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Review: Quality of animal-source foods

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ABSTRACT

This article critically reviews the current state of knowledge on the quality of animal-source foods according to animal production and food processing conditions, including consumer expectations-behaviours and the effects of consumption of animal-source foods on human health. Quality has been defined through seven core attributes: safety, commercial, sensory, nutritional, technological, convenience, and image. Image covers ethical, cultural and environmental dimensions associated with the origin of the food and the way it is produced and processed. This framework enabled to highlight the priorities given to the different quality attributes. It also helped to identify potential antagonisms and synergies among quality attributes, between production and processing stages, and among stakeholders. Primacy is essentially given to commercial quality attributes, especially for standard commodity animal-source foods. This primacy has strongly influenced genetic selection and farming practices in all livestock commodity chains and enabled substantial quantitative gains, although at the expense of other quality traits. Focal issues are the destructuration of chicken muscle that compromises sensory, nutritional and image quality attributes, and the fate of males in the egg and dairy sectors, which have heavily specialised their animals. Quality can be gained but can also be lost throughout the farm-to-fork continuum. Our review highlights critical factors and periods throughout animal production and food processing routes, such as on-farm practices, notably animal feeding, preslaughter and slaughter phases, food processing techniques, and food formulation. It also reveals on-farm and processing factors that create antagonisms among quality attributes, such as the castration of male pigs, the substitution of marine-source feed by plant-based feed in fish, and the use of sodium nitrite in meat processing. These antagonisms require scientific data to identify trade-offs among quality attributes and/or solutions to help overcome these tensions. However, there are also food products that value synergies between quality attributes and between production and processing phases, particularly Geographical Indications, such as for cheese and dry-cured ham. Human epidemiological studies have found associations between consumption of animal-source foods and increased or decreased risk for chronic non-communicable diseases. These associations have informed public health recommendations. However, they have not yet

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considered animal production and food processing conditions. A concerted and collaborative effort is needed from scientists working in animal science, food process engineering, consumer science, human nutrition and epidemiology in order to address this research gap. Avenues for research and main options for policy action are discussed.

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Implications

A group of scientists from complementary disciplines analysed the quality of animal-source foods according to animal production and food processing conditions. Quality has been approached in its various dimensions, by jointly characterizing safety, commercial, sensory, nutritional, technological, convenience and image attributes. The role of the various factors influencing the quality of animal-source foods was characterised at each step from production to consumption. The framework of joint analysis of the various quality attributes made it possible to single out the factors that induce synergies or antagonisms among attributes. This expert evidence-based analysis identified avenues for research and options for policy action.

Introduction

Per-capita consumption of animal products is high in higher-income nations, and global demand continues to grow. This consumption of animal-source foods in the mainstream Western-pattern diet has come under fire on several fronts: (*i*) its environmental impacts (pollution, resource use, erosion of biodiversity), (*ii*) human health, as high intakes of red and processed meat have been associated with increased risk for some chronic non-communicable diseases, and (*iii*) food ethics, with mounting consumer concern around animal welfare and production, transport and slaughter conditions. Both the World Health Organization and the Food and Agriculture Organization of the United Nations (**FAO**) recommend reducing the share of animal products in human diet, for health and environmental protection reasons. *Santé Publique France*—the French national public health agency—updated its official nutritional guidelines for adults in 2019, adding new recommendations for red and processed meat. It also recommended re-balancing plant- and animal-protein sources in diet, whereas the average diet in France and Western Europe contains around 65–70% animal proteins (Billen et al., 2018). EU countries are progressively introducing pro-protein programmes designed to shift animal feed towards locally sourced protein-rich plant-based feed commodities, while also providing opportunities to develop plant-based protein foods. These changes are in line with the European Green Deal and are promoted by the European Commission in its Farm-to-Fork Strategy (EU, 2020).

However, these challenges are set to play out in a sector marked by a mosaic of production and processing models, each of which has major effects on the core quality attributes of food products. This review analyses how the quality of animal-source foods is constructed and mediated by farming system conditions and food processing routes. It considers the various core quality traits of animal-source foods, i.e. attributes that give foods the ability to satisfy the stated or implicit needs of a user (International Organization for Standardization (**ISO**), 9001), along with their effects on human health. The animal-source foods considered include meat from monogastrics (pigs and poultry), ruminants (cattle, sheep), farmed fish, milk (from cows, goats and sheep), eggs from hens, and their associated processed products—whether 'standard' commodity foods or quality-labelled products. The purpose of food processing routes is to stabilise the food products as safe and proper for consumption to extend shelf life, valorise cuts that are less attractive and/or less in demand (using braising cuts in ground beef patties, using pork cuts in pâtés, ready-made meals, etc.), diversify the market offer, and propose easy-to-cook, easy-to-store, or even tasty ready-to-eat foods. Curing, cooking, drying, smoking and fermentation are the processes most frequently used to confer microbiological and shelf life stability, and they typically make use of salt and food additives, which have greatly increased in number since the industrialisation intensification of agrifood processing.

We also review the available science on the way consumer behaviours intersect with the quality of animal-source foods. Humans are omnivores, and this status gives eaters freedom and flexibility to adapt to various biotopes, but also exposes them to the risk of potentially life-threatening contamination, leading them to eat foods that feature in their cultural foodways. Consumers thus swing between enjoyment and apprehension as they forge their food choices, and diets are deeply culturally rooted (Danezis et al., 2016). The risks surrounding foods therefore cannot be fully assessed and evaluated through over-simplistic food safety dimensions. The authentication of on-farm practices and food processing conditions offers a route to re-assure consumers. Consumer demands, commodity chains committed to quality labels, complexity throughout the production and processing chain, and risk of fraud, all together add importance to authentication issues, as shown by the surging number of papers reporting research on this topic (Danezis et al., 2016). This review pinpoints out the gaps that research needs to address and the avenues and opportunities for policy action.

A pluridisciplinary scientific assessment

This paper summarises the main lessons learned from a collective scientific assessment carried out by the French National Research Intitute for Agriculture, Food and Environment (**INRAE**), at the request of the French Ministry of Agriculture and FranceAgriMer, a public agency dedicated to trends and challenges in agriculture (Prache et al., 2020a). Twenty public-sector scientists investigated the different factors affecting the quality of animal-source foods, the impact of their consumption on health, and the regulatory instruments that could bring transitions to improve the diet. The expert group included specialists in cattle, sheep, pig, poultry and fish farming, food processing, economics, sociology, law, human nutrition, toxicology, epidemiology, and microbiological and chemical food safety. This pluridisciplinary approach was adopted in order to get a wide-angle view of the question. The expert assessment was based on a broad analysis of the scientific literature, and used input from around 3 500 papers to write the global report. Most of these papers were primary articles, but the human health chapter was mainly based on reviews and meta-analyses.

The framework encompassed all stages from farm to fork. There was abundant scientific literature on the factors that shape the quality of raw animal products. These factors start with the characteristics of the animals (sometimes even before the animal's birth), then move through on-farm conditions, transport, slaughter, processing, storage, marketing, and ultimately to culinary practices.

There are more data on the quality of raw products than processed foods due to the huge variety of processed products and the fact that the many recipes used are generally protected by trade secret. Few studies cover the entire chain from farm to fork. Here, we studied food quality *via* a broad multicriteria approach, which is rarely reported in review papers. Food quality was broken down into seven dimensions: safety, commercial, sensory, nutritional, technological, convenience and image (Fig. 1). This original approach enabled to pinpoint the priorities that different stakeholders give to different quality attributes and it helped to identify the antagonisms and synergies among quality attributes.

