Animal 16 (2022) 100425

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Review: Production factors affecting the quality of chicken table eggs and egg products in Europe

J. Gautron [a,*], C. Dombre [a], F. Nau [b], C. Feidt [c], L. Guillier [d]

[a] INRAE, Université deTours, BOA, 37380 Nouzilly, France
[b] STLO, INRAE, Institut Agro, 35042 Rennes, France
[c] Université de Lorraine, INRAE, URAFPA, 54000 Nancy, France
[d] French Agency for Food, Environmental and Occupational Health and Safety (ANSES), Risk Assessment Department, 94700 Maisons-Alfort, France

ARTICLE INFO

Article history:
Received 12 May 2021
Revised 8 November 2021
Accepted 18 November 2021
Available online 23 December 2021

Keywords:
Edible eggs
Egg characteristics
Production systems
Quality attributes
Variability

ABSTRACT

The hen's egg (*Gallus gallus*) is an animal product of great agronomic interest, with a world production of 70.9 million tonnes in 2018. China accounted for 35% of world production, followed by North America (12% of world production), the European Union (7.0 million tonnes, 10% of world production) and India (5.0 million tonnes, 7% of world production). In France, 16–17 billion eggs are produced annually (14.5 billion for table eggs) and more than 1 200 billion worldwide. In 2019, egg production increased by 3.3% compared to 2018, mainly due to the increase in Asian production, which has risen by 42% since 2000. Chicken eggs are widely used either as a low-cost, high nutritional quality food cooked by the consumer (more than 100 billion eggs consumed in Europe), or incorporated as an ingredient in many food products. The various production methods have changed considerably over the last 15 years with the consideration of animal welfare and changes in European regulations. In Europe, fewer and fewer eggs are produced in confinement and there has been a strong growth in the number of systems giving access to an outdoor run. In this review, we describe the different ways in which eggs are produced and processed into egg products to meet the growing demand for ready-to-use food products. We analyse the effect of this evolution of hen-rearing systems on the set of characteristics of eggs and egg products that determine their quality. We describe the risks and benefits associated with these new production methods and their influence or lack of influence on commercial, nutritional, microbial and chemical contamination risk characteristics, as well as the evolution of the image for the consumer. The latter covers the ethical, cultural and environmental dimensions associated with the way the egg is produced.

Implications

Consumers are increasingly demanding eggs from animal welfare-friendly farms. Beyond the ethical aspects, the consumer associates eggs produced in alternative systems (e.g. not cages systems), as a food providing added value in terms of acceptability, nutrition, taste. Despite the numerous publications, advantages and disadvantages of each production system in terms of egg quality remain very controversial. Therefore, we have analysed objectively the various factors associated with egg quality attributes in relation to different housing systems for laying hens. Alternative production systems have no impact on egg quality, a negative impact on performance, but meet the ethical needs of the consumer.

Introduction

The table egg is the cheapest of animal proteins and a complete food, low in calories – providing 75 kcal per egg. It is a high-quality protein source for humans because of their high digestibility and well-balanced amino acid composition. It does not suffer from the prohibitions of most religions and is therefore a basic human food product widely consumed all over the world. Asia is the world's leading producer (53.3% of world production in 2018), ahead of the European Union comprising 28-member states (10% of world production) and the United States (8.6%) (Magdelaine, 2017; FranceAgrimer, 2021; Nys et al., 2018). China alone accounted for 32% of global production in 2018 (ITAVI, 2019). The annual world consumption is about 150 eggs per year and per capita. European consumption is on average 217 eggs per year and per capita with a great disparity between countries (from 141 to 183 eggs in Greece and Poland to 301 in Denmark). The French

* Corresponding author.
E-mail address: joel.gautron@inrae.fr (J. Gautron).

https://doi.org/10.1016/j.animal.2021.100425
1751-7311/

annual consumption of 218 eggs per year and inhabitant in 2018 is similar to the European consumption corresponding to an average daily consumption of 30 g/day, which corresponds to 60% of the consumable part of a 60 g egg (Nys et al., 2018).

The various production methods have changed considerably since the World War Two. Before the war, production was only in backyards and corresponded mainly to production for self-consumption. After the war, agriculture evolved and had to face a drastic decrease in the number of people working in the primary sector (from 50% of the population to a 1.5% nowadays) (Chardon et al., 2020). Farmers no longer had to produce only for a small number of people, but for large quantities while their own numbers were dwindling. Production has therefore evolved to meet the demand (in quantity) and control the health risk of food poisoning for human health, which has led to a model of raising 'productive eggs' in confinement and cages. In the 1980s and 1990s, this production model was practically the only one. Since the end of the 1990s, new consumer demands have emerged to take into account animal welfare, thus segmenting the market. At the European level, there has been a strong public awareness of agricultural production systems in general and animal production systems in particular, including poultry and eggs. This consumer demand has resulted in a strong diversification of farming methods. Current European production models are the result of this social demand. They are regulated within the framework of the directive on the welfare of laying hens (UE, 1999). Classical cages with a surface of 550 cm^2/hens and without enrichments were banned in Europe in 2012, and only enriched cages and alternative systems (e.g. aviaries, free-range or free-range flooring systems) are allowed.

These eggs are consumed in the form of shelled eggs, or egg products used as ingredients in the preparation of culinary dishes. After describing the different egg production systems, as well as the processes of transformation into egg products, we will describe in this review the different properties that characterise the quality of eggs and egg products and the factors affecting these properties. These properties were divided into seven core attributes (sanitary, commercial, sensory, technological, nutritional, use-value and image-value), for which the effect of different production methods was analysed on these properties that characterise the quality of eggs and egg products.

Characteristics and importance of the different modes of egg production and transformation

Characteristics of the table egg production methods

The current production of eggs for consumption in Europe is regulated by a European directive of 1999 (UE, 1999), which is also the result of scientific research to satisfy the five freedoms of animal welfare: absence of hunger; absence of thirst; possibility of movement; absence of fear/distress, and allowing the expression of natural behaviour. This directive defines the rearing of hens in enriched cages and the rearing of hens in alternative systems. It contains general provisions applicable to all rearing systems: (1) The animals must be inspected at least once a day; (2) The presence of perches is mandatory. If no minimum height is specified, hens must be able to put their claws underneath; (3) The presence of a nest is required. The nest is a separate space whose floor is not made of wire mesh. This nest can be provided for one or more hens. The nest is not considered a usable surface area. (4) The light programme must follow a 24-hour rhythm. An uninterrupted period of darkness of an indicative duration of approximately 8 hours must be practised in order to allow the animals to rest and to avoid eye problems. Light intensity must be sufficient to allow the animals to see and be seen, particularly by the breeder during daily inspection. Eggs are marked on the shell according to the mode of production, each one being defined by specific rules: Code 3 for the rearing of hens in enriched cages, Code 2 for hens raised in a building, on the ground or in aviaries, Code 1 for free-range hens, and Code 0 for organically produced eggs. The different characteristics of these rearing methods are summarised in Table 1.

Enriched cages

Code 3 corresponds to hens raised in cages. According to the directive on the welfare of laying hens came into action (UE,1999), all European production in cages must be carried out in enriched cages (new installations since 1 January 2003, then all buildings since 2012). These cages must have an available surface area per hen of minimum 750 cm^2 and are housed in cages of at least 2 000 cm^2. These cages have perches (15 cm/hen), separate nests and a scratching and pecking area that is also for dust bathing. In addition, the hens have a minimum of 12 cm feed trough per hen.

Alternative systems

For alternative systems, the European directive indicates that the buildings must be equipped with a nest (one minimum for seven hens or, in the case of collective nests, 1 m^2 minimum for 120 hens), a litter that must occupy at least 1/3 of the floor area and consist of friable material (250 cm^2 /hen) and perches with a wall–perch distance $\geq$20 cm and a distance between two perches $\geq$30 cm minimum. In the case of the free-range system, the buildings must have hatches for access to the outside with a total opening length $\geq$2 m/1 000 hens, distributed over the entire length of the building. The height of the hatches must be $\geq$35 cm and the width $\geq$40 cm. The directive mentions the presence of shelters on the run. In addition to these constraints, in the case of organic farming or farming under a quality sign, there are also the constraints defined (density on the run, access time, etc.) in the regulations and specifications specific to these systems (EC, 2007; UE, 2008). Eggs laid in alternative systems will be marked with codes 2, 1 or 0 depending on the type of hen rearing.

Code 2 corresponds to hens reared in aviaries or on the ground. Laying hens are raised in flocks of 30 000 on average hens per house. Code 1 corresponds to eggs from hens housed in aviaries or on the ground with an outdoor run (free-range). The farms consist of buildings with 30 000 hens, with an outdoor run of minimum 4 m^2 per hen (i.e. 12 ha of run for a building with 30 000 hens). In the case of French Label Rouge, specifications were added (JORF, 2017). These specifications provide for the use of rustic strains with 6 000 hens per building and a maximum of 12 000 per farm. Feed must consist of a minimum of 60% cereals (with a maximum of 15% by-products). The booklet prohibits synthetic colourants and most additives (technological additives of the functional groups' emulsifiers, stabilisers, thickeners and gelling agents). The run must be covered with vegetation and shaded and layers must have access to the outdoor run at 25 weeks of age at the latest. The available outdoor surface area must be a minimum of 5 m^2/hen. The maximum laying age must not exceed 72 weeks and the egg weight must be a minimum of 48 g, and does not include eggs laid outside the nest. Collection is manual and must be done at least twice a day. The Label Rouge production method is highly developed in France and is therefore cited as an example in this review. Other production systems are also being developed in Europe.

Code 0 refers to organic eggs, which uses special specifications (EC, 2007; UE, 2008). The strain is chosen according to adaptability to environmental conditions, vitality and resistance to disease, and preference must be given to native strains. The farm must be made up of a maximum of 6 000 hens with no more than 3 000 hens/building and a maximum density of 6 hens/m^2 in the building.

Table 1
Main characteristics of European laying hen-rearing systems.

