such as diterpenoids and hexanals that can be stored in the fat tissue and are commonly associated with meat off-flavours (Elmore et al. 2004; Calkins and Hodgen 2007; Miller 2020). The animal's diet can therefore negatively or positively affect meat quality.

Consumer criticism on meat production has resulted in the introduction of quality standards, codes of practice, and certification programs aiming at ensuring safe and good-quality animal products based on ethically acceptable production practices (Webb and Webb 2022). Today, ethical animal production emphasises that modern meat production should ideally occur without causing suffering to the animals (Webb and Webb 2022). Since animal-friendly and sustainably produced meat have been well-accepted by consumers (Alonso et al. 2020; Edenbrandt and Lagerkvist 2021), such transformation in production system could drift individual decisions in purchasing and consuming meat with improved attribute linked to the production system (e.g. environmentally sustainable).

Most of these qualitative characteristics can be grouped in five main domains (Figure 1), namely:

1. *Nutritional quality*: Protein and fat content, FA profile, mineral content, etc.
2. *Safety*: Microbiological status, drug residues, heavy metal, etc.
3. *Technological quality*: Shear force, blood spots, pH values, drip loss, fat content, water content, connective tissue content, etc.

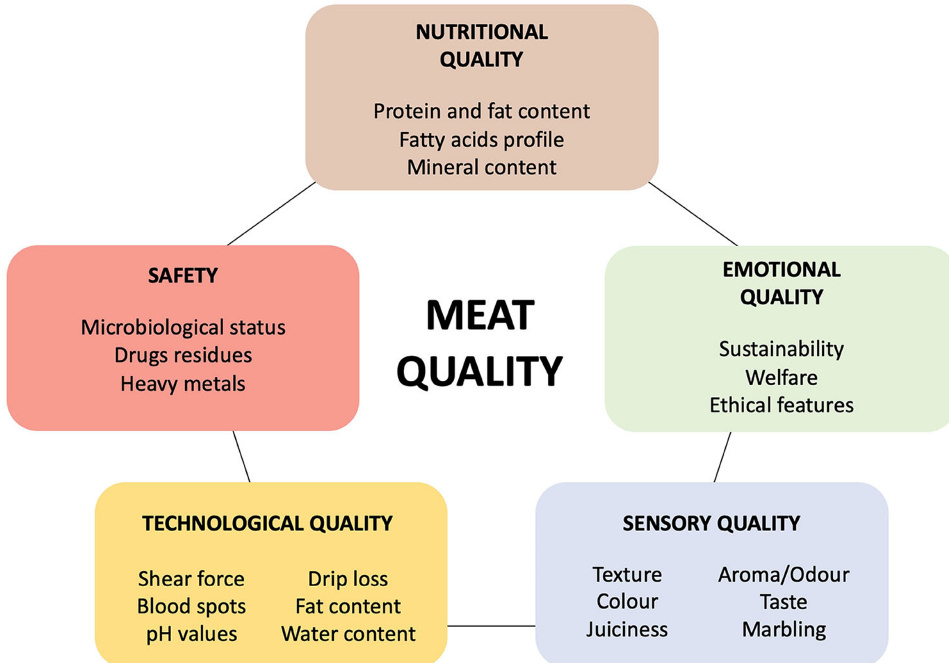

Figure 1. Meat quality parameters: five main domains.

4. *Sensory quality*: Texture, colour, juiciness, aroma/odour, taste, marbling, etc.
5. *Emotional quality*: Sustainability, welfare and ethical features.

The aim of the present review is to discuss the effects of alternative feed ingredients such as algae, insects, agro-industrial by-products (AIBPs) and former food products (FFPs) on red meat quality attributes.

Algae used in livestock animals and their effects on red meat quality

Algae are part of the blue bio-economy, which is the most unexplored treasures of the oceans and fresh waters. Being aquatic photosynthetic living organisms, they are classified into two main categories known as macroalgae/seaweed and microalgae/cyanobacteria. Macroalgae are multicellular whereas microalgae are unicellular and filamentous (Dineshbabu et al. 2019). Both of them can perform ecosystem functions, from carbon sequestration to water phytoremediation and environmental remediation. Additionally, algae have several advantages over terrestrial biomass including high efficiency in capturing solar energy, high crop productivity, no requirements for arable land or industrial fertilisation, and potential cultivation in saltwater (Taelman et al. 2015; Øverland et al. 2019). These features allow algae to alleviate the stress of intensive land use for food and feed crop cultivation and to increase the sustainability in meat production.

Macroalgae are classified into *Phaeophyceae* (brown algae), *Rhodophyceae* (red algae) and *Chlorophyceae* (green algae). Their nutrient contents vary widely among taxonomic groups, species, geographical location, season and temperature. In livestock production, the most common macroalga genera used as feedstuff or feed supplements are: *Ascophyllum*, *Laminaria* and *Undaria* (brown algae); *Ulva*, *Codium* and *Cladophora* (green algae) and *Pyropia*, *Chondrus* and *Palmaria* (red algae) (Costa, Gionbelli, et al. 2021).

