Review: Production factors affecting poultry carcass and meat quality attributes

Elisabeth Baéza, Laurent Guillier, Massimiliano Petracci

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E. Baéza [a,*], L. Guillier [b], M. Petracci [c]

[a] INRAE, Université de Tours, UMR BOA, F-37380 Nouzilly, France
[b] Agence nationale de sécurité de l'alimentation, de l'environnement et du travail (ANSES), Direction de l'évaluation des risques, F-94700 Maisons-Alfort, France
[c] Department of Agricultural and Food Sciences, University of Bologna, 47522 Cesena, Italy

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ABSTRACT

Poultry meat mainly comes from standard production system using high growth rate strains reared under indoor intensive conditions. However, it is possible to find also different alternative systems using outdoor extensive rearing conditions and slow-growing lines. These different production systems can affect carcass and meat quality. In this review, quality has been broken down into six properties: commercial, organoleptic, nutritional, technological, sanitary and image, the latter covering the ethical, cultural and environmental dimensions associated with the way the meat is produced, as well as its origin and being particularly valued in many quality labels. The quality of meat is built and can deteriorate along the continuum from the conception of the animal to the fork. Our review details the different factors implicated in the determinism of poultry meat properties and pinpoints critical periods, such as the preslaughter and slaughter periods, and key factors, such as the feeding regimen, via its direct effect on the fatty acid profile, the antioxidant and volatile compound contents, and indirect effects mediated via the growth rate of the bird. Our review also highlights potential antagonisms between different dimensions of quality. The genetic selection for breast meat yield, for example, has been effective in producing carcasses with higher meat yield, but resulting since a decade in the increased occurrence of quality defects and myopathies (white striping, wooden breast, spaghetti meat and deep pectoral disease). Outdoor access has positive effects on the image and nutritional properties (through its effect on the fatty acid profile of meat lipids), but it increases the exposition risk to environmental contaminants and pathologies (parasites, virus, bacteria); it also increases the variability in meat quality linked to the variability of animal performance and slaughter age. The orientation towards more agro-ecological low-input farming systems may present benefits for the image and nutritional properties, but also risks for the commercial (low carcass weight and low breast yield, irregularity in supply), organoleptic (stronger flavour, less tender and darker colour of the meat) and in terms of variability of the different properties that constitute quality. Efforts should be made in the future to better take into account the various dimensions of quality, in consumer information, payment to farmers and genetic selection.

Implications

Poultry meat comes from different production systems that can affect differently carcass and meat quality. The price of poultry mainly depends on the commercial properties of carcasses. The meat processing industry gives more attention to the technological properties of meat. The consumers are more interested in sensorial and nutritional properties, but the image properties take up an increasingly important place. Food safety remains a major concern for all actors, from the producer to the consumer. In order to understand how the different properties of poultry meat can vary, the following review describes how different factors can modulate them.

Introduction

Poultry meat consumption in Europe averages 28 kg per capita and it regularly increases (+17% in the last decade; FranceAgriMer, 2019). In France and in Europe, there are different production systems detailed in Tables 1 and 2. Within the conventional production, it is also possible to distinguish export chicken (broiler griller) and heavy chicken with an average live weight at slaughter of 1.4 and 2.5 kg, respectively.

* Corresponding author.
E-mail address: elisabeth.baeza-campone@inrae.fr (E. Baéza).

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Table 1
Main characteristics of the different rearing systems for poultry meat production in France (derived from Chenut et al., 2013).

	Rearing systems					
	Conventional	«Label Rouge»	Organic	Certified	Protected Geographical Indication	Controlled Label of Origin (only Bresse)
Claim		Meat sensorial quality different from that of conventional chicken	Organic free-range 1 antibiotic treatment/year	Specifications of the group	Defined geographical area	Defined geographical area
Chicken strain	High growth rate	Slow growth rate	Slow growth rate	Intermediate growth rate	Slow growth rate	Slow growth rate, "Gauloise" strain
Identification of individuals	No	Yes	Yes	No	Yes	Yes
Feed characteristics	No specification	75% cereals	95% organic ingredients in feed. No synthetic amino acids and no coccidiostat	Specifications indicated in terms of reference	75% cereals	D0-D35: 50% cereals D36-slaughter: 40% maize, 500 g dairy products, 500 g wheat or corn gluten Ten days finishing period in crates
Free-range access	No	Yes, from D28-D42 depending on the season, 2 m^2/chicken	Yes, 4 m^2/chicken	No	Yes, from D28-D42 depending on the season, 2 m^2/chicken	Yes from D36, $\geq$ 10 m^2/chicken
Slaughter age, days	35–42	86 (81 minimum)	87 (81 minimum)	56	86 (81 minimum)	140–147 (102 minimum)
Density, number of chickens/m^2	21–23	11	10	18	11	12
Maximum production, kg/m^2		25	25		25	24
Maximum rearing area, m^2		1 600	1 600		1 600	
Maximum outdoor access, m^2		400	480		400	
Maximum flock size		1 100 birds	4 800 birds		1 100 birds	4 200 birds
Number of flocks/year	6.4	3.3	3.3	4.6	3.3	2.9
Slaughter weight, kg	1.8	2.2	2.2	2.0	2.2	2.0
Daily weight gain, g	50	26	26	36	26	16
Feed conversion ratio	1.7	3.0	3.1	2.1	3.0	5.1–5.2

France dominates the European market for free-range poultry (Julien and Le Douarin, 2015). Chickens produced with alternative systems and reared with free-range access represent 16% of total volumes. The dominant model remains the "Label Rouge", a concept that remained French; far ahead the organic system to which is added the certified chicken, intermediate between conventional and "Label Rouge" systems. "Label Rouge" represents about two-third of the chickens sold in ready-to-cook (**RTC**) carcasses and the conventional chicken represents almost two-third of the chickens sold in cuts (Fig. 1).

In the UK, 20% of production is alternative (Julien and Le Douarin, 2015). Consumer expectations are more focused on animal welfare than on the environment, the «Free range» rather than the «Organic». For economic reasons, the free-range chicken (5% of volumes produced) is slaughtered at 56 days and organic (1% of volumes produced) at 70 days, with strains growing faster than in France. Among the alternative products, the production of "indoor" chickens (11% of the volumes produced), without free-range, dominates. It is a production close to the French certified with specific characteristics such as the enrichment of the farming environment (Chenut et al., 2013).

In the Netherlands, the alternative concept «Beter Leven», with 1–3 stars set up since 2005 by the Ministry of Agriculture, does not exceed 2–3% of the internal market share (Julien and Le Douarin, 2015). The 3-star "Beter Leven" corresponds to organic production. Since 2013, the chicken «Kip van morgen» (chicken of tomorrow) has been developed with the objective to supply 100% of the fresh domestic market in 2020, or about one-third of national production (Chenut et al., 2013).

In Belgium, in addition to organic chicken, there is a chicken called "differentiated quality", which would correspond to "Label Rouge" chicken, and a chicken called "intermediate quality", which is losing speed. These alternative production systems account for only 5–10% of total production (Chenut et al., 2013).

Germany is closer to the Netherlands in terms of consumer expectations and market is dominated at 95% by the conventional production. Since 2011, the welfare concept "Tierschutzlabel" with two levels has been developed. It is close to the Dutch "Beter leven" with two and three stars. The Wiesenhof Company has launched its «Priväthof Geflügel», a certified chicken with winter garden, low density and enriched environment.

In Italy, majority of broiler chickens is farmed under conventional conditions and mainly by the separate farming of females and males to obtain three different market classes of birds: light-size (females reared up to about 1.5 kg) for rotisserie-type products, medium-size (usually females, but might also be males reared up to about 2.5 kg) to produce carcasses mainly used for cut-up products, and heavy-size broilers (male reared up to about 3.5 kg) for the production of cut-up and further processed products. As in Germany, organic and free-range chickens' market share is progressively rising but currently it represents about 5% of market share. In 2018, 3.4 million poultry heads were reared under organic system in Italy, representing 7.2% of the EU poultry organic production. The main obstacles to the development of organic chickens in Italy are the high selling price for consumers and the need to import organic raw materials for poultry feed.

These different production systems can affect differently carcass and meat quality. The price of poultry mainly depends on the commercial properties of carcasses. The meat processing industry gives more attention to the technological properties of meat. The consumers are more interested in sensorial and nutritional properties but the image properties take up an increasingly important place. The sanitary properties remain a major concern for all actors, from the producer to the consumer. In order to understand how the different properties of poultry meat can be

Table 2
Main characteristics of the different rearing systems for poultry meat production in the European Union (derived from Chenut et al., 2013; Hubbard, 2020).