Rapid shifts in consumption levels, diet patterns and societal expectations

Consumption figures across Europe show that meat, fish, eggs and dairy have now reached a plateau or are in decline, except for poultry meat (Fig. 2). Consumers are moving away from beef and sheep meat (which have both fallen more than 40% in Europe over the past 30 years) and mainly towards poultry meat, which has grown by 60% over the same period. Pork remains the main meat consumed in Europe, with average consumption level reaching 35 kg carcass weight equivalent per person per year. Consumption practices in France are undergoing two parallel—and at first glance paradoxical—shifts. On one hand, demand is rising for ready-to-cook and ready-to-eat meals, and on the other hand, growth is surging in organic foods, even though the certified organic segment still accounts for only 5% of food market share in France (and close to 6% in Germany, the highest rate in the EU) (Agence Bio, 2020). Both these dynamics concern all the meat, fish, eggs and dairy commodity chains, albeit to varying degrees. The trajectory of change in food consumption between 2006–2007 and 2014–2015 observed in French national-scale surveys showed a 40% increase in meat and fish-based ready meals and a 53% increase in foods containing meat and fish 'ingredients' (pizzas, quiches, sandwiches) (Pointereau, 2019). For example, the share of purchases of ready-to-eat chicken products like nuggets and breaded tenders has doubled in 20 years and now accounts for 31% of poultry meat, whereas purchases of whole chicken have more than halved (from 52% down to 24% today) (Baéza et al., 2021). However, consumers are starting to voice concern over these ultra-processed products (Taillie et al., 2020), citing a growing separation - both geographical and technological-processing - distance (Bérard and Marchenay, 1995) between the raw food material and the final end-product. This distance creates the feeling of losing control over how food is produced, and prompts fears over food safety. In parallel, the rising demand for meat, fish, eggs and dairy produced under official signs identifying quality and origin, including organic and/or short food supply chains, is a reassuring countertrend (Bricas et al., 2013). In fact, these products offer dependable and credible credentials regarding the product's origin and production and processing conditions, despite being more expensive as a rule than 'standard' conventional products. We are also witnessing a Europe-wide move towards more plant foods and less animal foods, with momentum driven by the vegetarianism, veganism and animal welfare movements (Lund et al., 2016; FranceAgriMer, 2019). There is no precise definition (with quantified characteristics) of diets dubbed 'flexitarian', which counts diets that encompass variable reductions in meat-based products, but the fact that they have attracted so much press is a sign of a dietary transition towards more plant-based diets.

These fast-paced trends drive a need to better anticipate consumer needs and motivations and to provide food farming practices and processing routes with appropriate and sometimes even disruptive solutions (Table 1). For example, debate around eating animal-source foods has prompted research on the sources and social acceptability of alternative proteins, such as plant-based foods or other more radical alternatives (Hartmann and Siegrist, 2017). Prospective research on foods that are not yet on the market or only as 'exceptional situations', such as cultured 'meat', or not yet part of our food–feed culture, such as insect foods, shows that (*i*) meat from farmed livestock remains the cornerstone of our food ways (Graça et al., 2015) and (*ii*) new disruptive foods either have to 'look like meat' (such as plant-based meat analogues; Kyriakopoulou et al., 2019) and address their 'unnaturalness' (Bryant and Barnett, 2018) or else totally take the animal origin out of the equation, such as protein bars (Hartmann et al., 2015). To eat meat or not is a social marker (Fourat and Lepiller, 2017). Among the wealthier and educated higher-socioeconomic-status

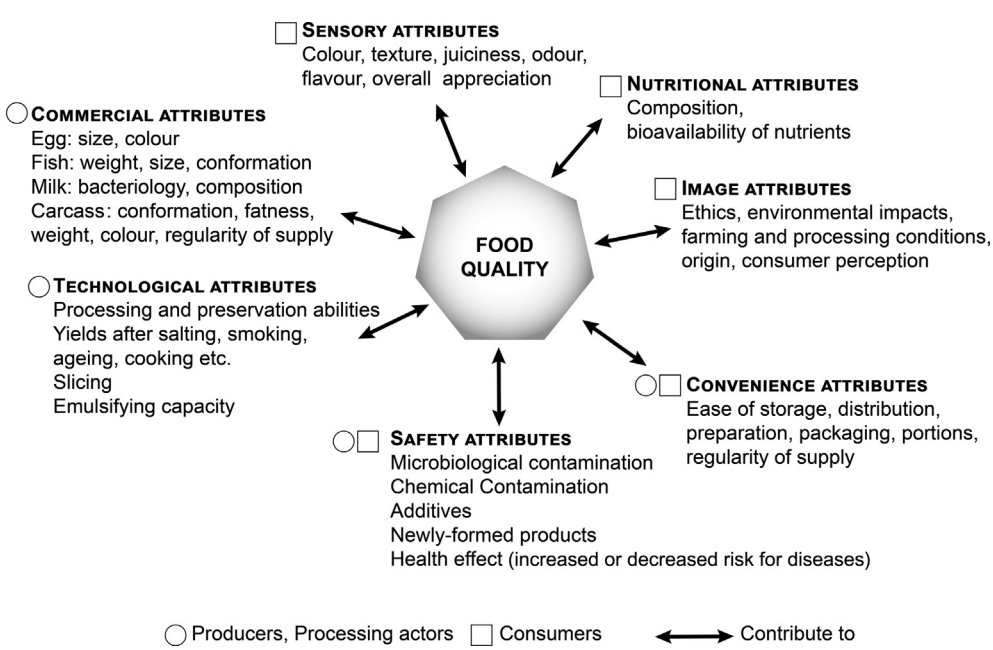

Fig. 1. The seven quality attributes of animal-source foods.

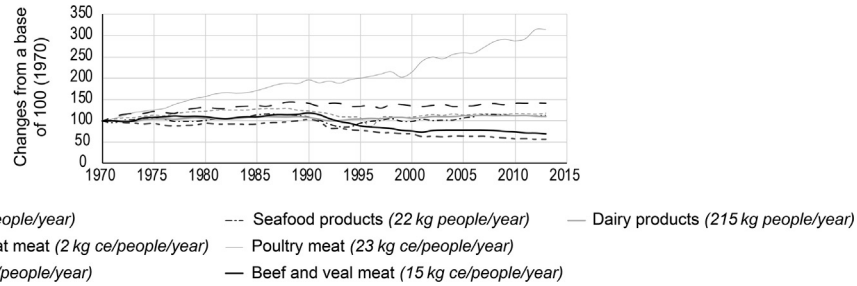

Fig. 2. Trends in the consumption of animal-source foods between 1970 and 2013, in kg/person/year (base 100 = 1970). Sea products = fish and seafood; dairy products = milk, for drinking and processed (excluding butter); data on meat are expressed in kilograms of carcass weight equivalent (kg ce). *Source:* Ourworldindata.org.

classes, the value of meat has been reshaped by issues tied to ethics, environmental impacts and human health, which explains why these consumer segments are eating less but better meat (Clonan et al., 2016). Other theories have emerged to explain the motivations driving the recent reduction of meat consumption (Leroy, 2018). In contrast, lower-socioeconomic-status populations are eating more meat through a range of affordably cheap foods but of lower nutritional quality. Note, here, that taxing meat, which is sometimes advocated as a policy tool to reduce meat consumption and mitigate its environmental impacts, would therefore hit these populations harder (Springmann et al., 2018). Research on the adoption of meat alternatives is therefore needed in order to understand the barriers and drivers of food substitutions in different populations, the factors prompting the adoption of alternatives at individual level (life path), and the pathways for transitioning from one diet to another (whether or not we take the meat analogue path, for example).

Core quality attributes and methods for assessing them

The safety attributes of an animal-source food are tied to the hazards associated with its consumption (such as pathogenic micro-organisms, chemical residues, environmental contaminants, toxins, neo-formed compounds during processing). These attributes are prerequisite conditions due to the perishability of animal-source foods and the risks associated with shelf life expiration, and they are therefore governed by specific regulations (Guillier et al., 2016). Whatever the type of food, the operators that produce, process and distribute it are legally responsible for its safety and hygiene, so they have a duty to analyse and control the risks by implementing control measures (Koutsoumanis and Aspridou, 2016). While raw-ingredient composition is relatively well profiled, there is only guarded or fragmented scientific scholarship on compounds that form through subsequent processing routes and on efforts to assess the associated risks (toxicity, compound–compound interactions).

The commercial attributes of an animal-source food are the basis on which producers get paid and a lead concern for professional livestock-sector operations. Commercial attributes depend on the kind of product. For milk, beyond the volume delivered, they are based on food hygiene indicators and compositional criteria. For the other animal products (meat, fish, eggs), they are grounded, in Europe, in weight and appearance criteria, and in some cases, batch homogeneity. Currently, beef, sheep and pork carcasses in Europe are priced based on weight and classification under the standardised EUROP grading system based on conformation and fatness for beef and sheep and on lean content for pigs. Qualified agents still often visually grade beef and sheep carcasses for conformation and fatness, which carries a degree of value-judgement subjectivity, whereas for decades, pork carcasses are graded using objective (and increasingly automated) classification methods. Other grading systems are used for beef outside Europe, notably USA, Japan and Australia (Polkinghorne and Thompson, 2010). Unlike the European carcass-based system, these systems incorporate meat quality criteria (colour, marbling). Furthermore, the Meat Standards Australia is based on a model that predicts eating quality for each muscle-cooking method combination from a dozen parameters, most of which are measured at the slaughterhouse, and it indexes the payment to farmers based on this eating quality outcome (Bonny et al., 2018).