Brown seaweed generally shows a highly variable composition but is characterised by a low protein (7.6–12.6% dry matter–DM) and fat content (0.8–6% DM). Red seaweed contains a higher protein content (16.9% DM) and fat content (8.9% DM) than brown seaweed (Corino et al. 2019). Although seaweeds contain lower concentrations of protein (11.6% DM), and therefore, amino acids, than those of traditional feed protein sources such as soybean meal and fishmeal (48.0 and 68.7% DM, respectively), their protein quality is still high when considering the ratio of total essential amino acids to total amino acids (Angell, Angell, et al. 2016; Angell, Mata, et al. 2016). Such ratio of macroalgae can reach 45.7 and those of traditional protein sources range from 43.4 to 46.0. For instance, the ratio of methionine and cystine to total amino acids in *Macrocystis pyrifera* and *Ulva* species is higher than those of soybean protein (Makkar et al. 2016). Nevertheless, when expressed as a percentage of the whole biomass on a DM basis, most essential amino acids in seaweeds are not comparable to those in soybean and fish proteins. Microalgae contain 12–65% DM protein, 2–23% DM lipid and 4.6–26% DM carbohydrate depending on species and growing condition (Becker 2013). They are also a source of polysaccharides, vitamins, essential amino acids, unsaturated FAs (monounsaturated FAs, MUFAs, n-3 and n-6 polyunsaturated FAs, PUFAs), bioactive compounds and pigments (e.g. carotenoids) (Geada et al. 2021). Currently, the most common microalgae in livestock diets are *Arthrospira platensis*, *Chlorella vulgaris* and *Schizochytrium* (Madeira et al. 2017). Although research has demonstrated that including algae in animal diets could improve meat quality in ruminants and pigs, these findings are highly dependent on the composition of the algae itself and the percentage included in the diet (Madeira et al. 2017; Costa, Gionbelli, et al. 2021).

Table 1 summarises the literature on the effects of selected microalgae and macroalgae on quality traits and nutritional values of beef, lamb, goat and pork.

Ruminants

In ruminants, the benefits of algae are associated to their n-3 PUFA contents, minerals and vitamins, although some effects observed regarding immunity and health may also be related to sulphated polysaccharides, phlorotannins, diterpenes and minor bioactive components (Morais et al. 2020).

In studies on steers and heifers, *Ascophyllum nodosum* was included in a grain-based diet at 2% DM at different feeding stages for 14 days (Anderson et al. 2006) or 29 days (Braden et al. 2007). The results showed that *A. nodosum* supplementation can increase meat marbling scores and tenderness as well as decrease off-flavour without detrimental effects on cattle performance. Accordingly, the authors suggested that 2% *A. nodosum* supplementation can improve overall quality, carcass traits and prolong retail shelf life, which represent an alternative strategy for overcoming the negative carcass characteristics traditionally observed in implanted feedlot cattle. Regarding the use of brown algae in small ruminants, adding 2% *A. nodosum* as top dressing to the basal diet of Arabic lambs for 10 weeks resulted in heavier carcass weight and larger eye muscle area but decreased abdominal fat (Tavasoli et al. 2009). Different results were found in a previous study where carcass weight, dressing proportion, grade rule fat and conformation scores were not affected by 2% *A. nodosum* administration for one week. The differences in carcass traits between the two studies may be explained by the duration of supplementation. However, the one-week administration did reduce the duration and intensity of *E. coli* O157:H7 faecal shedding by lambs, which can minimise the risk of carcass contamination and improve the safety quality of meat (Bach et al. 2008). Similarly, 2% *A. nodosum* extract supplementation for 2 weeks prior to slaughter was suggested to be a feasible strategy of *E. coli* decontamination in goat processing thanks to the antibacterial activity of phlorotannins from brown seaweed (Kannan et al. 2019). Furthermore, prolonged supplementation period (8 weeks) has been shown to increase colour stability of goat loin/rib chops by slowing down metmyoglobin accumulation that causes browning (Galipalli et al. 2004). In another study, 2% macroalga *Undaria pinnatifida* fed to Hanwoo steers for six months, twice per day, significantly reduced cholesterol concentration and PUFA/SFA ratio, which improved the FA profile of adipose tissue (Hwang et al. 2014). While not directly influencing intrinsic meat quality parameters, *in vitro* studies have demonstrated that *U. pinnatifida* has a great potential to enhance feed conversion efficiency in ruminants by stimulating rumen microbial growth and therefore VFA production (Choi et al. 2020). Additionally, its extract can suppress enteric methane production up to 48 h incubation by reducing the abundance of ciliate protozoa (Choi et al. 2021). These results suggested that *U. pinnatifida* could be used in ruminant diets to improve extrinsic and emotional meat quality.

As reported by Kinley et al. (2020), including red alga *Asparagopsis taxiformis* in steer's diet at 0.10% and 0.20% of feed organic matter significantly inhibited methane production (38% and 98%, respectively) without changing meat quality grading nor sensory evaluations such as juiciness, tenderness, flavour, consumer satisfaction and overall liking of the meat. Accordingly, effects of higher inclusion level of *A. taxiformis* on beef cattle and meat quality have been explored in more recent studies. Diets enriched with a low-dose (0.25% OM) or high-dose (0.50% OM) supplementation of *A. taxiformis* fed to steers for 21 weeks showed that meat derived from animals fed a high dosage was darker with higher microbial counts, which could lead to a shortened shelf life. The results suggested that a 0.50% OM inclusion of *A. taxiformis* did impair the microbial and the physicochemical characteristics of beef steaks during retail display while a lower dose did not (Bolkenov et al. 2021). With the same dose and experimental duration as described in Bolkenov et al. (2021), reduced enteric methane emissions from steers was observed but no alterations in carcass

Table 1. Effects of micro- and macroalgae on nutritional, sensory, technological, emotional quality of meat and its safety.