Item	Cage	Floor	Floor + outdoor access	Floor + outdoor access (Label Rouge)	Organic
Code on egg	3	2	1	1	0
Outdoor access (m^2/hen)	No	No	Yes (4)	Yes (5)	Yes (4)
Housing indoor density (number of hens/m^2)	13.3	9.0	9.0	9.0	6.0
Size of the flock	Usually 50 000–100 000	Usually 20 000	Usually 15 000	6 000 per building	3 000 per building
Mortality (%)	3–4%	6–8%	6–8%	6–8%	8–10%
Dust levels in the building	Weak	High	High	Moderate	Moderate
Feedstuffs	Cereals, proteaginous, Vegetal oils, vitamins and minerals				
Feed specificities	Synthetic amino acid, dyes and additives are allowed			Minimum 60% of cereals, No synthetic dyes, limitation of additives	Organic plant-based Raw materials (65% cereals). No synthetic amino acids, dye and additives.
Feed conversion ratio	2.2	2.4	2.4	2.6	2.6
Competition for the use of arable land	Weak	Weak	moderate	Moderate	moderate

The feed must consist of at least 65% cereals, and the raw materials used must come from organic farming. Genetically modified organisms (**GMOs**) and synthetic vitamins are prohibited. The outdoor run is 4 m^2/hen minimum, with access at the latest at 26 weeks. The outdoor area should have a rotation between two outdoor areas every 2nd year. Authorised treatments are preferably homeopathy, phytotherapy and oligotherapy. Vaccinations are authorised if there is a disease in the breeding area. One allopathic curative treatment per year and a maximum of two allopathic antiparasitic treatments per year are also authorised. It has to be noted that the regulation will evolve in 2022 with the following main points. At least 30% of the feed given to the animals must come from the region of the farm. The feed must be 100% organic with a derogation only for pullets for 5% of this feed until 2026. The regulation will provide for an obligation of organically produced chicks by 2036. These chicks will come from organic breeders and will have to be kept outdoors.

All of these production methods comply with European regulations, but there is growing consumer mistrust of eggs from caged hens. This consumer demand has resulted in a strong segmentation of the markets (80% of laying hens were in cages in 2003, 58% in 2018) (ITAVI, 2019). The proportion of hens kept in alternative systems is currently increasing strongly, even if it remains very heterogeneous in Europe (from less than 10% in Spain and Poland, to more than 90% in the Netherlands, Germany and Austria) (Nys et al., 2018; Gautron et al., 2021). Once laid, the eggs are collected, then possibly stored for a few days before sorting and grading. Eggs are sorted into three categories according to their defects and aspects (EC, 2008). Category A eggs constitute the eggs for consumption (shell eggs) (EC, 2004). They must be stored and transported at a temperature, preferably a constant temperature that best ensures the preservation of their hygienic qualities (EC, 2004). Indeed, a cold chain that will be disrupted could cause droplet formation on the surface, which would alter the cuticle, which is a natural biofilm deposited on the surface of eggs during their formation. This disruption may create a potential pathway for bacteria to penetrate. Only eggs coming from French overseas departments are dispatched chilled (OJEU, 2003). From the day of laying to day 9, eggs are said to be 'extra fresh'. From day 10 to day 28, eggs are called 'fresh'. After 28 days, the eggs are no longer marketable. Category B consists of 2nd-quality eggs or stored eggs, which no longer meet the criteria of quality A. They can be cracked or dirty but neither broken nor incubated and will be intended for food and non-food and in pasteurised egg products.

Processing of eggs into egg products

Egg products represent about 20% of total egg consumption in Europe, and range from 50% (149 eggs/person/year) in Denmark to 5% (eight eggs/person/year) in Poland; it is 35% in France (ITAVI, 2019). According to European regulations, the term egg products can only be used for foodstuffs intended for human consumption and resulting from 'the processing of eggs, or of various components or mixtures of eggs, or from the further processing of such processed products' (European Commission (EC, 2004)). Fig. 1 describes an example of the various steps of egg handling for shell egg marketing (left side of the figure) and the flow diagram for obtaining egg products (right side). Only quality-tested eggs, *i.e.* with a clean shell, complete and in the appropriate colour, without any crack and blood inclusion, can be marketed as shell eggs. The eggs not meeting these criteria are processed in egg products; quality-tested eggs can also be processed, depending on the market need for shell eggs with regard to availability. Eggs processing can start with egg washing, but this operation is not mandatory in EU. Eggs are then individually broken with machines making also white and yolk separation, as well as egg shell removal. Immediately after breaking and separation, egg white, yolk and whole egg are filtered and cooled, before transfer into refrigerated tanks. Thereafter, the three fractions can be pasteurised before packaging, to obtain liquid egg products, but they can also be spray-dried for marketing as powders. In that case, two different processes are applied depending on the fraction. Yolk and whole egg are pasteurised before spray-drying, whereas egg white is first fermented to remove glucose, then spray-dried and lastly pasteurised in hot rooms.

Egg products are practical, safe from a microbiological perspective, technically efficient and compatible with the constraints of the food industry and the catering industry. Practicality is probably the most obvious criterion for the food industry. Indeed, if the egg in shell is simple to preserve and use at the household level, things are different when a manufacturer implements hundreds of litres of egg products. Moreover, egg products enable the specific use of yolk or egg white. The safety offered by egg products that are heat-treated, and whose quality is controlled, is also a major argument in favour of these processed products, especially when the microbial risk is strictly limited. Finally, egg products also offer efficient technical solutions, adapted to the different uses of eggs. For instance, the egg product industry has developed technologies to offer high-foaming egg white, egg yolk that allows the pasteurisation of sauces in which they are incorporated, or more simply to

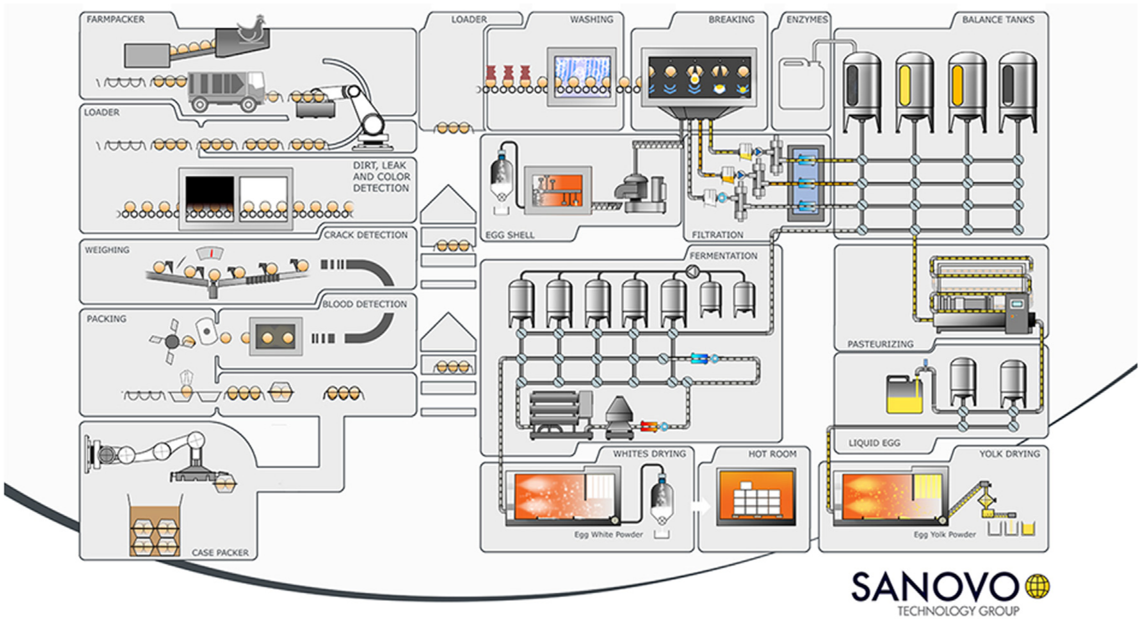

Fig. 1. Egg handling and flow diagram. Various steps of egg handling for shell eggs marketing (left side) and the flow diagram for obtaining egg products (right side). Credit of SANOVO TECHNOLOGY GROUP (www.sanovogroup.com) with written permissions obtained on 08 April 2021.

allow longer conservation at room temperature, such as with sweetened concentrated whole eggs or dried egg products. The egg powders also play a market regulation function. Indeed, laying hen farms, set up to meet the peak consumption of table eggs, which require a specific size (mainly large or medium size), produce surpluses of small and extra-large eggs at certain times of the year that can be stored for later consumption by processing into powder. Powders also allow the development of specific markets such as eggs enriched with long-chain polyunsaturated fatty acids (**FAs**) such as docosahexaenoic acid (**DHA**), or certified eggs (organic, free-range, kosher, hallal, etc.) by freeing them from the logistical constraints associated with small-scale production.

There are two main categories of egg products. The egg products known as 'first-stage processing' are the white, the yolk and the whole egg, pasteurised and sold in liquid form, concentrated, frozen or powder. The industry also produces egg products known as 'second-stage processing', which are either cooked eggs, or egg products with other ingredients and/or cooked. These ready-to-use products are intended for the consumer, but they reach them mainly through the catering industry.

First-stage processing egg products: the egg ingredient

Liquid egg products

Beyond the separation into white, yolk and whole egg, the egg producer has several simple levers to diversify their offer and meet the demands of each customer. The addition of salt and/or sugar is a common practice that allows offering the user with a preformulated product. It also protects the colour and flavour of the yolk during heat treatment, as well as its emulsifying properties (Campbell et al., 2005). When salt and/or sugar contents are high, liquid egg products may even offer special preservation properties due to a water activity ($\mathbf{a_w}$) of about 0.85. Salted yolk at 10% or sweetened at 50%, as well as salted or sweetened whole concentrate (volume concentration factor of about two), available on the market, are products that can be stored for several months at room temperature (Yanagisawa et al., 2009). Beyond the interest related to the ease of conservation of these concentrated salted/sweetened egg products, these formulations can in some cases also offer a functional interest (Damir et al., 1988). For example, the addition of 12% sugar to egg white, combined with an increase in the pasteurisation temperature (from 60 to 64 °C, 2 min), increases its foaming capacity. Under such controlled heating conditions, the conversion of the native protein structures into the "molten globule" state would favour protein adsorption at the air–liquid interface, because of higher surface hydrophobicity and increased flexibility. On the contrary, the higher viscosity of sugared egg white would decrease protein diffusion to the interface, thus leading to a limited protein concentration at the interface, and therefore to a lower foam stability, unless whipping time is increased. In that case, the higher viscosity of the bulk phase delays drainage and thus increases the foam stability (Raikos et al., 2007).

Hydrocolloids (guar gum, xanthan, carrageenans, pectins...) can also be added to egg products, for example to improve the foam stability of unheated and pasteurised egg white, due to an increased viscosity of the bulk and to the formation of strong elastic interfacial film as a result of putative protein-polysaccharide interactions at the air–water interface (Ibanoglu and Ercelebi 2007). However, the addition of thickening agents may reduce the foamability of the egg white, because the higher viscosity limits the amount of air incorporated, leading to lower foam volumes. Finally, it is possible to intervene upstream of the processing, through the feeding of laying hens, to modify certain composition criteria: yolk colour (Looten et al., 2003); yolk content of polyunsaturated fatty acids (**PUFAs**), such as omega-3 (Nys and Sauveur, 2004; Yannakopoulos, 2007); egg vitamin or mineral content (Stadelman and Pratt, 1989).