The sensory attributes of animal-source foods reflect characteristics perceived through experience via the senses, typically appearance (colour), texture (tenderness, juiciness), and flavour (odour and flavour). Sensory attributes are crucial to consumers and affect the purchase and re-purchase decisions at retail. Efforts to evaluate sensory attributes struggle with several issues. First, methodological challenges, with ongoing debate around the use of trained sensory panels or untrained ('naive') consumers, as consumer scores do not always match trained-panellist ratings (Hocquette et al., 2020). Second, the complexity inherent to determining texture, odour and flavour can undermine the reliability of indicators (Aberle et al., 2012). Thirdly, the lack of robust quality-predictive methods that can be used on-slaughter-line (Berri et al., 2019). Finally, variability in preferences between regions/countries and between consumers, which is tied to different cultural practices or foodways (Sañudo et al., 2007; Font-i-Furnols and Guerrero, 2014) makes it unreliable to extrapolate results from one geographical area to another.

The nutritional attributes of animal-source foods are evaluated on the basis of their nutrient composition (proteins, lipids, carbohydrates, vitamins, minerals) and their ability to cover humans' nutritional needs. For proteins and lipids, some amino acids and fatty acids (**FAs**) (linoleic acid, alpha-linolenic acid and docosahexaenoic acid) are considered as indispensable, as they cannot be synthesised by the human body or in insufficient quantity, and so they must be provided by the diet. The nutritional quality of a dietary protein is assessed by its ability to cover all the indispensable amino acid requirements. If ingested in excess, some nutrients can have adverse effects on health, such as atherogenic saturated FA (**SFA**), for which an upper limit has been set. Foods that are rich in indispensable nutrients in proportion to their energy density and that contain only modest amounts of nutrients to limit (like SFA, sodium and carbohydrates) can positively impact human health. Nutritional indicators like the front-of-pack Nutri-Score nutrition label displayed on prepackaged food (Julia et al., 2017) have been developed in France to rank foods according to their compositional balance of nutrients to aim for and nutrients to limit. The bioavailability of component nutrients is also a significant factor to consider, as well as the food matrix effect, because a nutrient can have different biological effects depending on its environment in the food (Thorning et al., 2017, Astrup et al., 2020). The criteria for assessing nutritional attributes are

Table 1
Research needs and public policy options.

	Lessons from the scientific expertise	Public policy options	Research needs
Consumers	Rising consumer expectations on farming and processing conditions, and need for (re) assurances Rapidly changing consumer diet patterns and consumer expectations	Information campaigns, labelling Scanning for weak signals and strategic foresight on shifts in consumption of animal-sourced foods	Anticipate changes in consumer diet patterns and demands Create innovative solutions Develop labelling tools Study new practices/preferences (such as eating less animal-sourced foods and more substitutes) and their consequences
	Loss of culinary knowledge in favour of ready-to-eat foods	Step up broad-audience education (on nutritional quality, seasonality, etc.)	Assess culinary practices and promote participative action research to identify the needs of consumers
Health	Current knowledge does not permit food production and processing conditions to be taken into account with regard to health effects		Better understand the links between health and food production and processing conditions, including ultra-processing
	Some food classifications are used to support nutritional recommendations, labelling and digital technologies. However, they are still being debated in the scientific community.	Control/accompany the development of digital applications for food choices	Refine methodologies and classifications, by taking into account the food production process routes
Production and processing	Commercial attributes take precedence over the other core quality traits: quantity produced outweighs all other dimensions, especially for standard commodity products	Endorse collective initiatives to get the whole farm-to-fork community to better internalise the various dimensions of product quality Support the development of quality signs and respect for animal welfare Support the transition of farming systems towards the production of quality animal-sourced foods	Better internalise the various dimensions of quality—for consumer information, for payments to farmers, and for genetic selection Support pathways for transitioning livestock systems/practices towards better-quality animal-sourced foods
	Lack of information and research on the fate of animals that are of low value, given the current business models	Support stakeholders in the change to production systems that make better use of animals that do not fit into current commercial production models, thus keeping as many animals as possible in the food chain (quality signs/seals/labels and/or short food supply chains)	Develop innovative solutions to improve the value of animals of both sexes, and to extend the productive life of females
	Lack of meta-analysis on the quantification of the effects of production and processing conditions on food quality		Perform meta-analyses to gain more robust quantitative evaluations of the effects of the different determinant factors of food quality
	Importance of the preslaughter and slaughter stages on meat and flesh quality	Minimise stress by a better coverage of the territory by slaughter-facilities	Evaluate the risks (for process hygiene and animal welfare) associated with mobile abattoirs. Develop procedures to control these risks and better manage slaughter-process by-products and waste streams
Quality management	Emerging research on functional units that consider product quality. Many approaches only consider a single quality attribute, and do not integrate the various dimensions of quality; but multicriteria assessment approaches are being developed (none of which yet cover all the core quality traits). Only few minimally or non-invasive tools available to assess quality and manage its variability		Develop multicriteria approaches to help manage antagonisms between quality traits and between stakeholders. Develop minimally invasive tools to evaluate quality and manage its variability
	Increasing demand for guarantees on the production and processing conditions and on the origin of food	Adapt control checks to the pace of intensification of international trade	Develop and test back-authentication methods that are transferable to operators

constantly changing with scientific knowledge (an illustrative example is the debate surrounding SFA or cholesterol) and in the nutritional guidelines, which means that studies and models based on nutritional value indicators have to be regularly re-updated.

The technological attributes of an animal-source food reflect the suitability of the raw material for processing (e.g. yield after salting, smoking, ageing and cooking) and preservation, which is shaped by chemical composition and microbiological status (susceptibility to oxidation, bacterial growth) and storage process routes (time, temperature, type of packaging). Technological attributes are a core concern for agrifood-industry and on-farm processors. The criteria and indicators for evaluating technological attributes vary with the type of food and type of processing route (e.g. raw milk cheese *vs.* ultra-high temperature milk, or cooked ham *vs.* dry-cured sausage). Some physico-chemical indicators are used to predict technological attributes (the pH of meat is one example, Aberle et al., 2012), but the aggregate picture is that predicting quality from raw food material remains difficult (Berri et al., 2019).

The convenience attributes of a food refer to its practical characteristics and use value (the time and effort it saves for consumers), and they are assessed through consumer surveys. However, even though these convenience attributes have gained importance with the development of ready-to-eat processed foods, the scientific literature has not yet formalised a set of methods for evaluating them.

The image attributes of a food encompass the ethical, cultural and environmental dimensions associated with how it is produced and processed, and its geographical origin. These attributes play a significant role in shaping consumer perceptions of the product and are particularly valued in products with quality signs. Image attributes interact strongly with the other quality attributes, which means that consumers may 'perceive' a quality gap when they are informed on the product's origin and production and processing conditions, while they would not necessarily see differences if they were not informed. The image attributes of food have barely registered as a significant factor just years ago but have since become major drivers of purchase decisions (Aboah and Lees, 2020). There are many factors that can all play a role in food image: ethics, animal welfare, naturalness, localness, environmental impacts, and signs, labels or assertions of quality, etc. Logically, then, a number of different methods, criteria and indicators have been developed for evaluating image quality attributes. Environmental aspects are complex to assess, as there are various dimensions to take into account (pollutant emissions, resource-usage, biodiversity). Impacts are commonly considered as being greater in animal *vs*. plant foods, and to vary wildly between livestock systems. However, farming system rankings largely depend on the metric selected. Recent studies suggest changing the functional unit (currently mass- or volume-based) underpinning the environmental indicators to account for the nutritional value of foods, such as indispensable amino acids (Tessari et al., 2016), n-3 polyunsaturated FA (**PUFA**) contents (McAuliffe et al., 2018), or, more globally, a composite indicator derived from multiple nutrients (McAuliffe et al., 2020). This shift would change system-to-system performance gaps or rankings by advantaging systems that produce foods with higher nutritional attributes. For example, McAuliffe et al. (2018) suggest changing the functional unit underpinning greenhouse gas (**GHG**) emissions in order to integrate animal-product quality through its n-3 PUFA content, which is chronically under-delivered in the Western-pattern diet. In this reconfiguration, the GHG emission indicator becomes kg CO_2eq GHG/g n-3 PUFA produced instead of kg CO_2eq GHG/kg product. Another study (Lynch et al., 2020) advocates changing the metric for global warming potential to better link reported GHG emissions to their respective warming impacts. The new metric proposed has great implications for methane due to its short lifetime in the atmosphere. The outcomes would be less unfavourable to ruminants than scientific reports generally are. Nevertheless, livestock's contribution to climate change remains crucial (animal feed cost in N_2O and CO_2 emissions through energy consumption, fertiliser application, land-use change, deforestation…). Regarding carbon sequestration, soil under grasslands is a major stock of carbon, but it has little and variable capacity for additional storage. However, grasslands need to be protected for many other reasons (biodiversity, landscape, eco-health) (Pellerin et al., 2019).