	Conventional	Organic	Free Range	Traditional Free Range	Freedom Food	Better Leven, 1 or 2 stars	Chicken of tomorrow
Claim		Organic free-range, 1 antibiotic treatment/year	Free-range system	Free-range farm system	Compliance with animal welfare standards established by RSPCA in 1996 (UK)	Compliance with animal welfare (Netherlands) Enriched environment (perches, straw bales, …)	Consideration of animal welfare and the environment
Chicken strain	High growth rate	Intermediate growth rate	No specification	Slow growth rate	Intermediate growth rate	Slow growth rate	Intermediate growth rate
Feed characteristics	No specification	95% organic ingredients No synthetic amino acids, no coccidiostat	70% cereals	70% cereals	No specification	No specification	Use of sustainably produced soybeans and preference for a local protein source
Free-range access	No	Yes, 4 m^2/chicken	Yes, 1 m^2/chicken	Yes, 2 m^2/chicken	No	Free-range or winter-garden	No
Slaughter age, days	35–42	70 minimum	56 minimum	81 min.	No specification	56 minimum	No specification
Density, number of chickens/m^2	21–23	10	13	12	15	12–13	19
Maximum production, kg/m^2		25	27.5	25	30	25	38
Maximum rearing area, m^2		1 600					
Maximum outdoor area, m^2		480					
Maximum flock size		4 800 birds			30 000 birds		
Slaughter weight, kg	2.2	2.2	2.2	2.2	2.2	2.2	2.2

RSPCA = Royal Society for the Prevention of Cruelty to Animals.

varied, the following review will describe how different factors can modulate them and present a few examples for illustration.

Factors affecting poultry carcass and meat properties and their effects on quality products

Market quality standards

The poultry market standard items depend on retailer and consumer requirements such as slaughter weight, RTC carcass yield, and carcass appearance (absence of visual defects such as inconsistent skin pigmentation, scratches, skin lesions, blisters, bruises, fractures, cellulitis, etc.). The slaughter weight and RTC carcass yield depend on strain, sex, farming and management system, and slaughter age while carcass appearance depends on diet, and rearing, preslaughter and slaughtering conditions. In a study carried out in 2012–2013 among five slaughterhouses throughout France, the rate of carcass downgrading for "outdoor" and conventional chickens was 0.49% and 1.36%, respectively (Baéza et al., 2015a). In a survey carried out on the technico-economic results obtained in 2017 in the west part of France, the rates of carcass downgrading were higher for export chickens (2.21%), conventional (0.96%) and heavy (0.88%) chickens compared to certified (0.40%), "Label Rouge" (0.36%) and organic (0.42%) chickens (Chambres d'Agriculture de Bretagne, 2019).

The poultry breast yield is also an important criterion taken into account by breeders and processors due to its economic valuation. Currently, the fillet yield of slow-growing chickens is around 16% and that of fast-growing strains is around 22%. The extraordinary breast yield increase obtained in modern hybrids was mainly achieved through selection (Petracci et al., 2017).

Meat safety hazards

Microbiological hazards

Poultry remains a major source of exposure to microbiological hazards in the European Union by continuing to cause substantial foodborne illnesses.

Among all the microbiological hazards considered by operators in the poultry industry, Listeria monocytogenes, Campylobacter and Salmonella are the subjects of special attention. Food products derived from poultry are one of the main sources of cases of campylobacteriosis and salmonellosis and are the subject of control or regulation plans in the poultry sector. The number of campylobacteriosis cases was relatively stable at the European level over the past five years. In the European Union, until 2001, the number of outbreaks where Salmonella was isolated was decreasing. This improvement has been attributed to the efficiency of Europe's policy on the safety of livestock and slaughterhouses. However, an increase in the number of confirmed human salmonellosis cases has been observed in the EU since 2014 (EFSA Panel on Biological Hazards, 2019).

In general, biosecurity measures are essential for the control of microbiological hazards. In Europe, the prevalence of Campylobacter in poultry farms and meat is seasonal with a higher proportion in summer and autumn. As mentioned above, the prevalence of Campylobacter in livestock and meat is strongly linked to non-compliance or inappropriate implementation of hygiene, prevention, cleaning and disinfection practices in livestock buildings. The age of animals, the farm size and flock thinning of animals during farming are also significant risk factors. Heuer et al. (2001) investigated the prevalence of Campylobacter spp. in batches of chickens from organic, conventional or extensive farming systems, but in confinement, in Denmark for the period 1998–2000. They observed a prevalence of 100, 36.7 and 49.2%, respectively. In Swe-

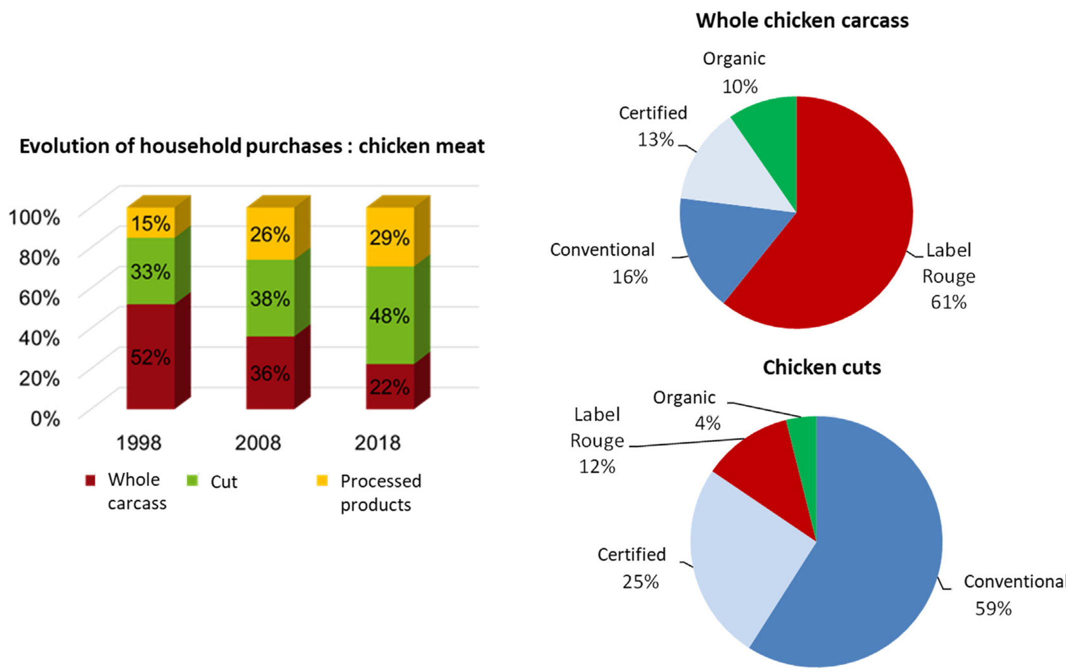

Fig. 1. Poultry meat consumption in France: breakdown of purchases of whole carcass, cut and processed products and product segmentation according to production system (derived from ITAVI, 2019).

den, Engvall (2001) found 100% of organic chicken batches contaminated with Campylobacter and 10% of conventional chicken batches. In Belgium, Van Overbeke et al. (2006) confirmed that organic chicken farms were more contaminated with Campylobacter than conventional chicken farms. Bokkers and De Boer (2009) also reported that organic chicken meat was more contaminated with Campylobacter than that from conventional chickens. Voidarou et al. (2011) showed that organic chickens had higher microbial contamination than conventional chickens.

The impact of the housing system on the presence of Salmonella in broiler chickens has only been studied in a limited number of studies which, for the most part, have not found significant differences or have conflicting conclusions. Studies indicate that the prevalence of Salmonella may be either higher in organic chickens compared to conventional chickens (Shengui et al., 2005) or lower (Heuer et al., 2001; Alali et al., 2010) or equivalent (Van Overbeke et al., 2006; Wierup et al., 2017). However, the limited data available show that stress, stocking density and increasing numbers of barns per farm increase susceptibility to salmonellosis.

For *L. monocytogenes*, a survey conducted in France, in 2005–2006, did not reveal any effect of the rearing system (conventional vs. outdoor) on the prevalence in broiler chicken (Chemaly et al., 2008).

As with other animals, the hygiene control of slaughter procedures is an element of control of all biological hazards in the chain of broiler poultry. At the slaughterhouse, surveillance by operators of the evisceration stage is a risk factor for contamination of carcasses by Salmonella. For Campylobacter, several steps are important for controlling the risk level: scalding temperature, plucking step, evisceration and carcass cooling conditions. For *L. monocytogenes*, cross-contamination by resident flora in slaughter houses and cutting plants appears to be the most important factor to consider (Schäfer et al., 2017).

Consumer practices play a role in the risk level of poultry meat products. The respect of the shelf life and temperatures of the products to be consumed allows to control the risk level. Inadequate cooking levels of poultry meat such as cross-contamination in the kitchen can lead to ingestion of Salmonella (Guillier et al., 2020). The same risk factors are recognised for Campylobacter.

Avian influenza viruses can infect humans. The majority of cases involved the Eurasian H5N1 HP virus and more recently the Chinese H7N9LP virus (Swayne, 2019). The first risk factor for human infection is direct contact with live or dead contaminated poultry. A few cases have resulted from consumption of uncooked poultry products, plucking infected wild swans, or close contact with another human case. Other influenza viruses rarely or not infect humans. Many wild birds, especially palmipeds, are often healthy carriers of these viruses, which they can spread throughout the world during migrations. Outdoor farming is considered to be the major risk factor for the introduction and spread of avian influenza, leading to confinement of animals during the passage of migratory wild birds (Koch & Elbers, 2006). The transport and export of poultry are also very limited or prohibited in the event of an alert.