Powdered egg products

Whole egg, white and yolk are not dealt similarly. Even if yolk is mainly used in liquid form, yolk powders are available on the market. When produced for pastry or dessert sectors, yolk powder is often sweetened by up to 10–20% (5–10% for the reconstituted liquid) in order to restore the foaming properties degraded during the drying process (Schultz et al., 1968). For applications in sauces and dishes, yolk powders salted by 5–10% (2.5–5% in reconstituted liquid) are common. Yolk may also be treated with phospholipase A2 before drying to increase the heat stability of

Table 2
Authorised food additives and conditions of use in processed eggs and egg products in Europe (EU, 2011) (Commission Regulation EU No 1129/2011).

E-number	Name	Maximum level (mg/L or mg/kg as appropriate)	Restrictions/exceptions
E 1505	Triethyl citrate	*quantum satis*	Only dried egg white
E 200-203	Sorbic acid - sorbates	1 000[(1),(2)]	Only dehydrated, concentrated, frozen and deep frozen egg products
E20-213	Sorbic acid – sorbates; Benzoic acid – benzoates	5 000[(1),(2)]	Only liquid egg (white, yolk or whole egg)
E 234	Nisin	6.25	Only pasteurised liquid egg (white, yolk or whole egg)
E 338-452	Phosphoric acid – phosphates – di-tri- and polyphosphates	10 000[(1),(3)]	Only liquid egg (white, yolk or whole egg)
E 392	Extracts of rosemary	200[(4)]	
E 426	Soybean hemicellulose	10 000	Only dehydrated, concentrated, frozen and deep frozen egg products
E 475	Polyglycerol esters of fatty acids	1 000[(1)]	
E 520	Aluminium sulphates	25[(5)]	Only liquid egg white for beaten in snow

(1) The additives may be added individually or in combination.
(2) The maximum level is applicable to the sum and the levels are expressed as the free acid.
(3) The maximum level is expressed as P_2O_5.
(4) As the sum of carnosol and carnosic acid.
(5) Expressed as aluminium.

acidic sauces in which yolk powders are processed (Dulith and Groger, 1981).

Drying strongly impairs the quality of whole egg, or even completely removes the foaming properties of the product. To counteract this, sugar or maltodextrins can be added to whole egg before drying, with levels up to about 40% carbohydrates in powdered eggs. The recovery of foaming properties is almost proportional to the amount of sugar or maltodextrin added (Kline et al., 1964). Carbohydrates addition into whole egg before drying would prevent fat release as rapidly forming a dense skin on the surface of the droplets during drying (Koc et al., 2011). However, salted whole-egg powders are quite rare; 5% salt in powder is a maximum. The addition of maltodextrins or glucose syrup also improves the flow capability of whole-egg powders (Lai et al., 1985).

Several factors explain why most of the egg white is dried, and why egg white powders are traded internationally. First, even raw, egg white does not favour bacteria growth, which allows large volumes to be transported to dedicated drying plants. Second, it is best from an economic standpoint to transport egg white powder internationally rather than liquid egg white because of the low DM content of the latter (about 10%). Lastly, since it is virtually lipid-free, egg white powder can be stored easily and over long periods of time. Because of its low DM content, liquid egg white is systematically concentrated before drying. In Europe, tri-ethyl citrate (E1505) can be added to egg white powder, in order to improve foam stability (Table 2) (EU, 2011). A particularity of the drying process of egg white is that pasteurisation occurs after spray-drying the raw product. Pasteurisation is then carried out by heating the powder in a hot chamber, using time–temperature parameters that are also unusual, in a range of 65 °C for 5 days, and this treatment guarantees the microbiological safety of the product (Baron et al., 2003). However, more intense heat treatments may also be applied: 80 °C for 5–10 days in static drying in a chamber; 90 °C for about 20 hours in dynamic drying in a stirred conical mixer. In that case, in addition to bacteria destruction, the foaming, emulsifying and/or gelling properties of the egg white are also considerably improved. The improvement of these functional properties is the consequence of protein modifications including the increase in surface hydrophobicity, in molecular flexibility, and in exposure of reactive residues (Kato et al., 1989; Mine, 1996; 1997; Hammershoj et al., 2006a; 2006b). Nowadays, this is widely carried out by all companies producing egg white powders to propose targeted products for specific applications ('high gel' egg white powder for surimi, or 'high foam' egg white powder for pastry and desserts, for instance).

Second-stage processing egg products: the egg 'like at home'

Depending on whether the eggs are directly cooked (for hard-boiled, poached or fried eggs) or previously prepared as liquid egg products (for omelettes, scrambled eggs, foamed egg whites, etc.), the hygiene constraints associated with the raw material used vary somewhat. In the former case, the raw material is shell eggs which do not need to be stored at 4 °C, whereas in the latter case, the raw material has been previously pasteurised, and therefore needs to be stored at 4 °C and for a limited time. Among all these products, hard-boiled eggs represent by far the largest volumes manufactured. If the industrial process only reproduces in an automated way and on a large scale the household preparation of hard-boiled eggs, it must still conform to a certain number of constraining quality criteria. The main criteria, beyond microbiological safety, are that: (1) the eggs do not burst when immersed in hot water or steam; (2) the cooked yolk is well centred; (3) the shell can be removed without tearing the white; (4) the yolk is completely coagulated, while limiting the appearance of a greenish iron sulphide (FeS) border at the interface between the cooked white and yolk.

Scrambled eggs and omelettes represent the second largest tonnage of egg products. However, in the absence of legal or normative definition, the term "omelette" designates a wide variety of recipes in which the liquid whole egg is always the main ingredient, but milk, egg white, or even fillings (cheese, bacon, vegetables...) can also be added. Here again, the industrial processes are varied and attempt to reproduce the household cooking on a large scale and in an automated way. Many other second-stage processing egg products are marketed to food service industry and catering companies. These include in particular poached eggs, fried eggs, stiffly beaten egg whites, and long-eggs particularly suitable for sandwiches. These latter require very specific equipment which enable separated cooking of egg white and egg yolk in cylindrical and coaxial tubes.

Factors that influence the properties of eggs from production units to consumption

The sanitary properties

Bacterial risk assessment

Non-typhoidal *Salmonella* is the main pathogen associated with eggs and egg products. Other pathogens such as *Bacillus cereus* or

Listeria monocytogenes are relevant, when the egg production is transformed into liquid egg products (EFSA, 2014). Two sources of contamination of the contents of intact eggs by *Salmonella* can be distinguished: the horizontal and the vertical transmission routes. For horizontal transmission, *Salmonella* penetrates through the eggshell. In the case of vertical transmission, also called the transovarial route, the egg is contaminated because of a *Salmonella* infection of the reproductive organs. The Enteritidis serovar is the main serovar concerned with egg contamination as it has the ability to contaminate the eggs by both routes (Howard et al., 2012). Consumption of eggs is regularly associated with salmonellosis outbreaks (Pijnacker et al., 2019). These outbreaks are mainly associated with the consumption of food products made from raw or undercooked eggs (Augustin et al., 2020). The heat resistance from 20 strains in egg products was characterised (Gurtler et al., 2015). The decimal reduction time at 60 °C, or D_{60} values, of these strains ranged from 0.34 to 0.58 minutes. Source attribution studies and case control studies have also found that among the different potential sources (pork and poultry meat consumption), the consumption of eggs represents a significant part of sporadic cases of salmonellosis (Mughini-Gras et al., 2014; Guillier et al., 2020). The storage conditions of eggs can increase the risk of salmonellosis. An extended storage is possible as long as the eggs are maintained refrigerated both at retail and the household (EFSA, 2014).

The incidence of egg contamination decreased until 2013, thanks to the systematic elimination of contaminated flocks, but also to better hygiene and controls (EFSA 2019). However, the number of human salmonellosis cases in the EU has tended to increase since 2014 (EFSA and ECDC, 2018). One of the reasons could be the increase in the prevalence of *Salmonella* Enteritidis in laying hens by about 17% in 2015 vs 2014 and 57% in 2016 vs 2015 (De Cesare, 2018). The mode of production of eggs can influence microbiological contamination. Eggs from floor and aviary systems generally have more aerobic bacteria on the egg surface than eggs from conventional systems and enriched cages (Englmaierova et al., 2014; Samiullah et al., 2014), but the differences are small and farmer practices seem to be more important than the production method (Mallet et al., 2010). One of the determining factors could be stocking density, which would allow propagation. There is currently evidence that there is a lower occurrence of *Salmonella* in laying hens for non-cage compared to cage systems. No effect of outdoor access or impact of the shift from conventional to enriched cages has been proven so far (EFSA, 2014). This risk appears to depend more on the density and size of the farms, as well as the hygiene practices of the farmer (Huneau-Salaun et al., 2010). EFSA, following a detailed analysis, recommends that future monitoring programmes record the type of housing of laying hens to allow the assessment of its impact on the presence of *Salmonella* (EFSA, 2019).

Chemical contamination of eggs

Contaminant levels in eggs reflect the quality of feed but also of the indoor or outdoor environment. Attention must be paid to control all sources and routes of exposure in order to ensure the lowest contamination as reasonably achievable, for both regulated and unregulated contaminants. In Europe, a crucial step was taken with the 'Belgian dioxin crisis' in 1999 (also called the 'dioxin chicken crisis'). Five hundred tonnes of contaminated feed containing around 50 kg of polychlorobiphenyls (**PCBs**) and 1 g of polychlorodibenzo-dioxins/-furans (**PCDD/Fs**) were mainly distributed to poultry farms (Van Larebeke et al., 2001). As 445 Belgian poultry farms have used this feed, Ministry of Public Health ordered removal of poultry, eggs and derived products. More than 2 million chickens were destroyed. In the spring of that year, the Belgian authorities ordered the withdrawal of Belgian poultry and eggs, followed by other European countries. A few weeks later, the European Community extended the ban and ordered the destruction of all food products containing more than 2% egg products. It has been estimated that this incident increased the body burden of the Belgian population by 42% in the case of polychlorobiphenyls and by 7% for dioxins, with eggs and poultry meat as the main contributors to the exposure (van Larebeke et al., 2001). The authors also concluded that there were real health consequences of this overexposure. They estimated that the total number of cancers resulting from this incident ranges between 40 and 8 000. This major sanitary crisis led to the creation of the Belgian Food Safety Agency (AFSCA) and the EFSA.

This event underlined the ability of animals to bioaccumulate organic compounds. These compounds have a similar profile, they are persistent in the environment, recalcitrant to biotransformation, lipophilic, and highly toxic. Main families of concern are chlorinated compounds (PCDD/Fs); (PCBs); dichlorodiphenyltrichloroethane (**DDT**) – or brominated ones: polybromodiphenylether (**PBDE**); hexabromocyclododecane (**HBCDD**). As they are highly toxic, the maximum limits in foodstuffs (set to protect consumer health) are quite low compared to levels that can occur when animals are exposed to these compounds. There are many possible sources depending on the contaminant. For PCDD/Fs, it is mainly the combustion of organic matter in the presence of chlorine (e.g. waste incinerator), for PCBs (fire or leakage of electric transformer) and for PBDEs from sewage sludge spreading. The main route of exposure is feed. In the case of the previously mentioned 'dioxin crisis', animal feed was contaminated by the use of transformer oil containing high levels of PCBs, unfortunately introduced into a recycled fat stock.