Furthermore, Van der Werf et al. (2020) flag the fact that life-cycle assessment—the most widely used method today for assessing environmental impacts—fails to account for essential issues like biodiversity loss, soil degradation and the impacts of pesticides, nor does it account for the ecosystem services provisioned by certain farming systems or the contribution of animals to food waste recycling. Food waste quantification is still a methodological challenge because the data are difficult to capture and there is still no shared framework for analysis, which is an essential prerequisite (Redlingshöfer et al., 2017). Regarding animal welfare, which is becoming increasingly important for consumers (Panzone et al., 2017), recent pan-EU-scale studies have developed methodological benchmarks for evaluating welfare in the various livestock commodity chains, but it should be noted that they have been specifically developed for the most intensive farming systems (Botreau et al., 2009). Animal welfare labelling is on the table at the EU level (EU, 2020).

There is an array of methods for assessing intrinsic food quality attributes, i.e. attributes related to the food itself. Many of them require destructive sampling procedures that are only operable late in the food production chain, and the analyses involved are generally long and expensive to run. The development of less-invasive online methods to characterise and predict the quality attributes of animal-source foods (or the raw material for processing) is thus a challenge. These methodological developments would have undeniable advantages for managing the variability of quality, by making it possible to orient the food towards different market segments and the raw material towards the most suitable processing technique, or for back-authenticating how the food was produced. Like the rapid analyses used for quality-indexed milk payment, the development and online deployment of spectroscopy-based and image analysis methods could make it possible to expand the range of quality attributes evaluated for meat and fish, e.g. fat content, marbling, fatty acid profile, or water-holding capacity (Guy et al., 2011; Mourot et al., 2014; Berri et al., 2019; Meunier et al., 2021). In the field of meat science, ongoing research is tackling the idea of tools that could 'live-test' livestock animals to characterise their quality potential (Boudon et al., 2020) or to run early (upstream) screening for quality defects that would make it possible to efficiently re-stream sub-quality meat into appropriate processing routes or even to readjust on-farm livestock management practices. For example, a blood marker is being developed in an effort to detect pigs liable to yield 'pale–soft–exudative' meat (Théron et al., 2019). A range of approaches are thus being trialled in an effort to develop predictive tools based on several types of biological (genomic or phenotypic) biomarkers (Picard et al., 2015) and physical markers (spectroscopic methods), or to develop databases linking meat eating quality with key animal, carcass and meat characteristics in interaction with the processing (cooking) conditions (Bonny et al., 2018).

Quality can be gained but can also be lost throughout the farm-to-fork continuum

An array of factors influences each set of core quality attributes, and one factor can influence several attributes (Table 2).

Given the plurality of factors and their multiple potential interactions, it is reasonable to state that '*quality is crafted*' progressively throughout production and processing. Analysis of the factors responsible for the spectrum of variability in the quality attributes of animal-source foods shows that these factors act at various stages of food production and processing: from intrinsic animal characteristics to on-farm, transport, slaughter, processing, storage, sale and retail conditions, and on to culinary preparation and eating (Table 2). The quality of animal-source foods can actually be shaped from upstream on-farm steps (sometimes even before the animal is born) right through to consumption, and it can be enhanced or decreased at any point up and down the farm-to-fork chain. There is an ample evidence base, but we need meta-analyses to obtain more robust evaluations of the effects of the determinant factors (Table 1). Some steps are crucial for shaping core quality traits and can prove a risk for altering some attributes or, conversely, an opportunity for improving or correcting others.

Table 2
Factors at play in shaping core quality traits of animal-sourced foods (eggs, milk, meat, fish, and processed foods) at various stages of the farm-to-fork continuum. In black: major factor of variation; in grey: weaker factor of variation; in white: not a factor of variation.

Stages	Factors	Quality attributes						
		Commercial	Technological	Sensory	Safety	Nutritional	Convenience	Image
Animal characteristics	Health and nutrition of the mother							
	Genetics, breed, strain							
	Gender							
	Physiological stage (milk)							
	Age/weight of the animal							
Farming practices	Geographic location (local region, peri-urban, etc.)							
	Animal habitat							
	Hygiene							
	Welfare, mutilation, castration							
	Stocking density							
	Feeds and diets							
	Medication (antibiotics)							
Transport and slaughter	Harvesting, transport							
	Pre-slaughter, slaughter (meat, fish flesh)							
Processing of the raw material	Conservation method							
	Fractionation/cracking							
	Cooking process routes							
	Salting, smoking, fermentation							
	Formulation (including additives)							
Distribution	Packing and portioning							
	Sale and retail							
Culinary practices	Storage (Conservation method)							
	Cooking process routes							

The safety attributes of a food**,** for example, are shaped by on-farm factors (animal living environment and feed), processing routes (processing and packaging methods, and formulation) and consumption practices (storage and preparation), which can vector contamination of the animal, its products, and ultimately, the food (Fig. 3). Meat, eggs and raw or undercooked meat/egg preparations along with fish and seafood (the statistics do not stratify for farmed fish) together accounted for 70% of all bacterial food poisoning outbreaks caused by pathogenic agents such as *Salmonella* spp., *Staphylococcus aureus,* or *Clostridium perfingens* officially confirmed over the 2006–2015 period in France (Anses, 2018). Animal-source food has been confirmed as an important driver of the global burden for all foodborne pathogens associated with sporadic human cases and outbreaks (Hoffmann et al., 2017). On the chemical pollutants front, animal foods are the biggest net contributors of persistent organic pollutants like dioxins, furans and polychlorinated biphenyls (**PCBs**) in human diet (Tressou et al., 2017). Antibiotic use is a specific issue on two fronts: drug residues in food, and antibiotic resistance. Few studies report meaningful data on veterinary drug and pest control product residues or other chemical contaminants (environmental micropollutants) in animal-source foods. The effect of processing on chemical risks is still under-documented, and the homes-and-household scale, although potentially involved, has rarely been studied. Little is known about the levels of toxicity and exposure to neo-formed compounds during cooking and smoking, or about the cocktail effect of interactions

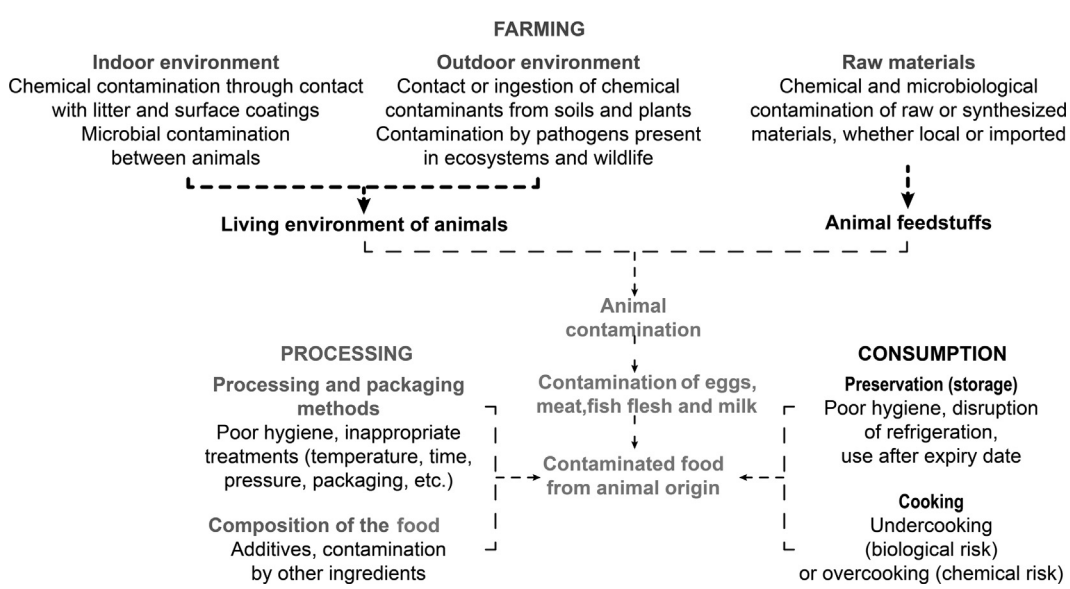

Fig. 3. Microbiological and chemical contamination pathways in animal-source foods.

between chemical contaminants (Meurillon et al., 2018). The cocktail effect is singled out as a key factor in the risks associated with the migration of molecules from packaging material in contact with foods. There are also possible cocktail effects with the additives used in food formulations.