People in contact with poultry may contract psittacosis. It is a zoonosis transmitted to humans by wild or domestic birds. It is associated with the bacterium Chlamydia psittaci. The sources of contamination most often incriminated are ducks (Vorimore et al., 2015).

Chemical hazards

Poultry meat may be contaminated with chemical residues or environmental pollutants. In European countries, chemical hazards are regularly assessed with national monitoring plans. The EU regulation has provided statutory limits in meat for a large panel of chemical contaminants. Chemical residues concern veterinary products for which the withdrawal period has not been respected or pesticides employed for the production of vegetable raw materials used for feeding manufacturing. Environmental pollutants include mycotoxins, heavy metals, dioxins, polychlorobiphenyls (**PCBs**) and brominated flame retardants (**HBCD**) (Dervilly-Pinel et al., 2017). Mycotoxins can be brought by vegetable raw materials not treated with fungicides especially in organic production or when these raw materials or food are poorly preserved. Exposure to other environmental pollutants is more related to accidents or degraded conditions of livestock buildings and their equipment, in particular insulation materials for HBCD. For example, in January 1999, in Belgium, a mixture of PCBs contaminated with dioxins was inadvertently added to recycled fat and used in animal feed (Bernard et al., 2002). Approximately 2 500 poultry farms may have been delivered with this contaminated feed resulting in a major food crisis that was resolved after a feed monitoring plan was put in place for these contaminants. Studies concerning the contamination of poultry meat with chemical residues and environmental pollutants according to the rearing system are rare. A recent survey conducted in France showed that levels of environmental contaminants (dioxins, PCBs, HBCD, Zn, Cu, Cd, Pb, As) of meat samples were certainly below the permitted regulatory values but higher in organic chickens compared to conventional chickens (Dervilly-Pinel et al., 2017). Indeed, organic chickens have a longer rearing period than conventional chickens and they have an outdoor access, which increases their risk of exposure to environmental contaminants (Dervilly-Pinel et al., 2017). A survey conducted in Netherlands also showed that levels of environmental and feed contaminants and veterinary drugs in poultry meat were below the permitted regulatory values (Banach et al., 2017).

Organoleptic properties

Meat colour

The colour of poultry meat can be affected by feed, especially when naturally occurring or supplemented carotenoid pigments are present in the feed because they are also accumulated in intramuscular fat. "Label Rouge" chickens with yellow skin have a diet richer in corn and carotenoid pigments than "Label Rouge" chickens with white skin. Their fillets are also darker, redder and more yellow. In a survey of several French slaughterhouses, Gigaud et al. (2011) showed that L^*, a^* and b^* values were 48.07, 0.88 and 15.15 for yellow-skinned chickens vs. 49.56, −0.01 and 10.03 for white-skinned chickens. For fatty liver production, ducks are overfed exclusively with corn. Their fillets are richer in carotenoid pigments and the lipid content is doubled in comparison with lean duck fillets (Chartrin et al., 2006). Its colour is rather chocolate brown while the colour of lean duck fillet is dark red. L^* and b^* values are 42.30 and 14.52 for fillets of overfed ducks vs. 32.37 and 9.37 for lean duck fillets (Chartrin et al., 2006). Dietary supplementation with spirulina, an alga rich in carotenoid pigments, at 0, 40 or 80 g/kg had no effect on the lightness and redness of chicken fillet. In contrast, the yellowness increased from 3.5 to 12.3 (Toyomizu et al., 2001). However, the ability to fix carotenoid pigments depends on the genotype. In fact, Le Bihan-Duval et al. (2011) found two SNPs (Single Nucleotide Polymorphisms) on the promoter of the gene encoding beta-carotene 15,15′-monooxygenase (**BCMO1**), a key enzyme involved in the conversion of beta-carotene to retinal. The fillets of chickens carrying one allele (**GG**) are richer in carotenoid pigments (lutein and zeaxanthin) and have a higher yellowness than those carrying the other allele (**AA**). The meat colour especially of yellow-skin birds also depends on the total content of lipids. The higher the lipid content, the lighter the meat and the higher the yellowness. When the average lipid content of duck fillet increases from 2.6 to 5.6%, the lightness and yellowness increase from 34.4 to 41.8 and from 10.4 to 14.2 with correlations of 0.49 and 0.47, respectively (Chartrin et al., 2006). Recently, it was also found that breast meat affected by white striping abnormality showed higher lightness and yellowness because of increased lipid content (Petracci et al., 2017).

However, lightness and redness of the meat are mainly affected by haem protein concentration (myoglobin, haemoglobin and cytochromes). With age, the content of haem pigments increases and the meat becomes redder and darker. Between 8 and 15 weeks of age, the lightness decreased from 45.7 to 35.4 and the redness increased from 8.4 to 16.1 in the fillet of Muscovy duck (Baéza et al., 1998b). In the abovementioned survey, the colour measurement on the fillets showed a darker, redder and more yellow colouration for "Label Rouge" chicken meat compared to certified and conventional chickens slaughtered at earlier ages and having higher fillet yields.

For white meats, the colour strongly depends on muscle glycogen stores at slaughter and postmortem evolution of pH which affects light scattering properties of the resulting meat. In conventional chicken fillets, Berri et al. (2007) showed that the correlation between pHu and glycolytic potential was −0.57 and with lightness it was −0.61. At the genetic level, the correlation between pHu and lightness of fillet is even stronger ranging from −0.65 to −0.91 depending on the strains studied (Le Bihan-Duval et al., 2001 and 2008; Chabault et al., 2012). A divergent experimental selection on fillet pHu of high growth rate chickens confirmed these relationships between this criterion and the colour of the meat (Alnahhas et al., 2014). After five generations of selection, pHu values were 6.09 and 5.67 for high and low pHu lines (pHu + and pHu-, respectively). The pHu + fillets were darker (L^* = 47.50 vs. 52.50), less red (a^* = −0.17 vs. 0.05) and less yellow (b^* = 9.49 vs. 11.02). In addition, the selection of chickens based on increased growth rate and breast muscle yield may result in decreased redness and increased yellowness and lightness by dilution of haem pigments.

However, glycolytic potential and postmortem pH onset are also affected by the preslaughter conditions as a consequence of acute or chronic animal stress. For example, Pekin ducks were exposed to a 10-minute forced exercise after 8 or 24 h of fasting. The fillets and thighs of these ducks were darker, less red and less yellow than those of the control ducks exposed only to 8 h of fasting. For slow-growing chickens suitable for "Label Rouge" production, the longer the duration of the hang-up on the slaughter line prior to narcosis, the redder the fillets are due to the high reactivity of these animals flapping their wings and making attempts at recovery causing a significant influx of blood into the breast muscles (Berri et al., 2005a). Fresh poultry meat colour changes during shelf life according to storage conditions and packaging solutions. For example, there was found a decrease in redness of chicken thigh muscles from 8–9 to 6–7 after 5 days of storage at 8 °C in an illuminated display case 12 h per day or after 9 days of storage at +4 °C in darkness. A decrease in redness was observed when storing duck fillets and thighs at +4 °C. Supplementation with vitamin E and selenium can help to reduce discoloration during cold refrigerated storage by preventing oxidation of haem proteins.

Meat juiciness

Tenderness and juiciness are considered to be the most important quality attributes of fresh meat and meat products. Increased water and/or fat content at the time of consumption are generally associated with increased juiciness. Cooking inducing a decrease in water binding capacity and loss of moisture or fat through drip would decrease juiciness. Therefore, meat juiciness is poorly affected by diet, with the exception of factors that affect meat lipid content. Indeed, when the lipid content of the duck fillet increases from 2.6 to 5.6%, the cooking loss increased from 15.0 to 17.8% with a correlation of 0.54 and the juiciness score increased (Chartrin et al., 2006). Meat juiciness is mainly influenced by age and genotype. For male Muscovy ducks slaughtered at 8 or 15 weeks, the juiciness note after grilling decreased from 6.2 to 5.8 (Baéza et al., 1998b). Culioli et al. (1990) and Rabot (1998) showed that conventional chicken meat cooked in whole roasting carcass (thighs and fillets) was juicier than that of «Label Rouge chickens». For slow-growing chickens slaughtered at different ages between 8 and 16 weeks, Touraille et al. (1981) also reported a decrease with age in the juiciness score of fillets and thighs. The postmortem process may also influence the juiciness of chicken fillets, as the shorter the time between slaughter and deboning, the drier the meat is in the mouth.