These compounds are accumulated in various tissues (mainly fat and liver) but are also heavily exported to the eggs of laying hens. Following an oral exposure to non-dioxin-like PCBs, 50% are sequestered in tissues, 16% excreted in faeces and 34% excreted in eggs (mainly in the egg yolk) (Fournier et al., 2015). A strategy to reduce dioxin in feed was adopted by the European Commission in 2001 (EC, 2001). Commercialised animal feed is now under surveillance for the main families of contaminants, with maximum values assigned (Commission Regulation EU No. 1881/2006). Because feeds are prepared by large operators, crises are now rare, but when a crisis does occur, it involves a large number of farms. The Directive 2002/32/CE set maximum levels in food. Some emerging contaminants, such as mineral oil hydrocarbons (Grob et al., 2001) or chlorinated paraffin (Meziere et al., 2021), may also be present in food and contaminate eggs. They are currently not regulated either in feed or in food.

Apart from feed, there are other routes of exposure. One route of great concern for free-range livestock practices is the potential ingestion of environmental matrices (De Vries et al., 2006; Jondreville et al., 2010). As previously stated, contaminants are persistent in the environment. In fact, due to their hydrophobicity, they accumulate in soil, bound to organic matter. Free-range animals may ingest soil, often unintentionally, and thus be exposed to contaminants. Although contaminants are bound to organic matter in soil, they are desorbed in the digestive tract and become available to animals. A relative bioavailability of PCBs close to 100% was demonstrated for laying hens (Fournier et al., 2012). The carry-over rate (**COR**) strongly depends on the contaminant property. The COR of PCBs ranged from 5 to 90% whereas it ranged from 5 to 48% for PCDD/Fs (Hoogenboom et al., 2006). The most chlorinated congeners are the least transferred (e.g. OCDD and OCDF) but among the light ones, some can be highly metabolised (e.g. PCB 52 and 101) due to the position of the chlorine atoms (Hoogenboom et al., 2006).

As soon as animals have access to a natural outdoor space, it introduces an additional route of exposure through grass, soil or pedofauna ingestion. But an increase in exposure to contaminants is not systematic, because it depends on their environmental level. This is the reason why, according to the area or country, observations are not convergent. In industrial or urban areas, levels observed in free-range eggs are often higher than those observed in cages (Lovett et al., 1998; Roszko et al., 2014; Squadrone et al., 2015; EFSA, 2018), whereas in area with lower anthropic emissions, this difference may disappear (Rawn et al., 2012; Luzardo et al., 2013). What is certain is that the variability of contamination level is higher in outdoor (Table 3) than in indoor ones (EFSA, 2018).

Another route of exposure, less described, is contact with building materials. High levels of HBCDD were found in eggs, but at a very low incidence. Hens were able to ingest small pieces of extruded polystyrene, used as insulating material in rearing buildings (Jondreville et al., 2017). This material may contain brominated flame retardant, such as HBCDD, which could be accessible for the hen, and therefore accumulated in animal tissues. After investigation into 60 hen egg farms (34 without an open-air range, 26 free-range) in France, no relationship was established between concentrations of brominated compound (PBDEs and HBCDD) in the egg and rearing systems (Huneau-Salaun et al., 2020). Litter may also be a source of exposure, as was the case in an Italian farm (Brambilla et al., 2009). The contamination was due to wood treated by pentachlorophenol, used as bedding material.

For a same exposure dose, physiological parameters may modulate the contaminant levels in egg. Fournier et al. (2015) built a model based on two submodels, one dedicated to the fate of contaminants (absorption, metabolism, distribution, excretion) and one dedicated to hen physiology (Fournier et al., 2015). Applied to PCBs, this model demonstrated that laying intensity was negatively correlated with contamination of eggs. As eggs are an efficient route of excretion, a low-productive hen with a quite similar feed ingestion to a high potential one will excrete less PCBs, and will therefore accumulate more PCBs in its tissues. At steady state, concentration in the low-productive hen's organism will be the highest, as well as the concentration in its eggs. This physiological factor probably has an additive effect with the high exposure frequently observed in free-range husbandries. Hens are more exposed and as they lay fewer eggs, excrete less contaminant, resulting in a higher bioaccumulation (Fournier et al., 2015). Eggs are therefore more contaminated. The dose in the feed can be exceeded without affecting the health of the hen. For the reported cases, there were no reports of health problems in the farms, and only measurement in the animal matrices or in the environment made possible to detect the contamination

The commercial value

Only Grade A eggs can be marketed as shell eggs in which category extra-fresh and fresh eggs are defined (see Characteristics of the table egg production methods section) (EC, 2008). The shell and cuticle must be clean, intact and of normal shape. The height of the air chamber must not exceed 6 mm. However, for eggs marketed as 'extra fresh', it must not exceed 4 mm. The yolk must be visible when candled as a shadow only, without any apparent outline. The white must be clear and translucent, the development of the germ imperceptible and the presence of foreign substances and odours are not tolerated. The washing and cleaning of Grade A eggs, before and after sorting, is prohibited. Another marketing criterion is the colour of the shell. In France, eggs for consumption are only brown eggs, while worldwide, white eggs are also consumed. This difference in colour is only genetic and does not affect the taste and characteristics of the eggs, but it is an essential criterion for their marketing. As far as egg products are concerned, a part of the eggs used white shelled eggs. The majority of these eggs come from cage production, but there is a growing demand from manufacturers for egg products from free-range hens, although the percentage is not known.

At the sorting centre, the eggs will be graded to categorise their destination. The egg weight varies due to the age of the hen, from less than 50 g (very young hens) to more than 80 g (very old hens) (Nys et al., 2018). Eggs sold as table eggs are sorted into four groups: Group S is for small eggs of less than 53 g; the medium egg group (M) includes eggs of 53–62 g; large eggs (L) weigh 63–72 g; and very large eggs (XL) are greater than 73 g. The M and L groups are the two groups that are mostly sold because they correspond to the consumer demand. The other groups are mainly used to obtain egg products. The share of alternative farming has increased significantly since the European directive of 2012 (UE, 1999).

The effect of chicken housing systems on egg characteristics has been the subject of a large number of studies in recent years. They have shown a decrease in the number of eggs laid per day, as well as a decrease in egg weight in free-range and floor systems compared to eggs from enriched cages (Nys et al., 2018; Dedousi et al., 2020; Philippe et al., 2020; Marelli et al., 2021). On the other hand, there are more dirty and downgraded eggs in floor systems compared to eggs produced by hens raised in cages. The most important factor of variation in the eggshell mechanical characteristics of eggs is definitely not the production system, but the genetics and feeding of the hens.

Egg storage conditions of time and temperature are other important elements of egg quality and marketing. Egg spoilage and safety depend on storage times and temperatures (EFSA, 2014). Eggs are a naturally storable ingredient at room temperature. Dealers should keep eggs at room temperature to avoid condensation on the shell surface that could create facilitation to bacterial penetration inside the egg. However, gas exchange between the interior of the egg and the atmosphere will alter the egg white properties, which also an important role in the natural egg defence against bacteria. The pH and viscosity of the egg white are protective systems that act directly on microorganisms by inhibiting *Salmonella*, for example, or modulating the antimicrobial activity of lysozyme or the chelating activity of ovotransferrin in the egg white according to the pH, and more generally by acting on the cell mobility of bacteria to reduce bacterial virulence. The ability of bacteria to grow in the egg white can therefore evolve positively or negatively in response to these variations, which are a function of pH and also of the age of the hen. Thus, it has been shown that the growth of *Salmonella* was higher in fresh egg white than in egg white stored a few days at 20 °C. In contrast, storage at 37 °C rapidly alters the antibacterial defence systems of the egg white (Rehault-Godbert et al., 2010) and lower temperature will slow down the growth rate of bacteria. Similar observations have been made with other bacteria (Yadav and Vadehra, 1977).

While the shell does not change during egg storage, the viscosity of the egg white, its pH, and the strength of the yolk membrane

Table 3
Levels of polychlorobiphenyls (PCBs) and of polychlorodibenzo-dioxins/-furans (PCDD/Fs) (pgTEQWHO2005.g/lipids[(1)]) in eggs according to the rearing system (EFSA, 2018).

Rearing systems	N	Mean	P50[(2)]	P95[(3)]
Battery eggs	102	0.20	0.12	0.5
Free-range	524	0.58	0.16	2.4
Organic	419	1.18	0.62	3.7
Outdoor growing conditions	412	1.58	0.36	5.1

(1) TEQ: Toxic Equivalent Quantity, WHO: World Health Organisation; 2005 date of the calculation of the TEQ.
(2) Percentile 50 (median value).
(3) Percentile 95.

will be greatly altered during egg storage (Guyot et al., 2016). The increase in pH observed after egg laying (from 7.43 to 9.32 in 10 days) has positive impacts on some technological properties of the egg (foaming capacity of the white, peeling of hard-boiled eggs...), but weakens the strength of the yolk membrane, which is a crucial technological criterion of the egg product industry and the consumer to avoid any mixing of white and yolk (Guyot et al., 2016). There is no effect of the production system on these factors. The factors influencing the quality of the egg after laying are only related to the time and temperature of egg storage, as well as the age of the hen. Indeed, a hen at the end of production has more fragile and porous shells and therefore the physicochemical properties of the white are affected (Nys et al., 2018).

The sensory properties

The sensory qualities of food are all the properties perceived by the sense organs that allow us to know and appreciate them. The colour of yolk is one of the major characteristics of the egg sensory characteristics. Birds cannot synthesise the carotenoids that give yolk its colour. These pigments in the yolk are a direct reflection of the hen's feed intake, which can be a natural component in the feed ingredients or added synthetically. Although they have no effect on taste, they are a very important criterion for the commercial quality of an egg, since consumers now have preferences or specific levels of yolk colour intensity. It is therefore a subjective criterion of the palatability and perception of this product. Chickens do not transfer beta-carotene or other carotenes, but xanthophylls (carotenoids with a hydroxy group). Their transfer into target tissues (fat, egg yolks) requires compounds to be fat soluble and depends first of all on the nature of the carotenoid (e.g. zeaxanthin, lutein) and their structure (cis or trans form; type of optical isomers). The better-used trans forms are dominant in plants, but the cis form develops during storage of raw materials or foods (Nys et al., 2018). Carotenoids are unstable over time, so their stability is an important factor in their use (during storage and transit through the anterior digestive tract). The synthetic forms or those derived from plant extracts are therefore saponified and encapsulated to protect them. The technological process of source preparation is continuously adapted to optimise the efficiency of the carotenoid sources. The main natural sources are corn, alfalfa and flower extracts (marigolds, tagetes) for yellow, paprika for red (Nys et al., 2018). A preferred yellow-orange colouration in many countries is obtained by combining 10–15 mg/kg of yellow carotenoids combined with 1–3 mg of red carotenoids (Nys et al., 2018).