Algae	Meat type	Nutritional quality	Sensory quality	Technological quality	Safety	Emotional quality	References
Ascophyllum nodosum	Beef	N/A	+++	+++	N/A	+	Anderson et al. (2006)
	Beef	N/A	=	+++	+	N/A	Braden et al. (2007)
	Lamb	N/A	N/A	=	++	+	Bach et al. (2008)
	Lamb	N/A	N/A	+	N/A	N/A	Tavasoli et al. (2009)
	Goat	N/A	++	N/A	N/A	N/A	Galipalli et al. (2004)
	Goat	N/A	N/A	N/A	++	+	Kannan et al. (2019)
Undaria pinnatifida	Beef	+++	N/A	N/A	N/A	N/A	Hwang et al. (2014)
	Beef	N/A	N/A	N/A	N/A	++	Choi et al. (2021)
Asparagopsis taxiformis	Beef	=	–	=	=	N/A	Bolkenov et al. (2021)
	Beef	N/A	=	=	N/A	++	Kinley et al. (2020)
	Beef	=	=	=	N/A	++	Roque et al. (2021)
Schizochytrium	Lamb	+++	N/A	=	N/A	+	Hopkins et al. (2014), Meale et al. (2014), Ponnampalam et al. (2016) and Díaz et al. (2017)
	Pork	+++	N/A	=	N/A	N/A	Sardi et al. (2006) and Vossen et al. (2017)
	Pork	+++	=	+	N/A	N/A	
	Pork	+++	– –	– –	N/A	N/A	Jon Meadus et al. (2011)
Arthrospira platensis	Pork	=	–	+++	N/A	N/A	Šimkus et al. (2013)
	Pork	+++	– –	=	N/A	N/A	Altmann et al. (2019)
Chlorella vulgaris	Pork	+++	+++	=	N/A	+++	Coelho et al. (2020)
	Pork	+++	+++	+++	N/A	N/A	Martins et al. (2021)

The scale used to summarise the data is: (+) positively affects; (+++) affects very positively; (–) negatively affects; affect (– –) affects rather/quite negatively; (=) no effects; N/A: not available.

chemical composition, overall meat quality and sensory properties were found (Roque et al. 2021).

Diets enriched with 1.92% of microalga *Schizochytrium* (Hopkins et al. 2014; Díaz et al. 2017) fed to lambs for 6 weeks, or 3% for 18 weeks (Meale et al. 2014) and 1.8% for 20 weeks (Ponnampalam et al. 2016), improved meat quality by decreasing the n-6/n-3 ratio. Similarly, lambs fed a diet supplemented with 2, 4 or 6% DM of *Schizochytrium* for 77 days showed an improvement in EPA, DHA and n-3 PUFA concentrations and a reduced n-6/n-3 ratio and meat cholesterol. However, a high dose (6% DM) increased the lipid oxidation in the meat (de Lima Valença et al. 2021). These results thus suggest that algae can be used in meat-producing ruminants as natural 'feed additive'. By altering the intramuscular marbling as well as extending the shelf-life, they could prove a viable alternative to current industry supplementation strategies focusing on similar outcomes. The mode of action of algae is not fully clear. However, antioxidants and specific vitamins may be involved, especially when improved meat colour stability and extended shelf-life are observed. The proposed inclusion levels are limited and they are dependent on different management factors (rearing systems, feeding regimes, etc.) as well as the type of algae used.

Pigs

Although algae in pigs have mainly been investigated as a booster for the immune system, antioxidant status and gut health (Corino et al. 2019), studies focusing on meat quality found their major effects on fat quality. As with most marine fat sources, algae are able to increase PUFA levels in pork, which represents nutritional benefits to consumers.

A long-term microalgae *Schizochytrium* supplementation (7% as-fed in a weaning diet and 5% as-fed in a finishing diet) in pigs starting from grower period showed elevated essential n-3 PUFA concentrations such as EPA and DHA in skeleton muscle. The only effects on carcass and meat quality were increased protein proportion and water holding capacity (Kalbe et al. 2019). These changes could be associated with the additional n-3 PUFAs provided by microalgae as evidence suggests that n-3 PUFAs allow muscle cells to build a flexible lipid bilayer membrane for water retention (Jiang et al. 2017) and that DHA can stimulate muscle protein synthesis in grower pigs (Wei et al. 2013). Improved n-3 PUFA contents and n-6/n-3 ratio in fresh pork can also be observed when *Schizochytrium* was supplemented to pigs merely during finisher period and even with lower microalgae inclusion level (Sardi et al. 2006; Jon Meadus et al. 2011; Vossen et al. 2017). Following these results, Vossen et al. (2017) further assessed the quality of dry cured hams originating from algae fed pigs. The proportion of EPA and DHA was enriched while instrumental texture and TBARS values were inferior, which means that the ham was softer and prone to rancid aroma. However, the adverse effects of n-3 PUFAs on sensory quality of ham were not noticed by the consumer panel. Another species of green microalgae, *Chlorella vulgaris*, also demonstrated their positive effects on meat FA composition.