Meat texture

Poultry are slaughtered at very early ages compared to red meat species therefore resulting meat is generally considered to be rather tender. The texture of poultry meat is mainly affected by age, genotype, rearing system, slaughter conditions and postmortem carcass processing techniques (electrostimulation, cooling rate, and slaughter-deboning interval) which will influence the evolution of pH and rigor mortis while feeding has negligible effect. For male Muscovy ducks slaughtered at the ages of 8 and 15 weeks, the tenderness score of grilled fillets decreased from 7.06 to 5.94 (Baéza et al., 1998b). For slow-growing chickens slaughtered at different ages between 8 and 16 weeks, Touraille et al. (1981) showed a decrease in tenderness of fillets and thighs with age. The shear force value of cooked fillets and thigh muscles of "Label Rouge" chickens was higher than that of conventional chickens (53 vs. 43 N/cm^2 and 95 vs. 80 N/cm^2, respectively) and the tenderness score was lower (5.66 vs. 7.13, Culioli et al., 1990). This difference is certainly due to the difference in slaughter age (6 vs.12 weeks) but other elements could intervene such as a significantly more acidic meat pHu, a smaller diameter of muscle fibres (Berri et al., 2005b) or an outdoor access of "Label Rouge" chickens that allows them to have greater physical exercise and greater muscle activity. The texture of the meat will also depend on the postmortem evolution of the pH and the rigor mortis phase. When pHu is greater than 6.0, the meat is classified as DFD for "Dark, Firm and Dry" and when pHu is less than 5.7, the meat is classified as acid and it has the characteristics of PSE meat for "Pale, Soft and Exudative". However, this impact on texture only affects raw meat. In fact, after cooking, the opposite is observed. In two experimental chicken lines with an average pHu of 6.09 and 5.67, the shear force value of cooked fillets was 10.9 and 16.0 N/cm^2, respectively (Alnahhas et al., 2014). Roasted fillets and thighs of pHu + chickens were also considered tenderer than those of pHu- chickens (Alnahhas et al., 2015). Recently, it was found that broiler breast fillets affected by growth-related abnormalities exhibited abnormal texture. Indeed, if wooden breast showed a marked increase of toughness assessed by both instrumental and sensory analyses, white-striped and spaghetti meat breasts had slightly lower shear force value than normal fillets (Petracci et al., 2017). The delay between slaughter and deboning has a very marked effect on the tenderness of cooked meat. It is recommended to wait at least 4 h before cutting the fillets from the keel bones to avoid a meat judged hard by the consumer. Chicken fillets cut 45 min or 2 h after slaughter have a higher post-cooking firmness score than chicken fillets cut 24 h after slaughter (6.6 and 6.4 vs. 4.7; Zhuang and Savage, 2011). Meat hardness decreases as a function of the slaughter-deboning interval. The negative effect on the meat texture of early carcass deboning just before or during the period of rigor mortis may, in some cases, be offset by a longer maturation phase. For example, Muscovy duck meat cut 0.5 h after slaughter and stored at +4 °C for 4 days is as tender as duck meat cut 4 days after slaughter (Knust et al., 1997). The negative impact on the meat texture of a short delay between slaughter and deboning is verified regardless of the type of production, with a more marked effect on the fillets of «Label Rouge» chickens whose meat is firmer than that of certified and conventional chickens (Berri et al., 2006).

Gas narcosis, which deprives muscles of oxygen more quickly than electric narcosis, accelerates the entry into the rigor mortis phase, which shortens the delay between slaughter and deboning (Joseph et al., 2013). It is also possible to reduce this delay without altering the meat texture by electrostimulation of the carcasses during the slaughter process. Electrical stimulation after bleeding is more effective than after plucking (Zhuang et al., 2010). The delay between slaughter and deboning can then be reduced to 2 h. The meat texture is also influenced by the cooling temperature of carcasses. When this temperature is around 0 °C, the muscle undergoes a cold contraction phenomenon, especially during the first hour after slaughter not followed by relaxation and altering the subsequent tenderness of meat (Dunn et al., 1993; Papinaho and Fletcher, 1996).

Meat flavour

Meat flavour and taste are mainly thermally derived, since uncooked meat has little or no aroma. Meat become flavoursome only after cooking process, and a series of thermally induced complex reactions that occur between the different non-volatile compounds of the lean and fatty tissues. Diet formulation will therefore have a strong influence on content of flavour components by modulating particularly the lipid content and composition and levels of antioxidants and water soluble volatile compounds. Fillets of overfed ducks, which are richer in fat, have a higher flavour than fillets of lean ducks (Chartrin et al., 2006). Duck meat is richer in phospholipids that are precursors of aromas after cooking, and it has then a flavour considered more pronounced than that of chicken meat. The same applies to thighs compared to fillets (Rabot, 1998). Fatty acid composition is also important, in particular the long-chain *n*-3 PUFA content. The use of fish oils at concentrations greater than 1.5% in the feed has a negative impact on the flavour of chicken meat. Feed supplementation with 2% microalgae is detected during sensory analysis of roasted chicken thighs, with an abnormal flavour qualified as fish taste (Baéza et al., 2015b). On the other hand, the flavour of the fillets, which are less rich in fat, was not modified. Bou et al. (2001) analysed the effect of dietary lipid source on the flavour of cooked chicken thighs after 13 months of storage at −20 °C. The rancid flavour was much more pronounced for PUFA-rich linseed oil than for beef tallow or sunflower oil. Feed supplementation with 225 mg of vitamin E/kg greatly reduced this defect. Sheldon et al. (1997) also showed that feed supplementation with high doses of vitamin E (250–300 ppm) had a positive effect on the flavour of turkey fillets cooked after a storage for 8 days at +4 °C or 90 days at −20 °C. It also reduced the formation of unpleasant flavours after cooking chicken thighs previously stored for 3 or 5 days at +4 °C or 5 or 10 weeks at −20 °C (O'Neill et al., 1998).

The meat flavour and taste are also influenced by age, sex and genotype by their effect on lipid content and composition. Touraille et al. (1981) showed that the flavour of chicken fillets and thighs increased between the ages of 8 and 14 weeks. Comparing slow- and fast-growing chickens slaughtered at 48 or 83 days, Farmer et al. (1997) also observed an increase in fillet flavour with age. However, Culioli et al. (1990), Girard et al. (1993) and Rabot (1998) did not reveal any difference in flavour of "Label Rouge" roasted chicken fillets and thighs compared to those of conventional chickens. The flavour score of roasted Muscovy duck fillets increased from 4.83 to 6.23 between 8 and 15 weeks of age (Baéza et al., 1998b). The selection on chicken fillet pHu also had an impact on the perception of the acidity of roasted or grilled fillets, the chickens of the experimental pHu- line having a higher score than pHu + chickens (Alnahhas et al., 2015). Finally, the storage duration and conditions may also have an impact on the meat flavour. For example, Haugen et al. (2006) noted the development of the rancid odour of skin-free turkey thigh muscles, crushed and stored at −10 °C or −20 °C under an air-permeable or vacuum-sealed plastic film. The rancid odour developed more intensely during preservation under plastic film at −10 °C especially after 20 days of storage. The formation of unpleasant odours during storage at +8 °C of chicken fillets under a modified atmosphere (0, 2 or 4% oxygen) was faster (2 vs. 5 days) and more important (score 5 vs. 4) than that observed at +4 °C (Pettersen et al., 2004). Chicken fillets stored under a modified atmosphere (70% CO_2, 30 % N_2) had higher taste and odour scores than fillets stored under air-permeable plastic film, especially after 6 days of storage at +4 °C (Latou et al., 2014).

Nutritional properties

Proteins and amino acids

Chicken meat has a high protein content around 23–25% in the fillet and 18% in the thigh (Rabot, 1998; Berri et al., 2005b; Baéza et al., 2012). The main amino acids are glutamine, asparagine, lysine, leucine, arginine and alanine. The amino acid composition of poultry meat is relatively stable. However, it can vary slightly by modulating the amino acid intake of the diet. Increasing the dietary level in valine, isoleucine and leucine to 150% of the growth requirement, 10 days before slaughter, increased the glutamate content (precursor of the umami aroma sought in some Asian countries) of chicken fillets (+30%) compared to fillets of chickens fed a diet at 100% of the growth requirement.

The protein content of poultry meat is mainly influenced by the slaughter age. For a heavy strain of conventional chickens, the protein content of fillets increased from 23.5% to 24.9% between 35 and 63 days of age (Baéza et al., 2012). The protein content of mule duck fillet increased from 20.6% to 22.4% when animals were slaughtered at 8 or 13 weeks of age (Baéza et al., 2000). With selection on the growth rate, the slaughter age of conventional chicken is steadily decreasing. This results in an increased ratio of moisture/protein contents of the fillets, which according to European legislation should not exceed 3.40. It was showed that, in Germany, for conventional chicken production, this ratio increased from 3.10 in 1993 to 3.31 in 2012, with an increased proportion of fillets exceeding the legal limit value. Age will also affect the collagen content of the meat. This content is halved in the Muscovy duck fillet between 8 and 12 weeks of age (Baéza et al., 2002). In chicken fillets and thighs, it varies between 8.7 and 7.3 mg/g and 16.1 and 17.4 mg/g, respectively, between 8 and 16 weeks of age (Touraille et al., 1981). Recently, with the appearance of growth-related abnormalities such as «white striping» or «wooden breast», there has been a significant decrease in muscle protein content and an increase in collagen content associated with their occurrence (Mudalal et al., 2014; Mazzoni et al., 2015).