Farming system practices significantly shape some quality attributes, particularly image attributes. A study looking at using the table-egg farm-system labelling model for other animal products showed that, on average, consumers not only have a positive attitude towards more welfare-friendly farming systems that provide access to outdoors and adequate space, but that they are also willing to pay a higher price for products from such systems (Janssen et al., 2016). On-farm practices also influence food safety. Farms that barn-raise at high animal density are more exposed to contagious diseases (Nørrung and Buncic, 2008), under-roof pollution and chemical contaminants in feed rations (Saegerman et al., 2006). Farms that provide free-ranging access to outdoors are more exposed to parasites (Delsart et al., 2020) and to environmental contaminants (Tressou et al., 2017; Dervilly-Pinel et al., 2017 for meat; Pussemier et al., 2004 for eggs), which grounds a rationale for performing an environmental audit before starting a farm operation to identify the (past or present) contaminant-emitting human activities in the vicinity.

Animal diet is a major factor influencing the quality of meat, fish and dairy (Table 2) and a major pathway to improving it, chiefly due to the role of diet in lipid content and FA profile, which together partly shape the nutritional and sensory attributes of animal-source foods. The Western-pattern diet is largely deficient in n-3 PUFA, both in their precursor, alpha-linolenic acid, and its long-chain derivatives, with people only getting on average around half the recommended daily intakes (Anses, 2015). This nutritional inadequacy is an aggravating factor in many chronic diseases. Part of the beneficial nutritional value of meat, fish, dairy and eggs is that they offer a valuable source of n-3 PUFA, and the animal-food commodity chains have worked to increase n-3 PUFA concentrations in food products. The FA composition of animal-source foods is heavily influenced by the FA profile of the diet fed to the source animals. The link between the FA ingested and FA accretion profiles in the animal's body tissues and products is tight for monogastrics and fish but less tight for ruminants due to in-body FA conversion processes. The FAs secreted in milk are also modulated by *de novo* FA synthesis in the udder. Oily fish is packed with long-chain n-3 PUFA (100 g of salmon fillet covers roughly three times the recommended daily intake level), which correlates to their typically marine-organism diet. Fresh green grass is packed with n-3 PUFA and antioxidants and provides a natural way to farm products that are richer in n-3 PUFA and antioxidants, both for ruminant milk and meat (Berthelot and Gruffat, 2018; Martin et al., 2019), pork and eggs (Mugnai et al., 2014). Compared to concentrate-fed beef, grass-fed beef contains around two-fold higher levels of n-3 PUFA, lower levels (−21%) of the pro-atherogenic palmitic acid, and higher levels of conjugated linoleic acid (Berthelot and Gruffat, 2018). In-stall finishing decreases these differences and may even eliminate them entirely (Ponnampalam et al., 2006). These nutritional benefits also conjugate with sensory (more intense flavour, more characterful products) and image benefits ('grass-fed') (Delanoue et al., 2018; Peyraud et al., 2019). All of these attributes are often up-valued via quality sign/seal/label schemes that advertise commitments to 'grass-fed', prompting research addressing the analytical challenge of back-authenticating grass-fed diet claims on the final product (Prache et al., 2020b). These win–win strategies for nutritional, sensory and image benefits of grass-fed meat and dairy are further enhanced on diversified and/or upland pastures (Provenza et al., 2019; Martin et al., 2019). Both the USA and the UK already run 'grass-fed' logos (Salami et al., 2019) and similar market niches are opening up in Germany, Spain, the Netherlands and France (Peyraud et al., 2019).

Animal-source food n-3 PUFA content can also be increased by dietary delivery of n-3 PUFA-rich oil or seed supplements, such as flaxseed (for ruminants and monogastrics), or marine-organism fishmeal (for fish) (Wood et al., 2008). However, as this added n-3 PUFA can have negative knock-on effects on sensory (rancidity) and convenience attributes (shelf life), it needs to be dose-limited and associated with an antioxidant supplementation (typically vitamin E), which may be natural (grass) or synthetic. A whole stream of research has investigated increasing the antioxidant content of foods as a strategy to protect their unsaturated FA from peroxidation, including by using plant-source antioxidants (Falowo et al., 2014; Salami et al., 2019).

Upcycling by-products in animal feed is one of the pathways to reduce food–feed competition and reduce dependency on imported feed resources. Livestock have a long history of using a number of food–farming industry by-products (oilcakes, brans, beet pulp, pomaces), but the practice is gaining ground and diversifying. A recent review paper on ruminant meat (Salami et al., 2019) showed that the use of bioactive-rich (vitamins, unsaturated FA, phenolic compounds, tannins and flavonoids) plant by-products can improve the nutritional attributes and shelf life of meat and meat products while reducing enteric methane and nitrogen emissions. However, these effects remain under-documented. Research is needed to characterise the nutritional value of these by-products and evaluate their effects on the various quality attributes of the end-products. A point of caution is food safety, as these resource-recycling strategies may increase the risks of contamination, if pathogenic agents in contaminated plants can be transferred to their by-products.

The preslaughter and slaughter phases are crucial steps that carry a strong risk of compromising meat and flesh quality (Table 2). Inadequate conditions for loading, transport, and/or slaughter generate stress that can compromise the sensory (typically tenderness, but also colour) and technological (e.g. cooking yield) attributes (Terlouw et al., 2021). Animal welfare, especially in transport and at the slaughter facility, is also a decisive factor for image quality attributes. Substandard evisceration practices can compromise meat safety. On-farm slaughter (using mobile abattoirs) is being trialled as a potential policy measure to minimise animal stress, but has attracted little research to date (Eriksen et al., 2013; Mancinelli et al., 2018; Prache et al., 2020a). Research is needed to evaluate the associated risks in terms of process hygiene and animal welfare and to develop procedures and protocols to control these risks and better manage slaughter-process by-products and waste streams (Table 1).

For meat, cooking is a key phase. It is essential for controlling microbiological hazards, for increasing protein digestibility, and for flavour and texture (Bajerholm and Aaslyng, 2004). The effect of cooking temperature on the meat protein digestion rate follows a bell-shaped curve that puts the maximum at a core temperature of 70–75 °C (Bax et al., 2012). However, cooking over flames or at excessively high temperatures can erode meat sensory and nutritional attributes—and even compromise safety through the formation of neo-formed compounds (i.e. aromatic hydrocarbons and heterocyclic aromatic amines, both of which are carcinogenic and increase in level with increasing cooking time and temperature) (Kondjoyan et al., 2016).

The industrialisation of food processes brought widespread standardisation of the farm raw material delivered to the downstream industry. The primary purpose of food processing routes is to ensure the food will keep during storage and meet consumer demand, which is increasingly directed towards convenient ready-to-use/ready-to-cook food of consistent quality. The backbone industrial processes—cooking, curing, smoking, fermenting,

and so on—have nearly always grown out of traditional time-honoured techniques. In addition to microbiological stabilisation, heating treatments as well as smoking and fermentation enable the generation of tastant compounds. Adding salt to foods increases taste perception. Industrialisation has enabled the development of the food supply on a large-scale, which has further increased with the evolution of large-scale distribution channels. In addition, within certain food sectors (e.g. dairy and eggs), processes for fractionating/cracking raw food materials have vastly expanded the range of products and ingredients (texturisers, gelling agents and so on) that can be assembled into a vast range of food formulations to increase the abundance of food supply (Fig. 4). Furthermore, food additives can be used to fine-tune core quality traits: to enhance flavour (e.g. salt and sugar), rectify defects (e.g. aroma compounds), or guarantee microbiological stability throughout storage (e.g. nitrite salts). However, this strategy direction brought widespread standardisation of the primary production, thus reducing the biodiversity of farm animals and the upstream diversity of farming practices (Provenza et al., 2019; Prache et al., 2020a) (Fig. 4). The diversification of animal-source processed foods poses the challenge of methods to classify them. There are currently a number of classification systems that have been developed in parallel. For example, the Nutri-Score grades processed foods according to their nutritional composition (Julia et al., 2017), whereas the Nova system takes into account processing-related criteria and categorises foods in four classes according to "the nature, extent and purposes of the industrial processes they undergo" (Monteiro et al., 2018). These different food classifications do not always match up (Prache et al., 2020a), which can lead to consumer confusion. Work is needed to develop robust and reproducible food ranking methodologies, in particular to integrate food processing-related criteria (Sadler et al., 2021). Some systems are already used to support consumer nutritional guidance, while others are developed by associations or come from private-sector initiatives (digital apps), but there is still a lack of consensus among the scientific community.