Feeding diets containing 5% *Chlorella vulgaris* to weaning or finishing pigs remarkably enhanced the proportion of EPA, DHA and total n-3 PUFA in muscle and decreased the n-6/n-3 ratio (Coelho et al. 2020; Martins et al. 2021). Furthermore, increased muscle total carotenoid content was observed, which confirmed the transfer of carotenoids from microalgae to meat as they corresponded strongly with diet composition (Coelho et al. 2020). Since carcass and meat characteristics as well as sensory panel scores were not affected by the microalgae-included diets, such pork with added nutritional benefits could successfully attract market attention.

Besides the positive influences of algae supplementation mentioned previously, some unfavoured effects were also reported. Providing 2 g fresh blue algae *Spirulina platensis* biomass with forage daily to fattening pigs caused a reduction in IMF content. However, parameters related to IMF such as tenderness and water holding capacity were comparable to the control diet (Šimkus et al. 2013). A stronger astringent aftertaste has been reported in pork from pigs fed microalga Spirulina (*Arthrospira platensis*), which could be unpleasant for consumers (Altmann et al. 2019). However, as the tested samples were frozen until sensory analysis, panel evaluation with fresh samples may lead to different results.

Taken together, supplementation of brown macroalgae *A. nodosum* up to 2% DM and microalga *Schizochytrium* up to 4% DM can be effective in improving carcass and meat quality in ruminants. In pigs, the most promising option to enhance healthiness of pork, especially the beneficial n-3 PUFA contents, would be a dietary *Schizochytrium* inclusion up to 7% as-fed. However, there are potential constraints in producing and feeding algae to farm animals. For instance, the bioaccumulation of heavy metals such as aluminium, arsenic, cadmium, lead and mercury in algal biomass (Lerat et al. 2018), seasonal variability in nutritional profile of macroalgae (Kulshreshtha et al. 2020), and high cost in large-scale production system (Costa, Gionbelli, et al. 2021). Hence, it is necessary to improve the current technology in algae cultivation, harvest and processing, to optimise supplementation level in an algae and animal species specific manner while considering the variabilities in nutrient contents in algae, and to monitor the accumulation of unwanted substances.

Insects used in livestock animals and their effects on red meat quality

Insects have been proposed as a high quality, efficient and sustainable alternative protein source for domestic animals. One exception in the Europe Union is using insect protein in ruminant feed, which is prohibited due to the modification of the Catalogue of Feed Materials (Reg. EU 2017/1017; EU 2017). Although insects do not express prion proteins, if reared on contaminated substrates, they risk absorbing prion and releasing it into the insect meal (van der Spiegel et al. 2013). Differently, insect fats are allowed to be used in ruminant feeding (Reg. EU 2017/893; EU 2017). Apart from ruminants, the European Commission loosened the 'feed ban' in 2021 by allowing the use of insects in poultry and swine farming (Reg. EU 2021/1925; EU 2021). Currently, insects are used in feed in different forms. Depending on the processing methods, insect meal can be classified into products with different protein and fat contents, namely (nutrient contents are expressed on a DM basis): full fat meal that contains 40–70% of crude proteins and 20–70% of fat (Oonincx and Finke 2021); partly defatted meal and defatted meal that contain about 55% of crude proteins and less than 12% of fat (Gasco et al. 2022). Although other forms (e.g. protein isolate usually defatted) can be found, these two are the most common for feed grade.

So far, two insect species seem to be the most promising owing to their greater growth rate and potential positive effects on domestic animals, which are black soldier fly (BSF, *Hermetia illucens*) and mealworm (MW, *Tenebrio molitor*). Below, the composition of these two species is reported on a DM basis:

- Black soldier fly larvae (BSFL): 41.1% crude protein, 35.5% crude lipids, 4.8–6.7% chitin and 11.7% ash (Pinotti et al. 2019; Weththasinghe et al. 2021; Lu et al. 2022).
- MW: 34.5% crude protein, 46.6% crude lipids, 5% chitin and 3.2% ash (Ruschioni et al. 2020; Wu et al. 2020).

Studies on swine fed BSFL confirm that this alternative feed ingredient could potentially improve carcass weight and lead to a different FA profile (Yu et al. 2019; Chia et al. 2021).