The rearing system will only affect this parameter to the extent that the rearing is associated with a particular dietary intake. For example, hens with access to an outdoor run will ingest grass, which is a source of pigment and may cause a change in colouration (Hammershoj and Johansen, 2016). However, the lutein provided by grass can just as easily be provided by corn concentrate or corn gluten used in all types of production. Therefore, in the literature, results on the influence of rearing system on egg composition, including yolk colour, are inconsistent and highly variable (Dvorak et al., 2010; Nys et al., 2018). It should also be noted that regulations related to the specifications of a production system can influence this composition. For example, canthaxanthin (red pigment) and other synthetic pigments are prohibited in organic farming (EC, 2007), so the yolks from these eggs are often less orange than for other systems. These variations will not affect the nutritional properties of the eggs.

Egg flavour is a broad topic that has been the subject of numerous publications in the past. For example, Maga (1982) explores the various sources of variability in the flavour of eggs and egg products. He describes a list of more than 50 volatile compounds found in cooked eggs (Maga, 1982). The most studied flavour is that of fish in eggs associated with a feed containing fish products or rapeseed. This odour is associated with trimethylamine (**TMA**) levels above a few micrograms in the egg (Honkatukia et al., 2013). This odour is now highly controlled by nutritionists, which are using appropriate formulation to avoid this issue. However, some strains of hens are more sensitive to TMA. Indeed, this fishy odour is linked to a mutation (A to T at position 1 034) in the FMO3 gene in hens (Wang et al., 2013). On the other hand, the genotype–nutrition interaction is an important factor in this odour (Wang et al., 2013). This risk is well controlled in commercial farms although still present in family farms. In addition, although the effect is not directly dependent on the rearing system, hens with access to an outdoor run may consume feedstocks that can sometimes contribute to this type of defect. Flavour can also be related to the level of omega-3 in the yolk and must be controlled for enriched eggs in particular. Thus, the intake of flaxseed oil should be limited to 10% and less than 2% of fish oil to avoid the appearance of unpleasant taste (Sirri and Meluzzi, 2011).

The nutritional properties

The overall composition of eggs has been described in many reviews and is summarised in Table 4 (Seuss-Baum et al., 2011, Nys et al., 2018, Rehault-Godbert et al., 2019). There is a heterogeneity in the composition described among countries. However, this is due to the diversity of egg sampling, the physiological variability of its composition depending on the diet and the genetic strain and the different methods of analysis performed. Despite this heterogeneity, the egg contains proteins, lipids, water, minerals and carbohydrates as main compounds. The proportion of these

Table 4
Composition of the whole egg and white and yolk components. Adapted from Nys et al., 2018; Rehault-Godbert et al., 2010).

Item	Whole egg	White	Yolk
Lipids (g/100 g of egg)			
Fatty acids saturated	2.64	0	8.47
16:0 Palmitic acid	1.96	0	6.04
18:0 Stearic acid	0.65	0	1.73
Fatty acids monounsaturated	3.7	0	11.9
Fatty acids polyunsaturated	1.65	0	4.07
18:2 Linoleic acid (*n*-6)	1.38	0	3.28
18:3 Linolenic acid (*n*-3)	0.061	0	0.15
20:4 Arachidonic acid (*n*-6)	0.12	0	0.37
20:5 Eicosapentanoic acid (*n*-3)	0	0	0.001
22:6 Docosahexaeonitic acid	0.09	0	0.025
Cholesterol	0.398	0	0.939
Minerals and trace elements (mg/100 g of egg)			
Calcium	56	7	129
Sodium	142	166	48
Phosphorus	198	15	390
Potassium	138	163	109
Magnesium	12	11	5
Iron	1.75	0.08	2.73
Zinc	1.29	0.03	2.3
Selenium	0.03	0.02	0.056
Iodine	0.021	2	0.18
Manganese	0.028	0.011	0.055
Copper	0.072	0.023	0.077
Vitamins (μg/100 g of egg)			
Vitamin A	193	0	624
Vitamin D	1.5	0	4.7
Vitamin E	1.3	0	8
Vitamin K	0.3	0	0.7
Vitamin B1	40	4	176
Vitamin B2	450	640	430
Vitamin B3	80	154	30
Vitamin B5	1 710	260	7 370
Vitamin B6	170	5	350
Vitamin B9	47	4	146
Vitamin B12	0.89	0.09	1.95

compounds varies according to the egg components (shell, yolk and white) (Fig. 2). The composition of the white and the yolk is very different. The white is a saline solution with 11% protein and no lipids, while the yolk contains 50% water, 16% protein and 34% lipids. There is a very high stability of the major constituents of the egg. The composition of the egg is mainly modulated by the white/yolk ratio, which depends on the genetic origin of the animals and especially on the age of the hen. Indeed, at the beginning of the production cycle, a hen's egg contains 23% yolk (mass content) and this percentage increases to more than 28% at the end of production (Nys et al., 2018; Rehault-Godbert et al., 2019).

Eggs are rich in cholesterol (200 mg per yolk, representing about 10 mg of cholesterol per g of yolk). Several studies have shown that the consumption of eggs is unlikely to have substantial overall impact on the risk of cholesterol health disease (Hu et al., 1999; Rehault-Godbert et al., 2019). Nevertheless, the quantity of cholesterol was the reason for their bad reputation, which is widely reported in the press and the medical world. In 1984, the front page of *Time* magazine ran the headline: 'Cholesterol and now the bad news' with a sad smiley face with fried eggs in its eyes. The mouth with the sad smile was made with a piece of bacon, but it is the eggs that will be put to the test. The bad reputation of the egg was established. Despite the new front page of the newspaper 15 years later, which depicted a cheerful smile made with a slice of melon and the same fried eggs for the eyes ('Cholesterol and now the good news'), the egg's reputation remains bad to this day. However, many studies have now established that this risk from cholesterol intake is limited for the vast majority of the population able to regulate dietary intake (Miranda et al., 2015). The work associating cholesterol and the risk of cardiovascular disease indicates that plasma cholesterol levels are only a secondary factor compared to the consumption of saturated fatty acids, or other factors such as excess BW and diabetes (Griffin, 2011; Miranda et al., 2015). Furthermore, the presence of high mono and polyunsaturated FAs in eggs tends to reduce this risk (Table 4) (Griffin, 2011; Miranda et al., 2015).

The proportion of proteins, cholesterol, minerals, vitamins and sugars in the egg is not influenced by the production system (Nys et al., 2018). A change in protein and/or essential amino acid content in the hen's diet will have a very moderate role and its impact on nutritional value is small (Nys et al., 2018). The overall lipid and protein compositions of the egg are very stable. The yolk lipids represent 35% of the fresh yolk and are associated with proteins. These lipids are composed of 65% triglycerides, 31% phospholipids and 4% cholesterol. If the proportion of saturated and unsaturated FAs is stable in the egg, the profiles of mono- and polyunsaturated fatty acids are very variable and reflect the composition of these FAs in the hen's feed. It is therefore not the rearing system that will influence this composition, since the composition of the feed is globally identical in all these systems. However, it should be noted that the hen raised in the open air will consume soil or vegetation from the ground cover. This additional consumption may have an impact on the minerals or fatty acids in the egg (Hammershoj and Johansen, 2016). These variations will be dependent on the outdoor range present and are not reproducible within the same rearing system. This explains the great variability of the results obtained on egg composition according to the rearing system. In addition, the specifications of organic farming and Label Rouge prohibit the addition of additives (JORF, 2017). Among there are pigments that give the colour to yolk.

The technological properties

The functional properties of eggs and their technological performance are influenced by different factors, such as the age of the

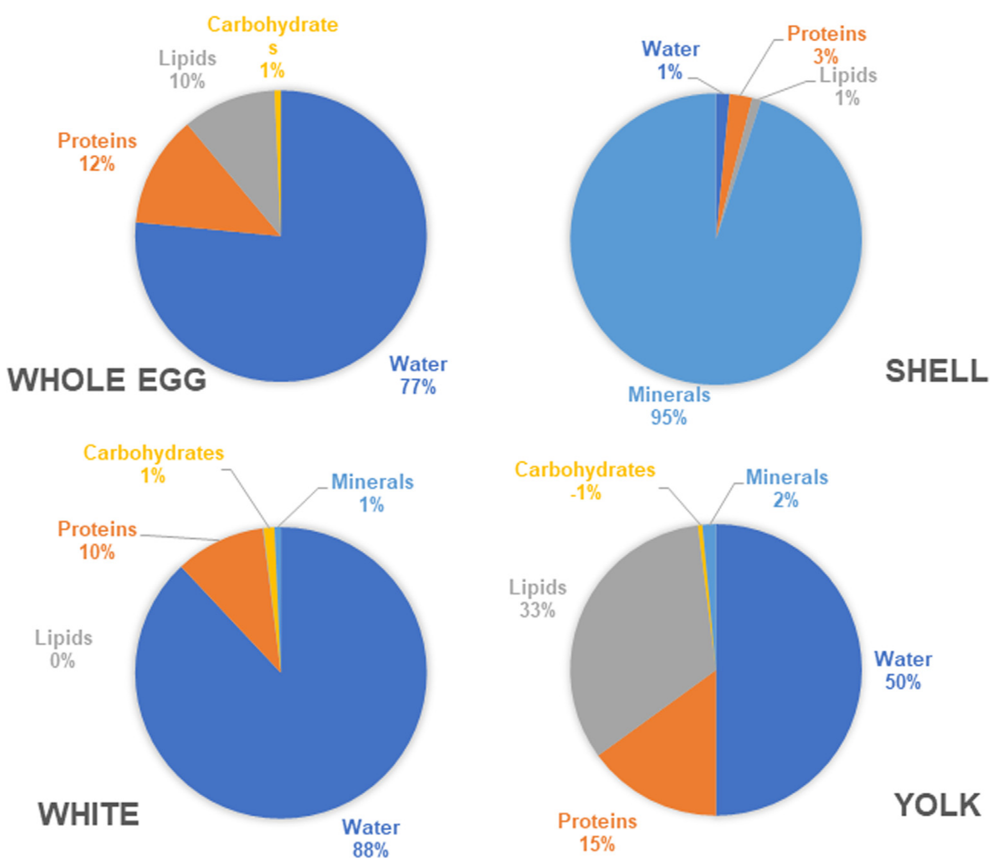

Fig. 2. Main components of the egg. Proportion of proteins, lipids, water, minerals and carbohydrates in the whole egg, the shell, the egg white and the yolk.

hen, the strain used and the diet. There are few studies on the influence of rearing systems on the technological quality of eggs from these hens. The gelling and foaming properties of egg white and whole egg according to hen age, rearing system or altered white composition were investigated, but the effects observed were variable and not correlated with the rearing system (Alamprese et al., 2011; Alamprese et al., 2012; Alamprese, 2017). The effects of rearing systems and layer age on the quality of eggs used for pasta preparation were studied. As the hen ages, the proportion of yolk and white is altered resulting in a less dense protein network in pasta produced with eggs from older hens. The production system has a small effect on the water loss of the cooked material, but this effect is imperceptible to the consumer. Only the age of the hen has an effect on the properties of fresh pasta. The foaming, gelling, and rheological properties of egg white as a function of both hen age and rearing system were studied. With increasing hen age, there is a loss of egg white consistency and egg white gel structure. The production system causes significant interactions that have no effect on the technological properties of the egg products. The technological properties of cage-raised, organic, and *n*-3 enriched eggs were observed and shown no differences between these groups (Filipiak-Florkiewicz et al., 2017).