Authentication tools are important for labelled but also standard products to prevent fraud. The review of the literature shows that there are far more studies on the back-authentication of farming practices and origin than on the downstream food processing and storage conditions (Fontanesi, 2017; Prache et al., 2020a). Methods to test for food-species adulteration are already operational (to detect fraudulent mixing of meat or milk from different species, for example). However, most of the research to date on other analytical authentication challenges, such as grass-feeding, is mostly still in the 'proof-of-concept' stage. The reasons are that most of these studies have compared extreme animals or samples for product origin or farming practices, which is logically conducive to discriminating these conditions, and that they often worked up from a relatively small sample size. It is now necessary to test the reliability of these methods under less contrasted conditions, on larger sample populations, and to develop suitable databases for scaling up to operationalisation.

Highlighting trade-offs between quality attributes

Our framework addressing quality through different attributes enabled us to pinpoint synergies and antagonisms among attributes and among stakeholders that may have different priorities. There are tensions between commercial and the other core quality attributes, but we also looked at some of the other tensions to address.

Commercial attributes given primacy, especially for standard commodity foods

One of the major lessons of this review is the observation that commercial attributes hold primacy, particularly for standard commodity food products. This primacy is manifested in the carcass value criteria dictating payments to farmers. It has driven genetic selection, led to increased animal specialisation and oriented livestock farming practices. It has brought substantial and significant productive gains in the animal sectors, such as lean meat content of pork carcasses (Schwob et al., 2020), breast meat yield in broilers (Baéza et al., 2021), and carcass weight of culled cows (Veysset et al., 2014). However, these 'quantitative' traits do not reflect other attributes, such as sensory and nutritional attributes. Bonny et al. (2016) showed that there was no correlation between commercial attributes of beef carcasses assessed via EUROP-grid grading and beef eating quality scores. The quantitative gains have sometimes even come at the cost of other key qualitative attributes. An emblematic example is in standard broilers, where selection to increase growth rate and breast meat yield has had negative consequences on the nutritional, sensory and technological attributes of most fillets. The broilers also have difficulty in moving and a high prevalence of myopathies (Baéza et al., 2021). The destructuration of broilers' muscle tissue makes it necessary to use additives for further processing; this sub-quality meat has to be re-streamed into ready-to-cook meals (Baéza et al., 2021). Muscle tissue destructuration is also observed in pork, where it causes waste and big economic losses at the slicer (Théron et al., 2019). In the case of beef too, selecting beef cattle breeds towards lean meat yield and feed conversion efficiency has led to less marbling and consequently less juiciness and flavour of the meat (Bonny et al., 2018). Furthermore, in beef cattle, this orientation towards later-maturing animals has made it harder to move to more agro-ecological practices such as grass-finishing that promotes meat nutritional (Berthelot and Gruffat, 2018) and image quality attributes (Provenza et al., 2019).

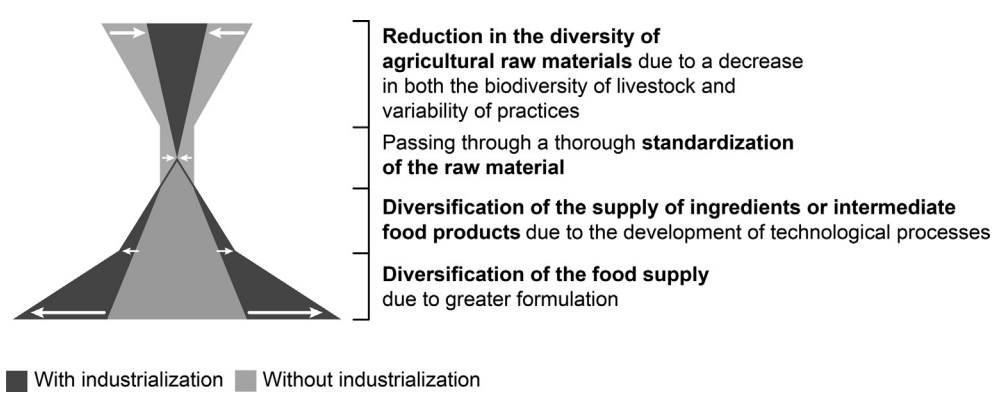

Fig. 4. Consequences of agrifood-sector industrialisation on diversity along the agrifood chain.

Table 3
Examples of farming system practices that create antagonisms between different core quality traits, for different animal-source foods.

Product	Farming system practice	Positive effects	Negative effects	Compromises/solutions
Pork	Non-castration of male piglets	Image-value (welfare-friendly) and commercial quality attributes (higher pork lean content)	Sensory quality attributes(off-flavour)	Immunocastration Earlier age at slaughter Selection for reduced androstenone levels Farming practices for controlled skatole levels Slaughter-line detection of taint-odoured carcasses
Lamb meat	Grass-fed	Image-value and nutritional quality attributes (fatty acid profile)	Sensory (risk of off-flavours and darker meat) and commercial quality attributes (risk of insufficient carcass fatness)	Supplementation with carbohydrates and/or condensed tannins Short stall-finishing period Educate consumers on the pastoral flavour of grass-fed lamb
Fish products	Shift from marine-origin fish oil and meal to terrestrial plant-based feed ingredients	Image-value (less impact on a wild resource) and food safety quality attributes (less risk of chemical contaminants)	Nutritional (lower contents of eicosapentaenoic and docosahexaenoic acids) and commercial quality attributes (reduced fillet yields)	Restore fatty acid profile by switching back to marine-organism fish meal and/or oil a few weeks ahead of slaughter

The over-specialisation of farm animals has led to dead-end situations, by excluding or devaluating some of the animals, such as male chicks in the egg industry (Gautron et al., 2021) and a part of male offspring in some dairy supply chains (kid goats (Anicap and Interbev, 2018) and veal calves in some countries). The fate of male animals is a major issue in commodity dairying and the egg industry that have over-specialised their animals for marketable productivity, leaving only productive females with any real economic value. In the egg industry, a major ethical issue is the culling of one day old male chicks of layer breeds, as the meat of the males cannot be readily marketed. Societal outcry over this issue has prompted France and Germany to legislate a ban on shredding male chicks by the end of 2021. The goat industry also fails to find food market options for a section of its kid goat stock (Anicap and Interbev, 2018).

These collateral effects of giving primacy to commercial attributes first, and thus with the allied selection strategy, should clearly give pause for thought. Research is tackling ways to redraw this hierarchy by bringing other quality attributes into play, in the payments made to farmers and the information given to consumers (Table 1). For example, the Meat Standards Australia methodology has been developed to predict beef sensory attributes at slaughter, to be used as a benchmark for consumer information and for indexing payments to the farmers (Watson et al., 2008). Scientists are currently testing this method in Europe (Bonny et al., 2018; Pogorzelski et al., 2020). There is still a need to equip livestock farming with solutions for commoditizing animals that would otherwise be considered commercially useless (Table 1). One route could be to re-instate mixed-purpose livestock, i.e. mixed-purpose breeds that offer a good trade-off between producing two products, e.g. meat and eggs (Gautron et al., 2021) or milk and meat (Lacaune sheep breed, as an example). Another route could also revolve around crossing breeds/lines (Dezetter et al., 2019) and developing quality signs/seals/labels and/or short food supply chains. In-ovo sexing for eggs and using dual-purpose breeds/lines or crossing breeds/lines are avenues to be considered (Gautron et al., 2021).

Other trade-offs show antagonisms or synergies between quality attributes or between production and processing

A given livestock farming practice may have positive effects on some core quality attributes but negative effects on others (Table 3). In pig production, abandoning surgical castration of male piglets to produce 'entire males' favours some image attributes (better animal welfare, lower nitrogen excretion due to higher protein retention) and commercial attributes (higher carcass lean meat yield, lower production costs due to higher feed efficiency), but it can degrade sensory attributes, with the risk of the so-called 'boar taint' off-flavours, and impair other image attributes due to the greater aggressiveness of entire males (Lundström et al., 2009; Lebret and Čandek-Potokar, 2021a). Ongoing research is attempting to predict tainted carcasses on the slaughter line in order to direct them into the most appropriate processing routes, and to propose genetic and farming strategies for reducing the contents of androstenone and skatole, respectively, the two main molecules involved in boar taint in pig tissues (Bee et al., 2015).