As reported by Yu et al. (2019), when soybean meal was substituted with BSFL full-fat meal in finishing pig's diet, a 4% as-fed inclusion level led to an increase in loin eye area, fat-free lean index, IMF content, marbling scores and inosine monophosphate content in *longissimus thoracis* muscle. The increased IMF is associated with an increased marbling score, both of which can improve juiciness and flavour of cooked meat. In addition, a greater inosine monophosphate content was found to enhance the umami flavour of pork (Jung et al. 2013). On the other hand, when increasing BSFL inclusion level to 8%, there were limited positive effects observed on meat quality. This is assumed to be related to the higher chitin content from BSFL diet, which is non-digestible for pigs. The inclusion of BSFL also resulted in an increased proportion of EPA and DHA in pork (Yu et al. 2019), which could be interesting for health-conscious consumers. However, the exact mechanism of modification in the FA profile is unclear yet. These results suggest that incorporating 4% BSFL in pig diets is feasible to partially replace soybean meal and may positively affect meat sensory quality. A similar conclusion was reported by Zhu et al. (2022). When pigs fed on diets where fish meal and soybean meal were substituted with BSFL full-fat meal (4% and 8% as-fed) for 16 weeks, *longissimus thoracis* muscle colour and pH did not change, while drip loss and IMF were improved in pork from BSFL fed pigs. The modification in drip loss and fat deposition might be influenced by the muscle fibre characteristics and expression level of lipogenic genes. However, whether the lipogenic gene expression was up or down-regulated was not consistent between studies (Yu et al. 2019; Zhu et al. 2022). Effects of higher replacement level of fish meal with BSFL full-fat meal in finishing pigs have been explored by Chia et al. (2021). From 9 up to 14% as-fed BSFL dietary inclusion resulted in heavier carcass weight and pork tissues with higher crude fat content. These findings can be attributed to the higher energy and crude protein contents in the BSFL-included diets, especially for growing pigs in which full fat BSFL has been proposed as a better source of net energy.

In addition to the nutritional values of meat, consumers are also pursuing sensory and eating quality. An animal trial on growing-finishing pigs conducted by Altmann et al. (2019) revealed that pigs offered diet containing partially defatted BSFL meal produced pork with stronger overall odour and significantly higher juiciness, which is likely to influence consumer preference in a positive way. The increased juiciness could be linked to the lower cooking losses and the higher IMF content, although these values were only numerically different from the control group. Of note, there was a fivefold higher level of lauric acid (C12:0) found in backfat, suggesting the potential of using lauric acid as a biomarker to distinguish pork produced from pigs fed a diet containing BSFL.

Regarding MW, there are very few studies available in swine nutrition. This could be due to the large number of larvae needed for performing experiments (Hong et al. 2020). Moreover, no papers in relation to pork quality were found but the impacts of MW inclusion on pig growth and metabolism have been studied.

The number of studies conducted on the use of the BSFL and MW in pig diets is insufficient to provide a detailed assessment of their effects on meat quality and composition. However, almost no adverse effects have been observed in carcass and meat quality. One exception is the high content of lauric acid, on which consumers may exert doubts since it is still unclear what role lauric acid plays in cholesterol synthesis (Dayrit 2015).

To carefully balance feed containing insect meal is important so as to avoid negative effects caused by incorporating excessive level of insects (Dicke 2018). For instance, chitin from insects can interfere with protein utilisation and inhibit nutrient absorption in the intestinal tract (Marono et al. 2015; Lee et al. 2022), which might further lead to slower growth of animals. Nevertheless, the effects of insect materials on the performance or the pig meat quality are affected by several elements including the study design, nutritional values of the insects in use and their inclusion level as well as the final diet formulation (Veldkamp and Vernooij 2021). It is important to highlight that various growing substrates can influence the body composition of insects (Pinotti and Ottoboni 2021), which concerns the safety issues (Grisendi et al. 2022). These factors limit the use of certain materials in rearing insects for nutritional purposes. One solution could be designing selected substrates for insects by combining poor materials and other authorised biomass so as to enable the upgrade of surplus materials into valuable feed ingredients. This approach can raise consumer awareness about circularity in livestock production and acceptance of new and sustainable feedstuffs (Pinotti et al. 2021). The feed industry however has a limited tolerance in the variability of the composition of feed ingredients. Thus, seeking innovative substrates that can guarantee a better insect performance and a more homogeneous meal composition is required. The latter can be achieved by formulating different materials in an appropriate ratio and maintaining specific environmental conditions such as high temperature and controlled humidity for successful insect growth (van Huis 2021).

Today, the price of insect meal is still high and variable. Considering insects as alternative protein sources for livestock and developing their use are nevertheless of interest (Gasco et al. 2020), especially as a soybean alternative. Although the use of insects has been investigated in many farmed species, their actual use is still limited. Hence, to provide a comprehensive estimation of their future potential, more studies are required.

Table 2 summarises the literature regarding the effects of insects on quality traits and nutritional values of pork.

Agro-industrial by-products used in livestock animals and their effects on red meat quality

AIBPs include a broad category of various biomass from vegetables to fruits products (Reguengo et al. 2022). They are increasingly being used in animal feeding regime thanks to their interesting nutritional characteristics, potential biological effects and the huge amount generated from the agro-food industry. Additionally, AIBPs could reduce feed costs and meet the need to recycle waste materials since waste disposal can be more expensive (Vasta et al. 2008). AIBPs can be obtained from the production of oil, sugar, fruit juice, canned or frozen vegetables, root and tuber (Rakita et al. 2021; Vastolo et al. 2022). Although in the literature there is a vast range of numbers and types of AIBPs, in the present paper, we decided to focus on just five of them that have been more studied. We therefore considered: citrus pulp (Caparra et al. 2007), olive cake (Luciano et al. 2013; Joven et al. 2014; Chiofalo et al. 2020), apple pomace (Fang et al. 2016; Alarcon-Rojo et al. 2019), grape pomace (Zhao et al. 2018; Flores et al. 2020; Flores et al. 2021; Alfaia et al. 2022; Tian et al. 2023) and tomato pomace (Valenti et al. 2018; Biondi et al. 2020), which have been successfully used as feed ingredients or supplements in livestock diets.