Use-value properties

The use of eggs is very widespread. The table egg is an ingredient used in cooking for various preparations (fried eggs, soft-boiled eggs, hard-boiled eggs, omelettes, pastries, cold cuts, ready-made meals...). Egg products represent 19% of eggs produced in Europe with large variations depending of the member states (40% in France, 3% in Italy, 22% in Germany, 10% in Nederlands) (ITAVI, 2019). Egg products are widely used by restaurants and food manufacturers. When eggs are used in cooking, they are used for their natural properties of expansion (the white), emulsion (the yolk) and colouring (the yolk). The white is used for meringues, mousses (expanding properties), cooked (coagulation) or uncooked. The yolk is used for its emulsifying properties (mayonnaise, white butter sauces, creams...).

These egg constituents meet a number of characteristics that vary according to the age of the hens, the temperature and the storage of the egg. The storage time of the egg is the most important element in the technological quality of table eggs. The egg is an ingredient that can be stored naturally at room temperature. Gas exchange occurs between the interior of the egg and the atmosphere. Prior to breaking the egg, the storage conditions of the egg will have a determining impact on the subsequent processing of the product. At room temperature, the pH of the freshly laid egg increases from 7.43 to 9.32 in 10 days. The increase in pH observed after laying has positive impacts on some technological properties of the egg (foaming capacity of the white, peeling of hard-boiled eggs...), but weakens the strength of the yolk membrane, which is a crucial technological criterion of the egg product industry in order to avoid any mixing of white and yolk (Guyot et al., 2016). The factors influencing the technological quality of the egg after laying are mainly related to the time and temperature of egg storage, as well as the age of the hen. Indeed, a hen at the end of production has more fragile and porous shells and therefore physicochemical properties of the white are affected.

Regarding egg products, the main issue is to increase the shelf life of the product by improving its sanitary quality and/or by conditioning the product in an environment not conducive to the development of pathogenic microorganisms. The egg products of first transformation include products intended for food industries, such as whites, yolks and whole eggs sold liquid or frozen, and as egg powder. They can present physicochemical properties improved by the transformation and thus represent technological assets, e.g. the white can be more foaming, the yellow more emulsifying... The evolution of the pH observed during the storage of the egg will play a significant role at the time of the development of pasteurisation process, a basification of the medium being able to deteriorate the effectiveness of the treatment (Silversides and Scott, 2001). The vitelline membrane, which separates the yolk from the white, will be less and less resistant during storage time. It will lose 18% of its resistance after 8 days at 18 °C (Berardinelli et al., 2003). These phenomena can be deleterious for the quality of the separation of the white and the yolk during the stage that follows the breaking of the egg. Refrigerated storage limits the loss of strength and thus avoids difficulties in breaking (Guyot et al., 2016). Once separated, the white, the yolk or a combination of both (called whole) will be pasteurised. Each fraction of the egg has its own physicochemical characteristics, the different viscosity between a yolk and a white will involve different rheological behaviours. The processes are thus adapted to the treated medium.

Image-value properties

For several years now, animal husbandry has been the target of numerous criticisms from different social actors and addressed to the industry, to breeders and to large- and medium-sized retailers. Eggs are no exception to the rule, particularly cage farming. Egg consumption is a good example of the major changes that have occurred in the agricultural sector in response to changing social demands. There is currently strong consumer pressure for the consumption of healthy, high-quality animal products that take into account animal welfare and sustainability (Gautron et al., 2021). In response to this societal demand, the consumer egg sector has been strongly modified with different production methods (see above 'Characteristics of the table egg production methods') (Gautron et al., 2021). Even if these different types of production have little or no influence on the nutritional, sensory and health aspects for humans, the egg market has become highly segmented to meet this consumer demand. In 1996, non-cage systems accounted for 8% of the EU laying hen population, 30% in 2009, 46% in 2017 and 51% in 2019 (ITAVI, 2019).

Despite those changes, Van Tilbeurgh (2017) indicates that the answers proposed by the sectors are not adapted as long as they remain posed in terms of acceptability. This author adds that the challenge ahead will be to contribute, with the various stakeholders in society, to the development of new shared consensus. These controversies in poultry farming have been the focus of multiple interrogations in recent years, as evidenced by the numerous communications presented at the last poultry research days (Dockes et al., 2017; Sans et al., 2017; Van Tilbeurgh, 2017). Supermarket chains and Hardiscounters have clearly positioned themselves for a stop to the marketing of cage eggs by 2025, creating significant difficulties in terms of adaptation for the different actors of the sector (Gautron et al., 2021).

In this context of strong social interpellation, various research projects (CASDAR ACCEPT, INRA ECOSERV metaprogram, EU Intact and PPILOW) have set themselves the objective of enlightening farmers on the controversies surrounding animal husbandry and to understand consumer perceptions (Dockes et al., 2017; Sans et al., 2017). In particular, Sans et al. (2017) subjected 181 consumers to a protocol that included surveys and sensory analysis tests aimed at rating agroforestry eggs compared to standard and organic eggs. For the sensory analysis, there are few perceived sensory differences between the three types of production if the sensory test is done blindly, but on the other hand, the organic or agroforestry egg is valued over the standard egg if the origin of the eggs is known. The socio-economic survey also confirms these

Table 5
Major factors in influencing egg quality.

Factors	Commercial properties	Sanitary properties	Sensory properties	Nutritional properties	Technological properties	Use-value and image properties
Genetic	–	+	+	–	+	+
Hen age	++	+	+	–	+++	+
Feed	+	+	+	++	–	–
Housing system	++	+	–	–	–	+++
Time of storage	++	++	–	–	+++	–
Temperature of storage	+	+	+	+	+++	–

No effect (–), Weak (+), Moderate (++), Important (+++).

results and the importance for the consumer of taking these aspects into account.

Table 5 summarises the degree of importance of major factors on the different egg properties. The effect of housing systems on egg quality has been the subject of numerous studies in recent years, showing limited effects on egg characteristics. The most obvious conclusions concern the performance of layers, which is lower in alternative systems than in intensive systems, with results on nutritional qualities varying and slightly in favour of extensive systems. Alternative systems have a positive effect on animal welfare, but with little or no impact on the quality of the egg product. The choice of these alternative systems therefore meets the ethical needs of the consumer, but does not add value in terms of egg quality.

Ethics approval

This review did not require any animal handling or procedures.

Data and model availability statement

No data or model were generated as part of this study.

Author ORCIDs

Joël Gautron: https://orcid.org/0000-0001-7800-0578
Clara Dombre: None
Françoise Nau: https://orcid.org/0000-0002-0167-8759
Cyril Feidt: https://orcid.org/0000-0003-3828-9543
Laurent Guillier: https://orcid.org/0000-0002-7867-2937

Author contributions

Joël Gautron: conceptualization, coordinator of the study, investigation, writing – original draft, writing – review & editing

Clara Dombre: investigation, writing – original draft, writing – review & editing

Françoise Nau: Investigation, writing – original draft, writing – review & editing

Cyril Feidt: Investigation, writing – original draft, writing – review & editing

Laurent Guiller: Investigation, writing – original draft, writing – review & editing

Declaration of interest

The authors declare that this review was written in the absence of any commercial or financial relationships that could be constructed as a potential conflict of interest.

Acknowledgements

This work is part of the collective scientific expertise (ESCo) on the 'Quality of animal-derived foods according to animal production and processing conditions' that was carried out by INRAE at the request of the French ministry responsible for Agriculture and Food, in cooperation with the agency FranceAgriMer. The authors are grateful to the other experts from ESCo panel for their fruitful discussions.

Financial support statement

This work was carried out with funds from the French Ministry of Agriculture and Food (agreement No 2017-424-2102316438) and the FranceAgriMer agency (agreement No 181911).

A part of this bibliographic review was realised under the framework of the Poultry and Pig Low-input and Organic Production Systems' Welfare (PPILOW) programme. The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 816172.

Transparency Declaration

This article is part of a supplement entitled '*Quality of animal-source foods*' supported by the French National Research Institute for Agriculture, Food, and Environment – INRAE.

References

FranceAgrimer, F., 2021. OEufs et ovoproduits. Les fiches de France Agrimer – Retrieved on 05 September 2021 from https://www.franceagrimer.fr/fam/content/download/66423/document/FICHE%20FILIERE%20OEUF%202021.pdf?version=2.

Alamprese, C., 2017. The Use of Egg and Egg Products in Pasta Production. In: Hester, P.Y. (Ed.), Egg Innovations and Strategies for Improvements. Elsevier Academic Press Inc, San Diego, CA, USA, pp. 251–259.

Alamprese, C., Casiraghi, E., Rossi, M., 2011. Effects of housing system and age of laying hens on egg performance in fresh pasta production: pasta cooking behaviour. Journal of the Science of Food and Agriculture 91, 910–914.

Alamprese, C., Casiraghi, E., Rossi, M., 2012. Foaming, gelling and rheological properties of egg albumen as affected by the housing system and the age of laying hens. International Journal of Food Science and Technology 47, 1411–1420.

Augustin, J.C., Kooh, P., Bayeux, T., Guillier, L., Meyer, T., Jourdan-Da Silva, N., Villena, I., Sanaa, M., Cerf, O., Blanchemanche, S., Bonnaud, L., Gautier, M., Gauchard, F., Nabec, L., Soler, L.G., Anses Working, G., 2020. Contribution of Foods and Poor Food-Handling Practices to the Burden of Foodborne Infectious Diseases in France. Foods 9, 1644. https://doi.org/10.3390/foods9111644.

Baron, F., Nau, F., Guerin-Dubiard, C., Gonnet, F., Dubois, J.J., Gautier, M., 2003. Effect of dry heating on the microbiological quality, functional properties, and natural bacteriostatic ability of egg white after reconstitution. Journal of Food Protection 66, 825–832.

Berardinelli, A., Donati, V., Giunchi, A., Guarnieri, A., Ragni, L., 2003. Effects of Transport Vibrations on Quality Indices of Shell Eggs. Biosystems Engineering 86, 495–502.