Grass-feeding lamb favours its nutritional and image attributes but may degrade its sensory (risk of off-flavours, darker colour) and commercial attributes (risk of insufficient carcass fatness) (Prache et al., 2021). Trade-offs can be obtained either by using grain supplements in pasture-fed lambs or by a short stall-finishing period, as skatole is quickly cleared from body tissue without substantially degrading the meat FA profile. Using plant supplements that contain condensed tannins is a win–win solution for both nutritional and sensory attributes (Rivaroli et al., 2019). Another potential route would be to educate consumers on the 'natural' characteristics inherent to grass-fed lamb. This antagonism is even sharper in organic farming (Prache et al., 2020a).

In aquaculture, shifting from fish oil and meal to terrestrial plant-based feeds, which is an unavoidable transition due to the scarcity of marine resources, improves image (less impact on a wild resource) and safety attributes (less risk of contaminations through fishmeal and fish oil feeds) but degrades nutritional (lower contents of eicosapentaenoic and docosahexaenoic acids) and commercial attributes (drop-in fillet-flesh yield due to greater fatness) (Le Boucher et al., 2013). Fatty acid profile can be restored by switching back to marine-organism fishmeal a few weeks before slaughter. However, while increasing substitution with terrestrial plant-based feedstuffs does reduce fish flesh contamination with trace metals and persistent organic pollutants (particularly PCBs), it increases the risks of contamination by other pollutant classes such as pesticides and mycotoxins.

There are also animal-source foods that value the natural synergies between different quality attributes and between production and processing stages. Dry-cured ham is an illustrative example, as its quality is hugely dependent on the quality of the original raw

ham joint together with the processing (salting, drying, ripening) conditions and duration (Lebret and Čandek-Potokar, 2021b). Extensive farming, using purpose-reared breeds or lines fed partially or even extensively on local resources, can optimise the attributes of the raw material: high fat accretion, darker colour, characterful aromas. These hams will be fattier at both external and intramuscular levels, and better set for air-drying, which will culminate in a combination of better technological and far more specific sensory attributes. These synergies get even stronger with local breeds and older animals (Pugliese and Sirtori, 2012). Note that extensive farming systems where pigs get to feed a natural diet rich in n-3 PUFA and antioxidants can increase meat n-3 PUFA concentrations without excessive oxidation, and thus escape potential antagonisms in nutritional attributes (Lebret and Čandek-Potokar, 2021a). Other products, like cheese, play host to strong interactions between production and processing stages. Studies have reported interactions between milk production and cheese-processing conditions that suggest that less-intense process routes enable cheese sensory attributes to better reflect the milk production conditions. For example, in the production of full-fat raw milk cheese, there is a cow breed effect on cheese texture, due to differences in cheese fat content caused by variations in the milk fat-to-protein ratio, and this breed effect is weaker when milk fat-to-protein ratio is standardised prior to cheese-making (Coulon et al., 2004). Likewise, studies that have observed stronger diet effect on cheese flavour when using raw milk *versus* pasteurised milk (Frétin et al., 2017) suggest that milk pasteurisation may mask the putative differences between diets by equalizing the raw milk microbiota, which significantly determines flavour-active compound profiles in the cheese (Cornu et al., 2009). Finally, studies have reported that longer cheese ripening times accentuate the effects of milk production conditions (Coppa et al., 2011).

The existence of antagonisms between quality traits or between stakeholders means that there is a need to search for solutions to help overcome these tensions. As detailed in the examples above, these solutions can involve finding trade-offs between positive and negative effects or finding solutions to counter the quality-adverse effects. Multicriteria approaches make promising tools to help manage these antagonisms and propose trade-off compromise solutions, but these methods are still just emerging. Multicriteria assessment sets out to help a decision-maker reach a decision in a multidimensional problem environment, via a decision-making process that determines the best solution or trade-off (as per predefined preferences). Decision-maker input is pivotal, as the outcomes will depend on the weightings and compensations applied on the various attributes, on the allocations made, and on the functional units chosen. Some studies have co-assessed the quality of animal-source products and the environmental performances of the livestock systems from which they were derived (Rey-Cadilhac et al., 2021). Some of the latest research has moved forward to work on the processing stage (processes employed, chiefly cooking, packaging and preservation) or the cold chain (Duret et al., 2019; Finnegan et al., 2018; Madoumier et al., 2020; Yun et al., 2018). These recent studies make it possible to chart the process-route scenarios that optimise the four-way trade-off between safety, convenience, image (including environmental impacts) and commercial attributes (integrating lean yields, for example) (Bonneau et al., 2014a; 2014b; Raffray et al., 2015; Rocchi et al., 2019). These multicriteria analyses still struggle to cover all operations across the farm-to-fork continuum. Note that an original piece of research mobilised multicriteria analysis on a composite food, i.e. pizza, in an effort to find the optimal trade-off between sensory, nutritional and environmental dimensions for the purpose of reformulating the pizza from a catalogue of 360 different recipes (Saint-Eve et al., 2018).

Product quality labelling schemes craft quality through their engagement

For diet-conscious consumers, official signs identifying quality and origin serve to vector reassurances. Certified products enable value chains to upsell and capture added-value and enable certain geographical areas to integrate product-driven positive externalities. The four official quality signs in Europe are certified organic, protected designation of origin, protected geographical indication, and traditional speciality guaranteed, which are recognised across the European Community. In addition to the official European signs, there is the *Label Rouge*, an official quality sign specific to France.

These official quality signs are each framed by a set of production standards specifying their respective commitments, which are regularly audited. It is possible to analyse the linkages between these specifications and core quality traits. The common-denominator quality trait here is image, as official quality signs afford scheme-certified products a reliable degree of credibility and thus afford consumers instantly recognisable (re)assurances. Even though every quality sign ultimately plays on all the core quality traits, each individual sign focuses particularly on selected quality traits: 'certified organic' focuses on safety attributes by prioritizing "*the use of processes that do not harm the environment [or] human health*", while protected designation of origin, protected geographical indication and traditional speciality guaranteed argue for uniquely authentic and characterful sensory quality traits, together with geographic origin (to varying degrees). *Label Rouge* stands apart from the other EU-regulated quality signs, as it is only recognised in France and is the only sign officially government-endorsed as defining "a superior level of quality". Analysis of the commitments made under beef *Label Rouge* production specifications (Raulet et al., 2021) served as a working example to formalise how these commitments link into the different core quality traits, and how *Label Rouge* constructs product quality. It mobilises pivotal factors for shaping quality (led by sensory and image attributes) at each stage of the chain, from animal type to on-farm conditions, transport to slaughter and on through to meat ageing. Furthermore, successive sorting is carried out on animals, carcasses and meats, which can be label-eligible.

With regard to organic animal-source products, we observed a broad heterogeneity in findings from studies comparing the quality of meat, fish and dairy in organic *vs*. conventional systems. This heterogeneity stems from the huge diversity in farming practices. Two meta-analyses—one on cow's milk and one on meat—showed that organic products offered higher nutritional attributes, which stemmed from their higher PUFA content, chiefly n-3 PUFA (Srednicka-Tober et al., 2016a; 2016b). The results were more robust for milk than meat, due to a higher number of studies on milk and the risks of biases in meat studies that came from uncontrolled differences in meat lipid content. Organic farming reduces the risks of drug, pesticide and antibiotic residues, but it also keeps animals longer on-farm with free-ranging access to the outdoors, which increases their exposure to environmental contaminants and thus the risk of bioaccumulation in milk, meat and eggs (Dervilly-Pinel et al., 2017). The effect of organic farming on image attributes varies with animal species, focal criteria (animal welfare, pollutant emission levels, resource-usage levels, biodiversity) and functional unit employed. A recent study argued for a shift to quality-based functional units that integrate product's nutritional value in the computation of GHG emissions to gauge product environmental footprints (McAuliffe et al., 2018). This pointedly concerns organically farmed animal products that tend to have a higher n-3 PUFA content than conventionally farmed counterparts. Another study flagged up the limitations of life-cycle assessment

method for evaluating product environmental impacts, which again particularly concerns organically farmed products (Van der Werf et al., 2020). Lastly, organic products generally show higher variability in quality, which can be explained by lower genetic selection (poultry), lower use of inputs and/or greater variability in farming conditions (for both ruminants and monogastrics). However, the scientific literature has not yet addressed what this greater variability means for the acceptability of raw organic products and for efforts to adapt processing routes, which opens a promising pathway for further research.