Citrus pulp includes peel, the inside fractions of the fruits, and seeds, representing 50–65% of the whole fruit. It is characterised by a high level of fibre that are mainly soluble (Watanabe et al. 2010). Due to the high content of fermentable carbohydrates, citrus pulp is considered nutritious. On the other hand, the content, digestibility and biological value of protein in citrus pulp are relatively low (Caparra et al. 2007). Citrus pulp can be used in animal diets fresh but just for a limited period of time coinciding with the citrus fruit season. If not, they can be used after ensilage or dehydration (Caparra et al. 2007).

In Mediterranean areas, the olive oil industry produces substantial amounts of by-products, with one of the most important being olive cake. Olive cakes represent a valuable and cheap fibre and energy source owing to their high level of oil content (18–25%) and high level of oleic acid (Chiofalo et al. 2020). The use of olive cakes is more studied in ruminants since this material has high lignin content and is rich in bioactive substances such as phenolic compounds (Joven et al. 2014). However, olive cakes may have negative effects on ruminal organic matter digestibility due to their high lignin content (Chiofalo et al. 2020). Nevertheless, such an issue can be ameliorated by removing the presence of seeds. Furthermore, recent extraction technologies have improved the product quality, which now contains more antioxidants such as tocopherols, retinol and bioactive phenols (Chiofalo et al. 2020).

Grape and olive pomace are derived from wine and oil production, whereas other fruit by-products (e.g. apples, pears, peaches and citrus fruits) are derived from juice, jelly and jam industries (Vastolo et al. 2022). These different types of pomaces can be a valuable source of bioactive components such as polyphenols and tannins (Fang et al. 2016). Generally, apple, grape and tomato pomace are rich in crude fibre (18–50%, 43–60%, 33–57% DM, respectively). However, the protein content is low in apple and grape pomace (3–11% and 8–14% DM), but relatively high in tomato pomace (18–22% DM) (Skinner et al. 2018). In general, apple, grape and tomato pomaces contain phenolic compounds, for example, anthocyanins. Such richness in bioactive components enable fruit pomace to have high antioxidant and inflammatory functions (Biondi et al. 2020).

Table 3 summarises the literature on the effects of selected AIBPs on quality traits and nutritional values of meat from ruminants and monogastric.

Ruminants

Caparra et al. (2007) studied the effects of substituting cereal grain with different levels of solar-dried citrus pulp (30 and 45% as-fed) in the concentrate mixtures

Table 2. Effects of insects on nutritional, sensory, technological, emotional quality of meat and its safety.

Insect	Meat type	Nutritional quality	Sensory quality	Technological quality	Safety	Emotional quality	References
Hermetia illucens	Pork	+	+++/=	=/+	+++	+++	Yu et al. (2019), Zhu et al. (2022), Altmann et al. (2019), Lee et al. (2022) and Chia et al. (2021)
Tenebrio molitor	Pork	N/A	N/A	N/A	+++	+++	Lee et al. (2022)

The scale used to summarise the data is: (+) positively affects; (+++) affects very positively; (−) negatively affects; (=) no effects; N/A: not available.

Table 3. Effects of different Agro-industrial by-products on nutritional, sensory, technological, emotional quality of meat and its safety.

AIBPs	Meat type	Nutritional quality	Sensory quality	Technological quality	Safety	Emotional quality	References
Citrus pulp	Lambs	=	−am	+/=	N/A	+++	Caparra et al. (2007)
Olive cake	Lambs	+	N/A	=/+	N/A	N/A	Luciano et al. (2013)
	Beef	=/+	=/+	+/−	N/A	N/A	Chiofalo et al. (2020)
	Pork	=	−	=	N/A	N/A	Joven et al. (2014)
Apple pomace	Lambs	+	=/+	=/+	N/A	N/A	Alarcon-Rojo et al. (2019)
	Pork	−	=	−−−	N/A	N/A	Fang et al. (2016)
Grape pomace	Lambs	+/=	+/=	+	N/A	N/A	Flores et al. (2021) and Zhao et al. (2018)
	Pork	+++	=	+++	N/A	+	Tian et al. (2023)
Tomato pomace	Lambs	+/=	+/=	N/A	N/A	N/A	Valenti et al. (2018)
	Pork	+	=	N/A	N/A	+	Biondi et al. (2020)

The scale used to summarise the data is: (+) positively affects; (+++) affects very positively; (−) negatively affects; (−−−) affects very negatively; (=) no effects; N/A: not available.

for fattening lambs on growth performance and carcass and meat quality. With an inclusion level of 30%, no adverse effects on growth and slaughter performance were noted. The carcass conformation, protein and fat content, colour, chemical and physical characteristics were not affected by the dietary treatment, either. However, with a 45% inclusion level of citrus pulp, negative effects were found in relation to feed conversion efficacy, carcass weight, dressing percentage and carcass compactness (Caparra et al. 2007). According to Bueno et al. (2002), this might be associated to the reduced intestinal absorption of Ca, P and Mg, which could further cause metabolic disorders in a long term. Hence, the author (Caparra et al. 2007) concluded that a higher inclusion level of citrus pulp in lamb's diet was not recommended nor economically favoured.