Lipids and fatty acids

The most variable fraction concerns lipids. The average fat content is 1.3% in the fillet and 4.5% in the thigh of conventional chicken (Rabot, 1998). Turkey and «Label Rouge» chicken meat is leaner (0.8% in the fillet). Duck meat is fatter (1.5–2% in the fillet depending on the species; Baéza, 2000). Within lipids, the most variable fraction is that of triglycerides, the amount of which is positively correlated with that of the lipid content: 0.7% in the fillet and 3% in the thigh of chicken (Rabot, 1998), 0.5–0.8% in the duck fillet (Baéza, 2000). Phospholipid content is 0.6% in the fillet and 0.8% in the thigh of chicken (Rabot, 1998). In duck fillet, this content is 1.1% (Baéza, 2000). The cholesterol content is 0.05% in the fillet and 0.09% in the thigh of chicken (Rabot, 1998). It is comprised between 0.07 and 0.12% in the duck fillet (Baéza, 2000). Feed will affect the intramuscular lipid content mainly by the energy content of diets and especially by the energy/protein ratio or when the intake of essential amino acids (lysine, methionine) is lower than the requirement for growth. By increasing feed lipid content by 30 or 90 g/kg, the lipid content of male turkey fillet was increased by 14% and 40% and that of thigh by 27% and 53% compared to the control, in parallel with an increase in BW (Salmon and Stevens, 1989). In this same study, when the energy/protein ratio increased from 65 to 83 KJ/g, the lipid content of the fillet decreased by 27% and that of the thigh by 5%, in parallel with a decrease in BW. Conde-Aguilera et al. (2013) compared two levels of dietary methionine intake in chickens between 7 and 42 days. By reducing this intake by 34% compared to growth requirement, the fillet lipid content was increased by 28% at the age of 42 days. In contrast, the energy source of the diet (carbohydrates or fats) had no effect on the intramuscular fat content of chicken (Baéza et al., 2015c). The dietary restriction decreases intramuscular lipid content, while overfeeding, practised only in ducks and geese, will double this content (Baéza, 2000).

The lipid content of poultry meat is also influenced by age, genotype, and production system. For a heavy strain of conventional chicken, the fillet lipid content increased from 1.29% to 1.68% between 35 and 63 days of age (Baéza et al., 2012). In male mule duck, the fillet lipid content increased from 1.79% to 2.74% between 8 and 13 weeks of age (Baéza et al., 2000). Comparing five genotypes of chickens with different growth rates, and therefore different slaughter ages and slaughter weight of 1.5–2 kg, Tang et al. (2009) showed that the average lipid content of breast and thigh muscles ranged from 0.96 to 1.42%. Old breeds of chickens with very slow growth rates are generally fatter than commercial hybrids because they have not been selected against fattening. This is the case, for example, of «Géline de Touraine» chicken, which had a lipid content in the fillet and thigh of 1.2% and 10.5%, respectively at 84 days of age, whereas for a strain used in «Label Rouge» production and reared under the same conditions, these contents were 0.9 and 7.0%, respectively (Baéza et al., 2010). During the last decade, there was observed an increase in meat lipid content of breast meat affected by growth-related abnormalities (Mudalal et al., 2014; Mazzoni et al., 2015). An aforementioned survey, carried out in several French slaughterhouses, showed that the fillet lipid content was 0.89, 1.07 and 1.31% for «Label Rouge», certified and conventional productions, respectively. Slow-growing chickens were reared in a closed building or with free-range access. The thigh lipid content was higher for chickens reared in confinement (10.3 vs. 8.5%) while the fillet lipid content (2.1 vs. 1.9%) was not affected by the rearing system.

Fatty acids (**FAs**) in chicken meat consist of approximately one-third of saturated fatty acids (**SFAs**), one-third of monounsaturated fatty acids (**MUFAs**) and one-third of polyunsaturated fatty acids (**PUFAs**) (Rabot, 1998). Oleic acid is the main MUFA (5/6) followed by palmitoleic acid (1/6). The main PUFAs are linoleic and arachidonic acids. Total lipids in chicken muscles also contain linolenic acid and long-chain PUFA from *n*-6 and *n*-3 series. The main factor of variation in poultry meat FA composition is the feed FA composition. Palm and copra oils increase the proportions of short-chain and saturated FAs; animal fat enriches the lipid deposits of chicken with palmitic and stearic acids. Conversely, with vegetable oils, the proportions of PUFAs with 18 carbon atoms increase. On the other hand, marine oils significantly increase the proportions of long-chain *n*-3 PUFAs (Lessire, 2001).

Since 2001, the replacement of animal origin fats (tallow and lard) by vegetable oils (rapeseed, soya or flax) in poultry feed increased the proportion of PUFAs in poultry meat. Before this date, a criterion to discriminate the nutritional quality of «Label Rouge» chickens relative to conventional chickens was a higher proportion of PUFAs in meat (30.9% vs. 27.2% in tender loin; Girard et al., 1993). Now, conventional chickens have higher meat content in PUFAs than "Label Rouge" chickens (30.02 vs. 21.21% in the fillet; Chartrin et al., 2005), due to a higher dietary intake (lipid content of conventional chicken diets is higher than that of "Label Rouge" chicken diets), and also a higher lipid content in meat (1.25 vs. 1.18%; Chartrin et al., 2005).

In Western countries, the daily intake in FAs is not satisfactory because the ratio of *n*-6 FAs/*n*-3 FAs is around 15, while a value of five is recommended. Several studies have been undertaken to enrich fresh chicken meat with *n*-3 FAs. The use of fish oils rich in long-chain *n*-3 PUFAs is the most effective way. Fish oils can be replaced by microalgae. It is also possible to use linseed or rapeseed oils that are rich in linolenic acid, although in this case, the proportion of long-chain *n*-3 PUFAs deposited in the muscles remains low. Baéza et al. (2015a) showed that the combination of extruded flaxseed with microalgae in feed for conventional chicken succeed to enrich the meat with linolenic acid and long-chain *n*-3 FAs with a *n*-6 FA/*n*-3 FA ratio of 3.65 in comparison with a soy oil based diet, rich in *n*-6 FAs and a *n*-6 FA/*n*-3 FA ratio of 11.52.

A given diet should be administered for at least two weeks in order to modify significantly the FA composition of meat as shown in Fig. 2 (Lessire, 2001).

Numerous studies have also investigated the enrichment of poultry meat with conjugated linoleic acids (CLAs). Du and Ahn (2002) and Sirri et al. (2003) tested different levels of dietary CLA intakes in chicken from 0.25 to 4% for 3 to 5 weeks. The deposition of CLA in meat increased with the increasing feed CLA content while the oleic, palmitoleic and arachidonic acid contents decreased. A combined dietary intake of CLA with fish oil increased the efficiency of deposition in the long-chain *n*-3 PUFAs and CLA in chicken muscles compared to a single intake of CLA or fish oil.

More recently, the use of fat from insect larvae was used as an alternative fat source to soybean oil. As a consequence, in the chicken meat (breast and thigh), the proportion of SFAs (particularly lauric and myristic acids) was increased to the detriment of PUFAs. The *n*-6 FA/*n*-3 FA ratio was also increased (Schiavone et al., 2017; Cullere et al., 2019).

The feed energy source may also influence the FA composition of poultry meat. A high-carbohydrate diet will promote liver lipogenesis and therefore the synthesis of SFAs and MUFAs, while a high-fat diet will rather promote the direct deposit of dietary FAs in peripheral tissues (Baéza et al., 2015c). In the extreme case of overfeeding, the daily intake of carbohydrates (corn starch) is very high. Hepatic lipogenesis is strongly stimulated and particularly the synthesis of palmitoleic and oleic acids that are then deposited in peripheral tissues (adipose and muscle tissues). In the fillet of overfed ducks, MUFAs and PUFAs proportions are 50 and 16% of total FAs, respectively vs. 36 and 31% in the fillet of mean ducks (Girard et al., 1993).

Other factors can affect the FA composition of poultry meat, such as age, species and genotype, which will intervene indirectly by modulating the lipid content of the meat. An increase in lipid content will result in an increase in the percentage of neo-synthesised MUFAs to the detriment of PUFAs and vice versa. For example, in fillets of mule duck slaughtered at 8 or 13 weeks, the proportion of MUFAs increased from 29.6 to 33.0%, while that of PUFAs decreased from 35.5 to 32.1% and that of SFAs remained stable (35.2 and 34.3%, Baéza et al., 2000). The rearing system will mainly intervene through feed and access or not to free range. Fillets of grass-fed geese and supplemented with 140 g corn per day from 10 to 24 weeks had higher SFA (33.1 vs. 29.9%) and PUFA (21.9 vs. 19.8%) levels and lower MUFA content (43.7 vs. 49.3%) than geese reared in confinement with a finishing diet from 10 to 14 weeks (Baéza et al., 1998a).