Effects on human health

Contribution to covering human nutrient requirements

The nutritional value of animal-source foods comes from their high content in high-nutritional value proteins; they are also a good source of often-specific FA, vitamins and minerals. Animal-sourced foods are the main source of long-chain n-3 PUFA and vitamin B12 in human diet, and they contain all the indispensable amino acids as well as readily bioavailable micronutrient minerals. The huge diversity in fat content and FA profiles of animal-source foods leads to contrasting effects. A high proportion of n-3 PUFA, as found in fatty fish or in foods sourced from animals fed n-3 PUFA-rich plants (essentially grass, or some oil crops), promotes good health (central nervous system and brain development in children, reduced risk for chronic non-communicable disease). However, some SFAs are claimed to have sufficiently adverse health effects to recommend keeping daily intake of total SFA down to below 12% of total energy intake. Vitamin B12, which plays a crucial role in foetal development and normal cognitive function, is specifically found in animal-source foods, without which people have to take food supplements. Animal-source proteins have a well-balanced and readily digestible indispensable amino acid profile. Their high indispensable amino acid content makes them well adapted to specific population segments like seniors, children, or athletes. Minerals (iron, calcium, zinc) are more readily bioavailable in animal-source foods than in plant-source foods (Higgs and Pratt, 1998). They are therefore valuable for preventing deficiencies, especially in pregnant women, young children, and older adults. Epidemiological studies have shown that vegetarians do not have more health problems than non-vegetarians, even though their body reserves have lower micronutrient levels. However, vegans have a higher prevalence of certain nutrient deficiencies, particularly vitamins D and B12, iron, iodine, calcium and zinc (Lemale et al., 2019; Sakkas et al., 2020).

Associations between consumption of animal-source foods and chronic diseases

Nutritional epidemiology studies can establish associations between consumption of animal-source foods and increased or decreased risk for certain chronic non-communicable diseases like diabetes, obesity, cancers, cardiovascular disease (**CVD**) and neurodegenerative diseases. These associations are qualified by the level of evidence supporting the results. Epidemiological data from meta-analyses (Schwingshackl et al., 2017a; 2017b; WCRF et al., 2018a; 2018b) showed that the consumption of some animal-source foods can have positive health effects but that excessive consumption of others can have deleterious effects. They showed that fish consumption is associated with decreased risk for premature death (before 65 years of age), CVD and neurodegenerative diseases, and that consumption of dairy products is associated with decreased risk for colorectal cancer, with a level of evidence reported as 'probable' in both cases (Table 4). Conversely, high consumption of processed and red meat (beef, sheep and goat, pork) is associated with higher risks. These studies actually showed that a 50 g/day increase in processed meat consumption is associated with a 23% higher risk for premature death and a 16% higher risk for colorectal cancer, with the level of evidence reported as 'convincing' in both cases (Schwingshackl et al., 2017b; WCRF et al., 2018a). These positive associations were used by the French National Nutrition and Health Program to establish maximum recommended intakes (150 g/week) for processed meat. Sodium nitrite and potassium nitrate, which are used as preservatives in processed meat, have been singled out for increased risk of colorectal cancer. The European Food Safety Agency (**EFSA**) report released in 2017 concluded that the nitrosamine levels formed in the human body following the use of added nitrite and nitrate were of little concern for human health if added at approved levels. If it was not possible to clearly discern nitrosamines produced from the nitrite added at the authorised levels from nitrosamines originating from the food matrix, the EFSA report indicated that some epidemiological studies have (i) linked dietary nitrite to gastric cancers and (ii) linked the combination of nitrite plus nitrate from processed meat to colorectal cancer. The International Agency for Research on Cancer therefore categorised dietary nitrates and nitrites as "probably carcinogenic" in 2010. Research is currently focusing on ways to reduce the relative risk of nitrosamine formation during the digestion of processed meat, either by reformulating the additives used (including antioxidants), reducing the use of sodium nitrite, or substituting the added nitrites with comparably effective alternatives (e.g. organic acids, plant-source antioxidants,...). Further research is now warranted to test and evaluate whether these substitutes have potential health benefit for consumers and their effects on the core quality traits of processed meat.

These studies also show that a 100 g/day increase in red meat consumption is associated with a 10% higher risk for premature death and a 12% higher risk for colorectal cancer (Schwingshackl et al., 2017b; WCRF et al., 2018a), with the level of evidence reported as 'probable' in both cases. The French nutritional guidelines thus recommend limiting red meat consumption to 500 g/week (on an as-fed basis). Food consumption figures for France, whether captured through food surveys or computed from FAO statistics based on trade slaughter records and import/export balances, converge to give 53 g/day for red meat and 35 g/day for processed meat (Prache et al., 2020a). The message on cutting down consumption targets the two-thirds of French consumers who eat more than the recommended daily intake of processed meat and the 28% of consumers who eat more than the recommended daily intake of red meat. Even in countries where average consumption of animal-source protein is above the nutritional requirements, some population segments—especially older adults and vulnerable

Table 4
Level of evidence of associations between the consumption of animal-source food groups and chronic diseases: Cancer, Cardiovascular diseases (CVDs) and Alzheimer's disease and related dementias (ADRD).

Animal-source food group	Cancer	CVD	ADRD
Processed meat	■	▒	
Red meat	▒	▒	
Poultry meat			
Eggs			
Fish		▨	▨
Dairy	▨		

■ Increased risk with 'convincing' level of evidence
▒ Increased risk with 'probable' level of evidence
▨ Decreased risk with 'probable' level of evidence

populations—may get less than their nutritional needs. Note too that diets that avoid meat (vegetarianism) or all animal-source products (veganism) are generally associated with a higher risk of bone fractures (Tong et al., 2020), sarcopenia (Marcos-Pardo et al., 2020) and anaemia (Papier et al., 2021), which are especially detrimental in the context of an ageing population.

Epidemiological studies and nutritional guidelines are framed at product-category scale, and therefore fail to account for their huge variability in nutritional composition originating from the variability in production and processing conditions (Van Vliet et al., 2021). The 'processed meat' and 'red meat' categories encompass a broadly diverse panel of products with widely varying nutritional compositions (iron content, salt content, nitrite content, FA profile, . . .) and that have been through various processing routes (cooking, drying, fermentation, and so on). Furthermore, based on associations established between the consumption of 'ultra-processed' foods and human health (Srour and Touvier, 2020), the new French National Nutrition and Health Program has endorsed greater use of raw products and cutting down the consumption of 'ultra-processed' foods. However, this remains a 'global' classification and more research is needed taking into account the degrees of processing and formulation (composition) in order to better understand the underlying mechanisms and redesign the processing routes accordingly. This is a further methodological challenge to address. There is clearly a need to pursue efforts to build bridges between research communities working on animal science, food processing, human nutrition, and epidemiology in order to better qualify the links between farming and processing practices and their effects on human health. Further, along the farm-to-fork continuum, research is also needed to understand the drivers and barriers of food substitutions in different populations, and the pathways for transition from one diet to another.

Conclusions

The quality of animal-source foods can be gained but can also be lost at any point throughout the farm-to-fork continuum. This review highlights that commercial quality attributes still take primacy for animal-source products, especially for 'standard' commodity foods, which has disturbing negative collateral effects. As these 'quantitative-first' commercial attributes determine payments to farmers, they have logically dictated genetic selection, output-focused livestock specialisation, and farming practices. Studies are investigating how to change course by considering other core quality traits in a more global and multidimensional approach. However, as these transitions run into the prevailing industry norms and roles, they require policy action to support collective initiatives for change. There is also a need to provide livestock farming with solutions for marketing animals that are currently considered commercially useless, and to provide the stakeholders involved with appropriate guidance, direction and support. A second instructive learning from this review is the gap between epidemiological studies and food-scale studies. Investigation into how farming practices and food processing routes potentially influence the effect of eating animal-source foods on health requires a collective effort between research communities working on farm-scale science, food processing, consumer attitudes, human nutrition, and epidemiology.

The pace of change in diet patterns and societal expectations also requires better anticipation of consumer needs and motivations, and appropriate—sometimes even disruptive—solutions for farming practices and processing channels. Consumers have increased demands towards animal production and food processing conditions, and this changing demand comes with a need for (re)assurances and transparency. There is a solid stream of research into the back-authentication of animal-source food farming systems and origin, but analytical authentication methods need to become more generic and robust in order to be transferred to practitioners. However, some practitioners fear that the profusion of information (quality assurance signs, nutritional value scores, information asserting quality value, etc.) may limit its value. Getting this information heard may well be a challenge. Finally, the rise in consumption of ready-to-eat foods is driving a decline in the art and craft of home cooking. To buck this trend and recreate self-reliance in food choices, education is critical to facilitate the acquisition of the basics of cooking, sensory appreciation, nutrition and seasonality. It remains a telling fact there are little data and scientific analysis on home cooking and consumption practices. This last step in the chain is nevertheless decisive for the quality of the food that people are going to eat.

Ethics approval

Not applicable.

Data and model availability statement

None of the data used in this review were deposited in an official repository.

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Declaration of interest

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