Different inclusion levels of olive cake (7.5 and 15% DM) for young growing-fattening bulls have been tested. Chiofalo et al. (2020) showed that the olive cake inclusion increased the body weight, average daily gain, slaughter traits and IMF content. However, the surface meat discolouration increased sequentially following the increasing olive cake inclusion level in the diet, which can be partially explained by the higher IMF content. Despite this, the values of meat redness and colour vividness were still higher than the threshold accepted by consumers visually. In addition, a reduction in cooking loss and shear force was observed in beef from bulls fed olive cake. This finding was linked to the increased IMF and oleic acid content, suggesting a more tender beef with higher palatability (Mwangi et al. 2019).

In the cases of small ruminants, Luciano et al. (2013) conducted a study in which 35% as-fed olive cake were included in the concentrate for lambs. There were no treatment effects found regarding animal growth, carcass yield and IMF content. However, in meat from lambs fed olive cake, extended oxidative stability was observed, which could be related to the increased concentration of vitamin E in muscle that plays a role as antioxidant (Servili et al. 2009).

The effects of including fruit pomace in lamb's diet on lamb meat quality traits have been reported by recent studies (Valenti et al. 2018; Zhao et al. 2018; Alarcon-Rojo et al. 2019; Flores et al. 2021). The inclusion of 11% DM fermented apple pomace resulted in reduced lipid oxidation of loin after storage at 4 °C, reflecting the antioxidative potential of fermented apple pomace and meat products with longer shelf life. At the same time, other meat quality traits such as colour, water holding capacity and tenderness retained unchanged (Alarcon-Rojo et al. 2019). When using grape pomace silage (25%, 37.5% and 50% DM, respectively) to substitute whole plant corn silage for lamb feeding, no effects on proximate composition in lamb meat were significant, except that the lipid and cholesterol levels increased in accordance with the increasing inclusion levels. This result could be associated to the great amount of PUFA in grape seeds (Guerra-Rivas et al. 2016). However, the sensory evaluation did not reveal any differences among different treatment groups (Flores et al. 2021). Another study with wine grape pomace found that 10% DM inclusion in lamb's diet led to meat with lower shear force, which was assumed to be a result of decreased collagen deposition (Zhao et al. 2018). In fact, evidence has been shown that the content of profibrogenic cytokine that promotes collagen synthesis was reduced in rats provided grapes (Seymour et al. 2010). Therefore, a dietary grape pomace supplementation is likely to modify tenderness of meat. Additionally, grape pomace can enhance muscle antioxidative enzyme activity and capacity thanks to its proanthocyanidin content (Bagchi et al. 1997). As a consequence, a reduction in oxidative stress in muscle was observed. When growing lambs were offered dried tomato pomace ad libitum, they consumed less commercial concentrate but maintained their growth performance. Meat quality parameters were not affected by the administration of tomato pomace except that a tendency of increased PUFA content in meat was found (Valenti et al. 2018). This was likely related to a higher intake of PUFAs from the tomato pomace, which can affect rumen bacteria metabolism and rumen biohydrogenation. The shift in the biohydrogenation pathways can further influence the accumulation of FAs in meat (Aldai et al. 2013). Nevertheless, the slightly increased meat PUFA content did not compromise the oxidative stability of lipids (Valenti et al. 2018).

Although the exact mechanism of actions of these AIBPs on ruminants and the resulting meat quality is not clear, some possible hypotheses are listed. The above mentioned AIBPs: (i) generally contain a great amount of antioxidant components (e.g. polyphenolic compounds and vitamin E) that can modulate the metabolism of nutrients and relieve oxidative stress when fed to ruminants; (ii) modulate the growth and activity of microbes involved in the rumen bio-hydrogenation of FAs (Vasta et al. 2019; Vinyard et al. 2021), which can increase the absorption and transfer of PUFA into meat at the expense of SFA. Once again, the effects of inclusion levels as well as possible additive effects with basal diets cannot be excluded. Utilising AIBPs in ruminant nutrition could allow the valorisation of local agricultural biomass and may also improve profitability for farmers.

Pigs

Most of AIBPs used in ruminants have also been evaluated in pig. Joven et al. (2014) evaluated the effects of incorporating olive cake as replacement of barley in the diet of finishing pigs. When 10% as-fed olive cake was provided, increased carcass weight, longer carcass length and wider ham perimeter were observed. In fact, these three parameters are correlated (Latorre et al. 2003) and such features of ham is preferred by Mediterranean consumers as they are recognised as high quality. However, in other regions, shorter carcasses are commercially preferred due to easier manipulation and processing (Joven et al. 2014).

Integrating fruit pomace in finishing pig's diet has been shown to alter the FA composition of pork (Fang et al. 2016; Biondi et al. 2020). The level of PUFA was increased in the backfat of pigs fed fresh apple pomace (Fang et al. 2016) and of those offered tomato pomace (Biondi et al. 2020), which could be resulted from the FA profile and amount of feed ingested (Pascual et al. 2007). When replacing wheat bran with dried grape pomace in feed for finishing pigs, the phenolic compounds in grape pomace can enhance pig's antioxidant enzyme system, which could further improve meat antioxidant capacity and make pork less susceptible to lipid peroxidation (Jin et al. 2021; Tian et al. 2023). Additionally, meat juiciness was found to be greater in group fed grape pomace (Tian et al. 2023). Consequently, these findings can contribute to meet consumer's expectation on high-quality pork.