Depending on the studies, the FA composition of poultry meat may also vary or not during storage at +4 °C or −20 °C. Cooking may have or not an effect on the FA composition. For example, Baéza et al. (2013) showed that curing-cooking process had few impacts on the FA composition of chicken fillets. The same was true after 30 min of cooking at 80 °C a mixture of ground turkey muscles (25% fillets, 25% thighs, 50% mechanically separated meat; Ahn et al., 1993). The CLA content of chicken thighs is little modified by roasting. On the other hand, it is decreased when the meat is boiled or fried (Franczyk-Zarow et al., 2017). After roasting whole chicken carcasses, the composition of the meat is modified because the fatty acids of the subcutaneous adipose tissue will migrate to the meat. These are mainly SFAs and MUFAs from triglycerides (Rabot, 1998). A MUFA increase in meat of mallard duck carcasses roasted with skin was also observed.

Minerals and trace elements

The mineral content (mainly calcium, phosphorus and potassium) of poultry meat is 1.1% (Rabot, 1998). This parameter is little affected by feeding and other rearing factors as long as the dietary intakes cover the animal requirements.

Poultry meat also contains different micronutrients (vitamins, carotenoid pigments, trace elements, Table 3) whose content will depend mainly on dietary intake.

Several studies have been undertaken to enrich poultry meat with vitamin E but also vitamins A and C. The deposition efficiency of dietary vitamin E in muscles depends on species. It is twice as high in chicken compared to turkey (Gong et al., 2010). Free-range access increases vitamin E content in chicken meat (Michalczuk et al., 2017). Poultry feed is often supplemented with carotenoid pigments to increase the yellowness of chicken skin. For example, fillets and thighs of chickens fed a diet containing long-chain PUFA *n*-3 rich microalgae had a carotenoid content twice as high as those of control chickens (Kalogeropoulos et al., 2010). The deposition efficiency of dietary intake carotenoid pigments depends on the genotype. The effect of a mutation on the promoter of the BCMO1 gene on the muscle's ability to store these pigments was discussed earlier (Le Bihan-Duval et al., 2011). The enrichment of meat with various trace elements such as selenium and magnesium has also been tested. By distributing supplemented feed with four increasing levels of selenium (0, 0.2, 0.4 and 0.6 mg/kg) to Pekin ducks from 0 to 49 days of age, Baltić et al. (2015) showed that the selenium content increased from 0.05 to 0.87 mg/kg in the fillet and from 0.04 to 0.64 mg/kg in the thigh. Selenium can be provided under different forms but the organic forms (selenium yeast, seleno-methionine) allow the most effective deposition in muscles compared to mineral forms (sodium selenite) (Briens et al., 2013 in chicken). Dietary zinc supplementation does not necessarily increase the zinc content of poultry meat (Bou et al., 2004; 2005).

Technological properties

The technological properties of poultry meat correspond to its ability to be used for processing and shelf life during refrigerated and frozen storage.

Processing ability of poultry meat

The processing ability can be assessed by the water holding capacity and by measuring the juice losses during storage at +4 °C or after thawing and/or cooking and by determining the technological yield by measuring material loss after processing. The water holding capacity depends largely on the meat protein content and ultimate pH (**pHu**) that affects the conformation of muscle proteins and their functionality. Le Bihan-Duval et al. (2008) estimated genetic correlations of −0.89 and −0.80 between pHu on one hand and exudate and juice loss from chicken fillets on the other. Many factors can affect water holding capacity of meat.

Feed has an indirect effect by first modulating the muscle glycolytic stores at slaughter and thus the meat pHu. For example, Berri et al. (2008) tested variable digestible lysine content of the finishing diet distributed to standard chickens. When this content increased from 0.83 to 1.13%, the juice loss after 4 days of storage at +4 °C decreased from 1.10 to 0.87%. Jlali et al. (2012) compared two isoenergetic finishing diets with different protein contents. Fillets of chickens fed diet containing 23% proteins had higher juice loss after 4 days of storage at +4 °C than chickens fed diet containing 17% proteins (1.30 vs. 1.08%). In order to better define the response governing changes in fillet quality as a function of amino acid intake, several studies have shown that beyond the amount of proteins, the amino acid profile of diet could influence meat pHu and some associated traits (colour, exudate). The results showed that an excess intake of amino acids (+10%), combined with a low intake of lysine (0.7–0.8%), favoured the production of acid and exudative meat. Beyond pHu, the degree of muscle oxidation can also affect the technological properties of meat. Thus, the use of DL-HMTBA (hydroxyl-analogue of methionine) significantly improved the functional properties of chicken fillet (juice loss after cold storage and technological yield) by reducing the muscle oxidation extent (Mercier et al., 2009).

Antioxidants have direct effect on the water holding capacity of meat. For example, by increasing the amount of selenium yeast in feed from 0.15 to 0.60 ppm, Oliveira et al. (2014) reduced juice loss after cooking chicken fillets from 21 to 16%. The feed supplementation with 40 or 80 ppm zinc also increased the water holding capacity of chicken fillets compared to not supplemented controls (63–66 vs. 56%).

The water holding capacity can also be influenced by age, genotype, preslaughter conditions and postmortem evolution of meat pH. The effect of age on the water holding capacity is variable according to species. For standard heavy chickens slaughtered between 35 and 63 days of age, juice loss after 4 days of storage at +4 °C and after cooking decreased from 2.02 to 1% and from 18.8 to 17.4%, respectively (Baéza et al., 2012). Conversely, for fillets of Muscovy ducks slaughtered between 8 and 15 weeks of age, the juice loss after 24 h storage at +4 °C increased from 0.68 to 1.62% (Baéza et al., 1998b). For fillets of mule ducks slaughtered between 8 and 13 weeks of age, juice loss after 24 h storage at +4 °C was not affected by age (Baéza et al., 2000).

The effect of genotype likely depends on the ability of the animal to store energy in muscles. For example, juice loss after 2 days of storage at +4 °C was higher in fillets of "Label Rouge" chickens compared to fillets of standard chickens (1.64 vs. 1.24%) (Berri et al., 2005b). Consistent with this result, the technological yield after curing and cooking fillets was higher in standard chickens compared to "Label Rouge" chickens (106.8 vs. 100.0%). A chicken line, selected for a high pHu in the fillet, had lower juice loss after 5 days of storage at +4 °C or after cooking than the line selected for a more acid pHu (2.20 vs. 3.80% and 10.2 vs. 11.9%, respectively) (Alnahhas et al., 2014). Consistent with these differences, the technological yield after curing and cooking was higher for the high pHu line (86.6 vs. 80.5%). Chicken fillets with a severe "white striping" defect had higher cooking losses than normal fillets (26.7 vs. 21.3%) (Petracci et al., 2013). Fillets with "wooden breast" defect had higher juice loss after cold storage but also after cooking than normal fillets (1.19 vs. 0.93% and 28.0 vs. 21.6%, respectively; Mudalal et al., 2015). Marinade intake and technological yield were also much lower for "wooden breast" fillets compared to normal fillets (6.94 vs. 13.15% and 87.3 vs. 94.5%, respectively).

The preslaughter conditions can also affect the glycolytic reserves of muscles and therefore its water holding capacity. For example, comparing exposure of chickens to different temperatures during preslaughter transport, Dadgar et al. (2011) showed that negative temperatures (−14 to −17 °C) induced a decrease in muscle glycogen reserves and thereby increased pHu and reduced fillet cooking loss (10.52 vs. 13.45%) compared with positive temperatures (20–22 °C).

Chemical shelf life of poultry meat

The shelf life basically depends on microbial spoilage and on time–temperature history of the products. The intrinsic properties of meat may also evolve which may lead to lipid and protein oxidation. Only the latter will be covered in this review. First, the oxidative stability depends on the muscle type and poultry species. Thighs having a higher lipid content than fillets are more susceptible to oxidation. Turkey meat is more susceptible to oxidation than chicken and duck meat (Fig. 3) due to its lower ability to bind antioxidant molecules such as vitamin E in muscle tissues (Gong et al., 2010). Poultry meat has a high content of unsaturated fatty acids that increases its susceptibility to oxidation.