Brambilla, G., Fochi, I., De Filippis, S.P., Iacovella, N., di Domenico, A., 2009. Pentachlorophenol, polychlorodibenzodioxin and polychlorodibenzofuran in eggs from hens exposed to contaminated wood shavings. Food Additives and

Contaminants Part A-Chemistry Analysis Control Exposure & Risk Assessment 26, 258–264.
Campbell, L., Raikos, V., Euston, S.R., 2005. Heat stability and emulsifying ability of whole egg and egg yolk as related to heat treatment. Food Hydrocolloids 19, 533–539.
Chardon, O., Jauneau, Y., Vidalenc, J., 2020. Les agriculteurs: de moins en moins nombreux et de plus en plus d'hommes. Retrieved on 20 July 2021 from https://www.insee.fr/fr/statistiques/4806717.
Damir, A.A., Elzalaki, E.M., Ibrahim, T.M., 1988. Préparation, foaming, electrophoretic patterns a, d storage of concentrated liquid eggs. Nahrung-Food 32, 881–888.
De Cesare, A., 2018. Salmonella in Foods: A reemerging problems. Advances in Food and nutrition Research 86, 137–179.
De Vries, M., Kwakkel, R.P., Kijlstra, A., 2006. Dioxins in organic eggs: a review. Njas-Wageningen Journal of Life Sciences 54, 207–221.
Dedousi, A., Stojcic, M.D., Sossidou, E., 2020. Effects of housing systems on keel bone damage and egg quality of laying hens. Veterinary Research Forum 11, 299–304.
Dockes, A.C., Delanoue, E., Chouteau, A., Philibert, A., Magdelaine, P., Roguet, C., 2017. Points de vue et attentes des consommateurs et citoyens vis-à-vis de l'élevage. Une étude quantitative auprès de 2 000 personnes en France. Proceedings of the 12ème Journées de la Recherche Avicole et Palmipèdes à Foie Gras, 5-6 april 2007, Tours, France.
Dulith, C.E., Groger, W., 1981. Improvement of product attributes of mayonnaise on enzymic hydrolysis of egg yolk with phospholipase A2. Journal of the Science of Food and Agriculture 32, 451–458.
Dvorak, P., Suchy, P., Strakova, E., Dolezalova, J., 2010. Variation in Egg Yolk Colour in Different Systems of Rearing Laying Hens. Acta Veterinaria Brno 79, S13–S19.
EC, 2001. Commission Adopts Strategy to Reduce Dioxins and PCBs in Environment, Feed and Food IP/01/1492, Brussels. Official Journal of the European Union C 322, 2–18.
EC, 2004. Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004 laying down specific hygiene rules for on the hygiene of foodstuffs. Retrieved on 05 March 2021 from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004R0853&from=EN.
EC, 2007. Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91. Retrieved on 05 November 2021 from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02007R0834-20130701&from=FR.
EC, 2008. COMMISSION REGULATION (EC) No 589/2008 of 23 June 2008 laying down detailed rules for implementing Council Regulation (EC) No 1234/2007 as regards marketing standards for eggs. Retrieved on 5 November 2021 from https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:163:0006:0023:EN:PDF.
EFSA, 2014. Scientific Opinion on the public health risks of table eggs due to deterioration and development of pathogens. EFSA Journal 12, 3782.
EFSA, 2018. Risk for animal and human health related to the presence of dioxins and dioxin-like PCBs in feed and food. EFSA Journal 16, 5333.
EFSA, 2019. Salmonella control in poultry flocks and its public health impact. EFSA Journal 17, e05596.
EFSA and ECDC, 2018. The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2017. EFSA Journal 16, e05500.
Englmaierova, M., Tumova, E., Charvatova, V., Skrivan, M., 2014. Effects of laying hens housing system on laying performance, egg quality characteristics, and egg microbial contamination. Czech Journal of Animal Science 59, 345–352.
EU, 2011. COMMISSION REGULATION (EU) No 1129/2011 of 11 November 2011 amending Annex II to Regulation (EC) No 1333/2008 of the European Parliament and of the Council by establishing a Union list of food additives. Retrieved on 05 November 2021 from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R1129&from=EN.
Filipiak-Florkiewicz, A., Deren, K., Florkiewicz, A., Topolska, K., Juszczak, L., Cieslik, E., 2017. PROCESSING AND PRODUCTS The quality of eggs (organic and nutraceutical vs. conventional) and their technological properties. Poultry Science 96, 2480–2490.
Fournier, A., Feidt, C., Travel, A., Le Bizec, B., Venisseau, A., Marchand, P., Jondreville, C., 2012. Relative bioavailability to laying hens of indicator polychlorobiphenyls present in soil. Chemosphere 88, 300–306.
Fournier, A., Martin, O., Travel, A., Puillet, L., Feidt, C., Jondreville, C., 2015. Modeling PCB Transfer into hen eggs: Influence of physiological charcateristics of the animal. Environmental Toxicology and Chemistry 34, 173–183.
Gautron, J., Réhault-Godbert, S., Van de Braak, T., Dunn, I.C., 2021. Review: What are the challenges facing the table egg industry in the next decades and what can be done to address them? Animal 15, 100282.
Griffin, B.A., 2011. 12 – Eggs, dietary cholesterol and disease: facts and folklore. In: Van Immerseel, F., Nys, Y., Bain, M. (Eds.), Improving the Safety and Quality of Eggs and Egg Products. Woodhead Publishing, Cambridge, UK, pp. 237–253.
Grob, K., Vass, M., Biedermann, M., Neukom, P., 2001. Contamination of animal feed and food from animal origin with mineral oil hydrocarbons. Food Additives and Contaminants Part A-Chemistry Analysis Control Exposure & Risk Assessment 18, 1–10.
Guillier, L., Thébault, A., Fravalo, P., Mughini-Gras, L., Jourdan-Da Silva, N., David, J., Kooh, P., Cadavez, V., Gonzales-Barron, U., 2020. Risk factors for sporadic salmonellosis: a systematic review and meta-analysis. Microbial Risk Analysis 17,. https://doi.org/10.1016/j.mran.2020.100138 100138.
Gurtler, J.B., Hinton, A., Bailey, R.B., Cray, W.C., Meinersmann, R.J., Ball, T.A., Jin, T.Z., 2015. Salmonella isolated from ready-to-eat pasteurized liquid egg products: Thermal resistance, biochemical profile, and fatty acid analysis. International Journal of Food Microbiology 206, 109–117.
Guyot, N., Rehault-Godbert, S., Slugocki, C., Harichaux, G., Labas, V., Helloin, E., Nys, Y., 2016. Characterization of egg white antibacterial properties during the first half of incubation: A comparative study between embryonated and unfertilized eggs. Poultry Science 95, 2956–2970.
Hammershoj, M., Johansen, N.F., 2016. Review: The effect of grass and herbs in organic egg production on egg fatty acid composition, egg yolk colour and sensory properties. Livestock Science 194, 37–43.
Hammershoj, M., Nording, J.A., Rasmussen, H.C., Carstens, J.H., Pedersen, H., 2006a. Dry-pasteurization of egg albumen powder in a fluidized bed. I. Effect on microbiology, physical and chemical parameters. International Journal of Food Science and Technology 41, 249–261.
Hammershoj, M., Rasmussen, H.C., Carstens, J.H., Pedersen, H., 2006b. Dry-pasteurization of egg albumen powder in a fluidized bed. II. Effect on functional properties: gelation and foaming. International Journal of Food Science and Technology 41, 263–274.
Honkatukia, M., Tuiskula-Haavisto, M., Arango, J., Tabell, J., Schmutz, M., Preisinger, R., Vilkki, J., 2013. QTL mapping of egg albumen quality in egg layers. Genetics Selection Evolution 45, 31.
Hoogenboom, L.A.P., Kan, C.A., Zeilmaker, M.J., Van Eijkeren, J., Traag, W.A., 2006. Carry-over of dioxins and PCBs from feed and soil to eggs at low contamination levels - influence of mycotoxin binders on the carry-over from feed to eggs. Food Additives and Contaminants Part A-Chemistry Analysis Control Exposure & Risk Assessment 23, 518–527.
Howard, Z.R., O'Bryan, C.A., Crandall, P.G., Ricke, S.C., 2012. Salmonella Enteritidis in shell eggs: Current issues and prospects for control. Food Research International 45, 755–764.
Hu, F.B., Stampfer, M.J., Rimm, E.B., Manson, J.E., Ascherio, A., Colditz, G.A., Rosner, B. A., Spiegelman, D., Speizer, F.E., Sacks, F.R., Hennekens, C.H., Willett, W.C., 1999. A prospective study of egg consumption and risk of cardiovascular disease in men and women. JAMA-Journal of the American Medical Association 281, 1387–1394.
Huneau-Salaun, A., Cariou, R., Royer, E., Jondreville, C., Balaine, L., Souchet, C., Coton, J., Venisseau, A., Thomas, R., Rousseliere, Y., Charpiot, A., Marchand, P., Dervilly-Pinel, G., Marcon, M., Le Bizec, B., Travel, A., Le Bouquin, S., 2020. Do farming conditions influence brominated flame retardant levels in pig and poultry products? Animal 14, 1313–1321.
Huneau-Salaun, A., Michel, V., Huonnic, D., Balaine, L., Le Bouquin, S., 2010. Factors influencing bacterial eggshell contamination in conventional cages, furnished cages and free-range systems for laying hens under commercial conditions. British Poultry Science 51, 163–169.
Ibanoglu, E., Ercelebi, E.A., 2007. Thermal denaturation and functional properties of egg proteins in the presence of hydrocolloid gums. Food Chemistry 101, 626–633.
ITAVI, 2019. Situation du marché des oeufs et des ovoproduits: Retrieved on 21 July 2021 from https://www.itavi.asso.fr/.
Jondreville, C., Cariou, R., Travel, A., Belhomme, L.J., Dervilly-Pinel, G., Le Bizec, B., Huneau-Salaun, A., Le Bouquin-Leneveu, S., 2017. Hens can ingest extruded polystyrene in rearing buildings and lay eggs contaminated with hexabromocyclododecane. Chemosphere 186, 62–67.
Jondreville, C., Travel, A., Besnard, J., Dziurla, M.A., Feidt, C., 2010. Intake of herbage and soil by free-range laying hens offered a complete diet compared to a whole wheat diet. World's Poultry Science 66, 4.
JORF, 2017. Cahier des charges du label rouge n° LA 03/99 "oeufs fermiers de poules élevées en plein air". M. d. l. A. e. d. l'alimentation. Bulletin officiel du ministère de l'agriculture et de l'alimentation, Journal Officiel de la République Française. Retrieved on 05 March 2021 from https://info.agriculture.gouv.fr/gedei/site/bo-agri/document_administratif-f3c62ec7-ffd3-42f4-a18c-e4f620be7716/telechargement.
Kato, A., Ibrahim, H.R., Watanabe, H., Honma, K., Kobayashi, K., 1989. New approach to improve the gelling and surface functional properties of dried egg white by heating in dry state. Journal of Agricultural and Food Chemistry 37, 433–437.
Kline, L., Meehan, J.J., Sugihara, T.F., 1964. Properties of yolk-containing solids with added carbohyrates. Journal of Food Science 29, 693.
Koc, M., Koc, B., Susyal, G., Yilmazer, M.S., Bagdatlioglu, N., Kaymak-Ertekin, F., 2011. Improving Functionality of Whole Egg Powder by the Addition of Gelatine, Lactose, and Pullulan. Journal of Food Science 76, S508–S515.
Lai, C.C., Gilbert, S.G., Mannheim, C.H., 1985. Effect of composition on the flow properties of egg powders. Journal of Food Science 50, 1618.
Looten, H., Wils, D., Saniez, M.H., Nys, Y., 2003. Xanthophyll profile of corn gluten meal throughout the year and transfer yield into egg yolk. In: Proceedings of the 16th European Symposium on the Quality of Poultry Meat and 10th European Symposium on the Quality of Eggs and Egg Products, 23–26 September 2003, Saint-Brieuc, France, pp. 186–191.
Lovett, A.A., Foxall, C.D., Creaser, C.S., Chewe, D., 1998. PCB and PCDD/DF concentrations in egg and poultry meat samples from known urban and rural locations in Wales and England. Chemosphere 37, 1671–1685.
Luzardo, O.P., Rodriguez-Hernandez, A., Quesada-Tacoronte, Y., Ruiz-Suarez, N., Almeida-Gonzalez, M., Henriquez-Hernandez, L.A., Zumbado, M., Boada, L.D., 2013. Influence of the method of production of eggs on the daily intake of polycyclic aromatic hydrocarbons and organochlorine contaminants: An independent study in the Canary Islands (Spain). Food and Chemical Toxicology 60, 455–462.
Maga, J.A., 1982. Egg and egg product flavor. Journal of Agricultural and Food Chemistry 30, 9–14.