The inclusion of AIBPs in feed can have several effects on meat quality. Meat colour, FA composition, tenderness and juiciness can be affected in different ways depending on the AIBPs used. Furthermore, a recent study suggested that bioactive compounds, such as hydrolysable tannins, derived from AIBPs can potentially reduce bacteria-mediated skatole and indole production in the colon, resulting in lower tissue levels of these two boar taint compounds in the adipose tissue of pigs (Tretola et al. 2019). However, cautions have to be paid to the compositional and nutritional variability of AIBPs due to different processing methods and materials used during feed production. Preservation treatments in AIBPs are also essential for product stabilisation and for compensating seasonal availability. Through preservation treatments, increasing shelf-life of AIBPs is achievable, particularly for those with high moisture and lipids contents.

Former food products used in livestock animals and their effects on red meat quality

FFPs are another alternative feed ingredients composed of processed and ready-to-eat food products (e.g. salty products such as bread, pasta and salty snacks and sugary products such as chocolate, biscuits and breakfast cereals), which are no longer suitable for human consumption due to logistical, manufacturing or packaging defects (Giromini et al. 2017; Tretola, Di Rosa, et al. 2017; Tretola, Ottoboni, et al. 2017; Luciano et al. 2020). The European Commission has published guidelines in the European Catalogue of Feed Materials, reporting that FFPs are suitable for feeding animals and serve as a key deliverable of the EU Circular Economy Action Plan on food waste (Reg. EU 2018/851; EU 2018; Pinotti et al. 2021).

Despite the authorisation of FFPs, their use in animal nutrition is still limited (Pinotti et al. 2021). This suggests that the collaboration among food processors, recycling sectors and feed producers needs to be strengthened and promoting their use to farmers is necessary. The nutrient composition of FFPs is comparable to cereals commonly used in animal nutrition except their higher and more saturated fat contents. From a circular economy point of view, it is possible to reduce food losses by reintroducing FFPs into feed sectors, especially those targeting at pigs, poultry and young animals as FFPs contain high amount of easily digestible carbohydrates (Luciano et al. 2020).

Luciano et al. (2022) investigated the partial replacement of standard ingredients with two types of FFPs (salty and sugary) and their effects on the FA profile of subcutaneous adipose tissue in post-weaning pigs. The results indicated that despite some differences in compound feed, piglets were able to rebalance the dietary FA profile (Luciano et al. 2022). The main differences were observed in the proportion of MUFA and PUFA in the adipose tissue. Fat from pigs offered FFPs-based diet had larger proportion of MUFA but smaller proportion of PUFA, which could be explained by the lack of PUFA in both salty and sugary FFPs. The impacts of including two types of FFPs in pig's diet has been further explored by a recent study (Mazzoleni et al. unpublished data). Feeding growing-finishing pigs salty and sugary FFPs led to no major changes in meat quality traits. However, salty FFPs did modify the sensory quality of pork by increasing sweetness and tenderness, which could be associated with the alterations in amino acid profile.

Regarding ruminants, Grossi et al. (2022) reported the effects of a partial substitution of corn and soybean meal with FFPs obtained from bakery industry on environmental sustainability, production performance and health status of beef cattle. None of the performance parameters nor the overall health status were affected by the FFPs inclusion. This thus highlighted that using bakery FFPs as partial substitution of classic feedstuffs did not have detrimental effects on productivity or welfare. The carcass characteristics in terms of fatness score, conformation, pH and colour index maintained comparable qualities as those from cattle fed on control diet. Noticeably, the inclusion of bakery FFPs helped improve environmental footprint of beef production by reducing greenhouse gases emission, water consumption and land use for feed crop production. These results can positively influence emotional quality of meat and create opportunities for beef produced in this way to be sold as premium meat.

Conclusions

Considerable advances have been made in understanding the potential of alternative, innovative and also circular feed ingredients. This review highlights that when added in adequate and proper amounts, these products could positively affect meat quality attributes, especially in terms of the nutritional, sensory and emotional quality. Furthermore, feed materials addressed in the present review are not only classical examples of circular food system, but also a new paradigm in livestock production that can contribute to the meat supply chain by using materials unsuitable for human consumption. This approach might affect the consumer perception of meat quality and its sustainability in the modern society. The current review has discussed just a part of the potential alternative feed ingredients that are under investigation by nutritionist. In conclusion, algae provide sources of essential PUFAs; insects represent a great source of protein and fat, AIBPs are featured by their bioactive components with antioxidative effects; and FFPs are comparable to cereal grains. The utilisation of these materials will certainly strengthen the sustainability in animal production system and thus the emotional quality of meat produced. Based on the results obtained so far, it can be expected that in the near future, other alternative materials for feeding farm animals are going to be keenly explored.

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ORCID

Luciano Pinotti http://orcid.org/0000-0003-0337-9426

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and available on motivated request. The authors report there are no competing interests to declare.

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