Oxidative stability is strongly influenced by feed that will affect the lipid, PUFA and antioxidant contents of meat. It also depends on the preservation conditions. For example, Cortinas et al. (2005) compared four levels of PUFA in feed (15, 34, 45 and 61%) and four conditions to preserve chicken thighs (raw meat, raw meat refrigerated 3 days at +4 °C, cooked meat and cooked meat stored 2 months at +4 °C). The oxidation susceptibility of meat increased with PUFA content (Fig. 4). The TBARS (Thio-BArbituric Reactive Substances) index (indicator of lipid peroxidation) increased with storage duration at +4 °C. Cooking also promoted oxidation (Fig. 4). Vacuum-packed and cooked chicken fillets stored at +4 °C were more susceptible to oxidation than raw chicken fillets vacuum-cooked only at the end of the storage period (Hong et al., 2015). Jankowski et al. (2012) compared three different oils in feed (soybean, rapeseed and linseed). The highest TBARS index in turkey fillets was obtained with the lowest ratio *n*-6 FA/*n*-3 FA in feed (17.07 vs. 15.64 and 10.91 nmol/g for linseed, rapeseed and soybean based diets, respectively). A storage of turkey fillets for 4 months at −20 °C strongly promoted lipid oxidation especially for the linseed oil-fed group for which the TBARS index was multiplied by 4.7 when compared to non-frozen meat. The use of linseed oil in the feed also promoted protein oxidation in

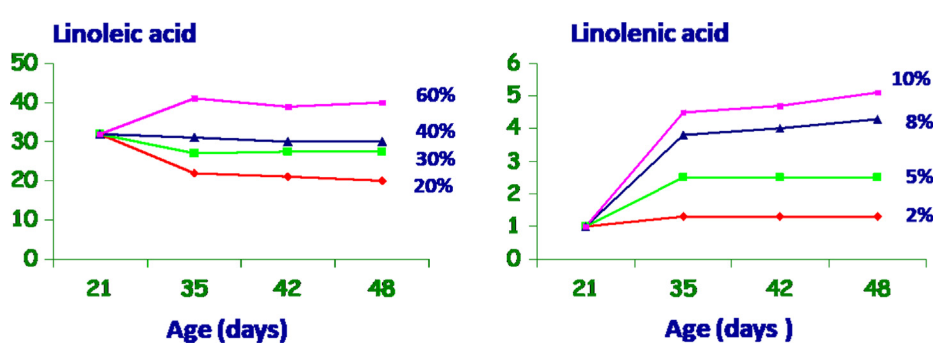

Fig. 2. Incorporation kinetic of linoleic and linolenic acids (% total fatty acids) in the triglycerides of chicken breast meat depending on dietary fatty acid intake and chicken age (derived from Viau et al., 1999; Gandemer et al., 1999).

Table 3
Micronutrient content of raw chicken meat (derived from Favier et al., 1995).

Micronutrients (mg/100 g)	Levels
Sodium	76
Magnesium	25
Iron	1
Retinol (μg)	12
Vitamin D (μg)	0.1
Vitamin E	0.22
Thiamine	0.08
Riboflavine	0.16
Niacine	7.7
Pantothenic acid	1.1
Vitamin B6	0.45
Vitamin B12 (μg)	0.4
Folates (μg)	10

chicken thighs (Kralik et al., 2012). Mercier et al. (1998) also showed that protein oxidation was higher in the Sartorius thigh muscle of turkeys fed diet containing soybean oil compared with turkeys fed diet containing tallow. The production system can also have an impact. The TBARS index of fillets and thighs from chickens reared under organic conditions was higher than that measured for chickens reared under conventional conditions, whereas for the lipid content, it was the reverse (Castellini et al., 2002).

The pH may also affect the oxidation susceptibility of meat. The more acid a meat is, the greater the risk of oxidation. In a chicken line selected for an acid pHu in breast muscle, the TBARS index of fillets preserved at +4 °C for 8 days was higher than that measured in chicken fillets of the line selected for a high pHu (0.65 vs. 0.50 mg MDA equivalent/kg meat) (Alnahhas et al., 2015).

The use of antioxidants in feed limits the oxidation susceptibility of meat. For example, a dietary supplementation with 400 mg vitamin E/kg feed induced a decrease in the TBARS value in the Pectoralis major and Sartorius muscles of turkeys stored at +4 °C for 1, 3 or 9 days. The TBARS value was divided by 2 to 3 depending on the muscle and the storage duration. Vitamin E supplementation also limited the formation of cholesterol oxidation products. For chicken meat cooked, then stored 12 days at +4 °C, this reduction was 42% and 75% for fillets and 50% and 72% for thighs when vitamin E supplementation was 200 or 800 mg/kg compared to a control diet supplemented with 20 mg vitamin E/kg (Galvin et al., 1998). The antioxidant effect of vitamin E can be increased when combined with other compounds such as oregano essential oil. The preservation of chicken meat placed under vacuum in a package composed of biopolymers with antioxidant molecules can also limit the oxidation risk. Chicken fillets vacuum-packed with a chitosan biopolymer combined with different concentrations of grape seed extracts (5, 10 and 15%) were stored at +4 °C. The 15% intake inhibited the oxidation of fillets after 15 days of storage.

Consumer attitudes and perception

Poultry meat is generally well perceived by consumers for its high protein content, low lipid content and high proportion of unsaturated fatty acids. The success of poultry meat is also due to its affordability, sensory properties, ease of preparation, and absence of religious restraints. In terms of taste, the consumer has a wide choice of red meats (thighs, duck fillets) or white meats (turkey fillets and chickens) of different tenderness and flavour (conventional chicken, chicken "Label Rouge"). Nevertheless, these positive points are counterbalanced by increasingly violent criticisms of production system, the conventional system remaining the main model in all producing countries. Critics can be classified into four categories: environmental impact, animal well-being and ethics, health risk and the economic and social organisation of livestock farming (Magdelaine et al., 2018).

The environmental debates concern the pollution caused by livestock farming, and more particularly by animal discharges (gases or manure) that contribute to global warming, and soil and water pollution. More locally, conflicts concern the production of nuisances (odours, noises, landscape modifications). The farming activity itself consumes resources which could be directly used by man. Poultry sectors try to respond to these criticisms by implementing different solutions. To limit manure, the feed efficiency of animals has been improved by genetic selection (De Verdal et al., 2011) and by supplementing feed with enzymes that promote digestion and absorption of nutrients (Beckers and Piron, 2009). In France, manure and slurry spreading plans are defined taking into account the standards which are reviewed regularly. To limit odours, farmers can use additives placed in bedding or slurry pits or cover them. There are also recommendations and regulations for the implementation of fertiliser application on soils (Gaillot et al., 2015). Poultry feed uses many co-products from the agro-food industry which could not be valued for human consumption, such as meal from the production of vegetable oils from oilseeds or wheat and maize distillers from the production of bioethanol or from the brewing process. The environmental impact of animal production has been the subject of several life cycle analysis studies (Aubin, 2014). Since food can account for 30–95% of the environmental impacts of animal products leaving the farm, a multi-objective formulation methodology has been developed to produce eco-foods with reduced impacts and controlled prices (Wilfart et al., 2018). Other solutions include the renewal of the livestock farm with better insulation, the use of heat recovery air exchangers and low-energy lighting to save energy and even the methanisation of manure and slurry.

Debates on the treatment of animals on farms, from their housing conditions (confinement or outdoor rearing) to the handling carried out by the hatchery, the farmer or the slaughterhouse continue to increase. More generally, the intensive farming system is assimilated by many associations to an industrial process. Faced with these criticisms, the animal sectors put in place different responses (Roguet et al., 2018). In partnership with animal protection organisations, for example, a distributor in France created an animal welfare labelling at the end of 2018 (Haverland, 2020). A tool for assessing animal welfare in livestock farming has also been developed for and by poultry sectors with a digital smartphone application (ITAVI, 2018) and based on the data of the European "Welfare Quality" research project (Veissier et al., 2005).

The use of efficient strains results in a greater animal susceptibility to pathologies and climatic hazards, higher mortality and probably higher use of drugs. However, the use of antibiotics on farm animals raises the question of the impact on human health of their possible residues in meat and the development of microbial resistance to these treatments. The use of antibiotics in feed as growth promoters has been banned in the EU since 2006. Since 2012, a reduction in the use of antibiotics during proven pathologies has also been implemented. The follow-up of sales of veterinary drugs containing antibiotics in France in 2017 reveals that the level of exposure of poultry to antibiotics has decreased by 21.3% since 1999 (ANSES, 2018). This reduction has been accompanied by the development of alternative products (probiotics, prebiotics, phytotherapy, etc.; Ducrot et al., 2017).

Tensions between the properties that constitute quality and stakeholders

The various properties that constitute quality can be in tension, as can the interests of the different stakeholders, which highlights

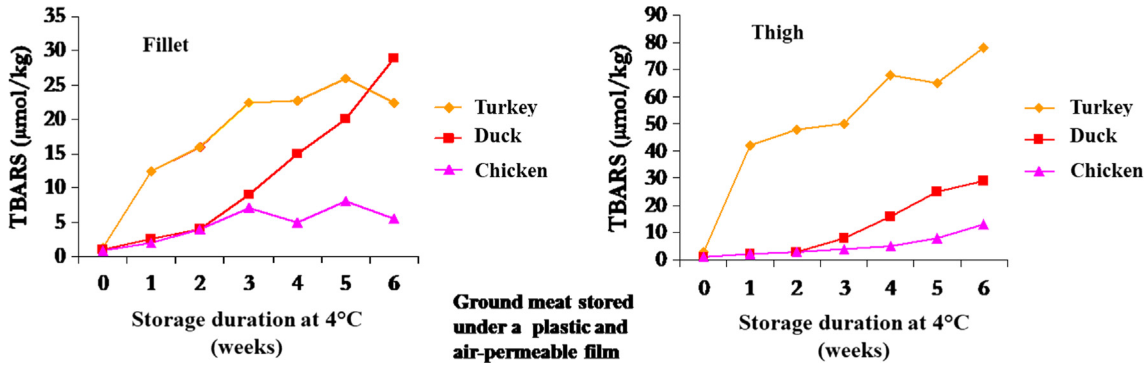

Fig. 3. Oxidation susceptibility of chicken, duck and turkey thighs and fillets stored at +4 °C and estimated with TBARS (thiobarbituric acid reactive substances) value measured on ground meat (derived from Gong et al., 2010).

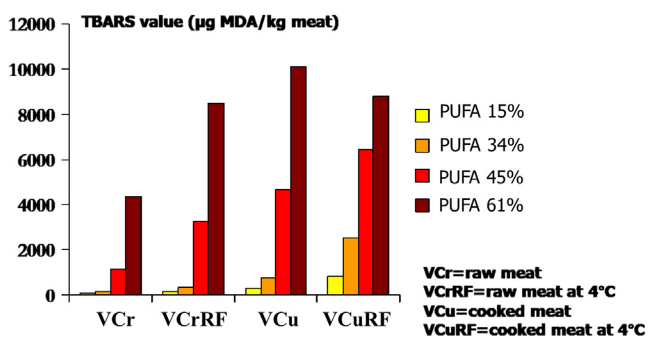

Fig. 4. Effect of dietary polyunsaturated fatty acid (PUFA) level on the oxidation susceptibility of raw or cooked chicken thigh meat stored or not at 4 °C (derived from Cortinas et al., 2005) MDA = malondialdehyde; TBARSs = thiobarbituric acid reactive substances.

the need to seek ways of trade-offs or solutions to overcome the negative effects.

Selection for high growth rate and breast meat yield

The production of conventional poultry meat is the majority. Alternative productions are mainly in the whole carcass and cut-off segment and their penetration rate in the processed segment is low. Three-quarters of the poultry production in France is sold under cuts or processed products (ITAVI, 2019). These products are largely derived from the conventional poultry production characterised by a high growth rate and high breast yield, the fillet being particularly popular for consumers and meat processing industry of Western countries. The selection therefore focused its efforts on the growth rate, but also on increasing the breast yield with spectacular progress achieved very quickly (Petracci et al., 2017). First, this induced a decrease in the muscle glycolytic reserves and increased pHu and thus technological yield of fillets. In recent years, new practices have been put in place that favour an older slaughter age (56–63 d vs. 35 d) in order to increase slaughter weight of fast-growing chickens used for conventional production. In connection with these developments, several quality defects affecting the integrity and composition of the muscles, particularly, the fillet have appeared over the past ten years (Petracci et al., 2015). The four main defects identified in poultry (chicken in particular) are "white striping", "wooden breast", "spaghetti muscle" and "Oregon disease" (Fig. 5). Several strategies have been tested to reduce the frequency or severity of these defects but none are satisfactory. The only effective solution would be to revert to the use of lines with lower meat yield.

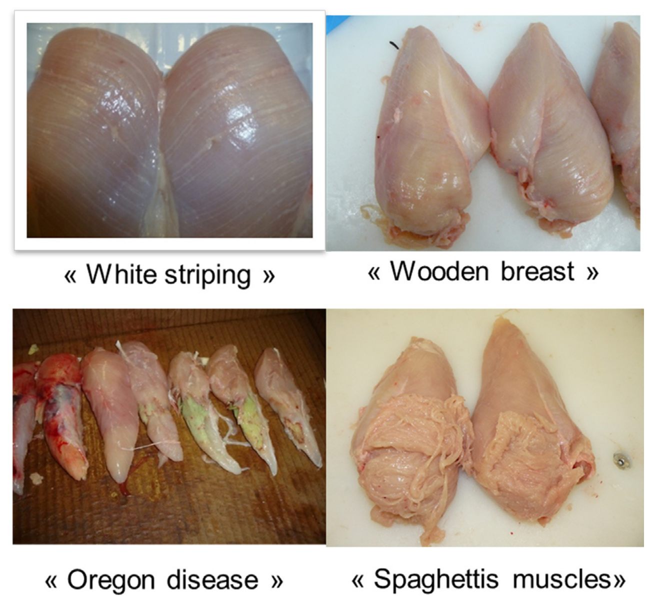

Fig. 5. Quality defects of chicken breast muscles.

Alternative productions vs. conventional production

Alternative products have been created to meet the expectations of consumers on organoleptic aspects («Label Rouge»), animal welfare, health (organic, "Bleu, Blanc, Coeur" gait) and production traceability (Protected Geographical Indication, Protected Designation of Origin, short circuits and direct sales) which has a rather positive impact on the social pillar of sustainability. However, the impact of alternative productions on the environmental pillar is not necessarily positive, since rearing period of these chickens is longer than that of conventional chickens involving a higher quantity of feed to be produced, more water consumption and higher amount of manure (Benoit and Méda, 2017). In addition, outdoor access also increases the land use. The impact on the economic pillar depends largely on the price at which these products can be marketed. Clearly, these alternative products are not competitive at all compared to conventional production and their economic viability is therefore based on a higher selling price (Benoit and Méda, 2017; Rocchi et al., 2019). Unfortunately, the apparent willingness to pay (**WTP**) for high welfare chicken meat does not always translate (Castellini et al., 2008). Price differential is a major barrier to purchasing high welfare chicken meat with consumers primarily choosing on sell-by date and appearance as

Table 4
Positive and negative aspects of "Label Rouge" and organic chickens compared to conventional chicken.

Properties	Positive aspects	Negative aspects
Commercial	Firmer skeleton Thicker and more resistant skin to tearing when pluming Lower carcass fatness	Lower carcass and breast yields Higher variability
Organoleptic	More pronounced flavour Darker and redder meat	Firmer and less juicy meat Higher variability
Nutritional	Higher protein content Lower lipid content	Lower polyunsaturated fatty acid content
Technological		Lower technological yield
Sanitary	Lower contamination with chemical residues (drugs, phytosanitary products) for organic chicken	Higher exposure to parasites, Influenza virus, Campylobacter and environmental pollutants
Image	Better consideration of animal welfare (density, outdoor access, farm size, enrichment of environment, slower growth rate) Greater traceability of animals and production system Annual control of compliance with the specifications	Greater use of land, soil degradation in the vicinity of buildings Greater feed consumption and greater manure production

Table 5
Main factors related to quality variability of poultry carcass and meat.

Factors	Commercial properties	Organoleptic properties	Nutritional properties	Technological properties
Strain (growth rate)	+++	+++	++	+++
Age	+++	+++	++	+++
Sex	+	+	+	+
Feed characteristics	++	++	++	+++
Rearing conditions	++	+	+	+
Preslaughter conditions	+	+	–	+
Slaughter conditions	+	+	–	+
Postmortem treatment of carcass and meat	+	+	–	+
Cooking conditions	–	+++	++	++

No effect (–), low effect (+), average effect (++), strong effect (+++).

a mark of quality and freshness (Hall and Sandilands, 2007). Kaygisiz et al. (2019) clearly showed that the income level had a significant effect on the probability of purchasing organic chicken meat. A survey in Canada showed that consumers' WTP was negatively affected by product price (Michel et al. (2011)). On the other hand, Mulder and Zomer (2017) showed that WTP was higher if consumers knew that animal welfare practices were subject to public or collective supervision. Their findings suggested that the market for broiler chickens could be improved by raising consumer confidence in the labelling system. For Van Loo et al. (2011), WTP depended on the purchase frequency of organic chicken meat and the confidence in the labelling system, USDA organic products being preferred to general organic label products. The negative and positive aspects of "Label Rouge" and organic chickens compared to conventional chicken are summarised in Table 4.

Conclusions

The main factors explaining the quality variability of poultry carcass and meat are summarised in Table 5. They are first related to animal characteristics and particularly species, strain, age and sex. The organoleptic and nutritional properties depend on muscle type or meat piece but also on preslaughter, slaughter and storage conditions. Feed has the greater impact on organoleptic, nutritional and technological properties of poultry products. The image properties depend mainly on rearing conditions (outdoor access, group size, area available per animal, housing arrangements). The cooking conditions have an effect on organoleptic and nutritional meat properties. It should be noted that most of the specifications of the alternative production systems make specific commitments relating to these different variation factors and that the common ownership of all of them corresponds to the image properties which group together factors that ultimately have few effects on the other properties of poultry products. The sanitary properties of the products are a prerequisite. First of all, they mainly depend on animal health practices and on the hygiene and bio-safety measures put in place by the farmer. The farm type (mixed or specialised) is an important factor because rearing several species (for example, chickens and cattle) may promote the spread of pathogens. The rearing system is also important, because the outdoor access and a longer rearing period increase the risk of exposure to pathogens (Campylobacter, parasites) and/or environmental contaminants. Finally, the slaughter, storage and cooking processes also have a major effect on sanitary poultry meat properties. The poultry sector has created various alternative production systems to answer the different consumer expectations. Now, the development of these alternative products mainly depends on the price the consumers are willing to pay.

Ethics approval

Not applicable.

Data and model availability statement

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

Author ORCIDs

E. Baéza: https://orcid.org/0000-0001-7658-3394.
L. Guillier: https://orcid.org/0000-0002-7867-2937.
M. Petracci: https://orcid.org/0000-0002-5671-5676.

Author contribution

E. Baéza: Writing-Review and Editing.
L. Guillier: Writing-Original Draft.

M. Petracci: Writing-Original Draft.

Declaration of interest

None.

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