Magdelaine, P., 2017. Marché de l'œuf et des ovoproduits: Retrieved on 21 July 2021 from https://www.itavi.asso.fr/.

Mallet, S., Huneau-Salaün, A., Herman, L., De Reu, K., 2010. Laying hen breeding systems and hygienic status of the eggs. INRA Productions Animales 23, 183–191.

Marelli, S.P., Madeddu, M., Mangiagalli, M.G., Cerolini, S., Zaniboni, L., 2021. Egg Production Systems, Open Space Allowance and Their Effects on Physical Parameters and Fatty Acid Profile in Commercial Eggs. Animals 11, 265.

Meziere, M., Marchand, P., Hutinet, S., Larvor, F., Baeza, E., Le Bizec, B., Dervilly, G., Cariou, R., 2021. Transfer of short-, medium-, and long-chain chlorinated paraffins to eggs of laying hens after dietary exposure. Food Chemistry 343, 124891.

Mine, Y., 1996. Effect of pH during the dry heating on the gelling properties of egg white proteins. Food Research International 29, 155–161.

Mine, Y., 1997. Effect of dry heat and mild alkaline treatment on functional properties of egg white proteins. Journal of Agricultural and Food Chemistry 45, 2924–2928.

Miranda, J.M., Anton, X., Redondo-Valbuena, C., Roca-Saavedra, P., Rodriguez, J.A., Lamas, A., Franco, C.M., Cepeda, A., 2015. Egg and Egg-Derived Foods: Effects on Human Health and Use as Functional Foods. Nutrients 7, 706–729.

Mughini-Gras, L., Enserink, R., Friesema, I., Heck, M., van Duynhoven, Y., van Pelt, W., 2014. Risk Factors for Human Salmonellosis Originating from Pigs, Cattle, Broiler Chickens and Egg Laying Hens: A Combined Case-Control and Source Attribution Analysis. Plos One 9,. https://doi.org/10.1371/journal.pone.0087933 e87933.

Nys, Y., Jondreville, C., Chemaly, M., Roudaut, B., Berthelot, V., 2018. Qualité des oeufs de consommationQualité des oeufs de consommation. In: Alimentation des animaux et qualité de leurs produits. Partie 2 - Déterminants alimentaires et non alimentaires en élevage de la qualité des produits (Chapitre 9). Tec & Doc Lavoisier, Paris, France, pp. 316–333.

Nys, Y., Sauveur, B., 2004. Valeur nutritionnelle des oeufs. INRA Productions Animales 17, 385–393.

OJEU, 2003. Official Journal of the European Union, L 305, 22 November 2003. Retrieved on 05 November 2021 from https://op.europa.eu/en/publication-detail/-/publication/cdfcf091-ce58-4cf7-a1d2-b7f73f0f0185.

Philippe, F.X., Mahmoudi, Y., Cinq-Mars, D., Lefrancois, M., Moula, N., Palacios, J., Pelletier, F., Godbout, S., 2020. Comparison of egg production, quality and composition in three production systems for laying hens. Livestock Science 232, 103917.

Pijnacker, R., Dallman, T.J., Tijsma, A.S.L., Hawkins, G., Larkin, L., Kotila, S.M., Amore, G., Amato, E., Suzuki, P.M., Denayer, S., Klamer, S., Paszti, J., McCormick, J., Hartman, H., Hughes, G.J., Brandal, L.C.T., Brown, D., Mossong, J., Jernberg, C., Muller, L., Palm, D., Severi, E., Golebiowska, J., Hunjak, B., Owczarek, S., Garvey, P., Mooijman, K., Friesema, I.H.M., van Der Weijden, C., van Der Voort, M., Rizzi, V., Franz, E., Le Hello, S., Bertrand, S., Brennan, M., Browning, L., Bruce, R., Cantaert, V., Chattaway, M., Coia, J., Couper, S., Cretnik, T.Z., Daniel, O., Dionisi, A. M., Fabre, L., Filipovic, S.K., Fitz-James, I., Florek, K., Florianova, M., Fox, E., Frelih, T., Grilc, E., Jankovic, V.K., Jourdan, N., Karpiskova, R., van den Kerkhof, H., Krisztalovics, K., Kuiling, S., Laisnez, V., Lange, H., deLappes, N., Leblanc, J., Luzzi, I., Mandilara, G., Mather, H., Mattheus, W., Mellou, K., Morgan, D., de Pinna, E., Ragimbeau, C., Roed, M.H., Salmenlinna, S., Smith, R., Smith-Palmer, A., Spackova, M., Torpdahl, M., Trkov, M., Tronnberg, L., Tzani, M., Utsi, L., Wasyl, D., Weicherding, P., Invest, I.O., T., 2019. An international outbreak of Salmonella enterica serotype Enteritidis linked to eggs from Poland: a microbiological and epidemiological study. Lancet Infectious Diseases 19, 778–786.

Raikos, V., Campbell, L., Euston, S.R., 2007. Effects of sucrose and sodium chloride on foaming properties of egg white proteins. Food Research International 40, 347–355.

Rawn, D.F.K., Sadler, A.R., Quade, S.C., Sun, W.F., Kosarac, I., Hayward, S., Ryan, J.J., 2012. The impact of production type and region on polychlorinated biphenyl (PCB), polychlorinated dibenzo-p-dioxin and dibenzofuran (PCDD/F) concentrations in Canadian chicken egg yolks. Chemosphere 89, 929–935.

Rehault-Godbert, S., Baron, F., Mignon-Grasteau, S., Labas, V., Gautier, M., Hincke, M. T., Nys, Y., 2010. Effect of Temperature and Time of Storage on Protein Stability and Anti-Salmonella Activity of Egg White. Journal of Food Protection 73, 1604–1612.

Rehault-Godbert, S., Guyot, N., Nys, Y., 2019. The Golden Egg: Nutritional Value, Bioactivities, and Emerging Benefits for Human Health. Nutrients 11, 684. https://doi.org/10.3390/nu11030684.

Roszko, M., Szymczyk, K., Jedrzejczak, R., 2014. Influence of hen breeding type on PCDD/F, PCB & PBDE levels in eggs. Science of the Total Environment 487, 279–289.

Samiullah, Roberts, J.R., Chousalkar, K.K., 2014. Effect of production system and flock age on egg quality and total bacterial load in commercial laying hens. Journal of Applied Poultry Research 23, 59–70.

Sans, P., Olivier-Salvagnac, V., Montian, G., Pichon, F., Moncé, T., 2017. Perception par les consommateurs des qualités de l'oeuf de poule produit dans un élevage en agroforesterie. Proceeding of the 12ème Journées de la Recherche Avicole et Palmipèdes à Foie Gras, 5–6 april 2007, Tours, France.

Schultz, J.R., Snyder, H.E., Forsythe, R.H., 1968. Co-dried carbohydrates effect on the performance of egg yolk solids. Journal of Food Science 33, 507–513.

Seuss-Baum, I., Nau, F., Guerin-Dubiard, C., 2011. The nutritional quality of eggs. In: Van Immerseel, F., Nys, Y., Bain, M. (Eds.), Improving the Safety and Quality of Eggs and Egg Products, Vol. 2: Egg Safety and Nutritional Quality. Woodhead Publ Ltd, Cambridge, MA, USA, pp. 201–236.

Silversides, F., Scott, T.A., 2001. Effect of storage and layer age on quality of eggs from two lines of hens. Polutry Science 80, 1240–1245.

Sirri, F., Meluzzi, A., 2011. 14 – Modifying egg lipids for human health. In: Van Immerseel, F., Nys, Y., Bain, M. (Eds.), Improving the Safety and Quality of Eggs and Egg Products. Woodhead Publishing, Cambridge, UK, pp. 272–288.

Squadrone, S., Brizio, P., Nespoli, R., Stella, C., Abete, M.C., 2015. Human dietary exposure and levels of polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), dioxin-like polychlorinated biphenyls (DL-PCBs) and non-dioxin-like polychlorinated biphenyls (NDL-PCBs) in free-range eggs close to a secondary aluminum smelter, Northern Italy. Environmental Pollution 206, 429–436.

Stadelman, W.J., Pratt, D.E., 1989. Factors influencing composition of the hens egg. World Poultry Science Journal 45, 247–266.

UE, 1999. Council Directive 1999/74/EC of 19 July 1999 laying down minimum standards for the protection of laying hens. Official Journal L 203, 53–57.

UE, 2008. COMMISSION REGULATION (EC) No 889/2008 of 5 September 2008 laying down detailed rules for the implementation of Council Regulation (EC) No 834/2007 on organic production and labelling of organic products with regard to organic production, labelling and control. CE/Eurotam, Official Journal of the European Union. Retrieved on 05 November 2021 from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008R0889&from=EN.

van Larebeke, N., Hens, L., Schepens, P., Covaci, A., Baeyens, J., Everaert, K., Bernheim, J.L., Vlietinck, R., De Poorter, G., 2001. The Belgian PCB and dioxin incident of January-June 1999: Exposure data and potential impact on health. Environmental Health Perspectives 109, 265–273.

Van Tilbeurgh, V., 2017. Enjeux sociétaux et adaptation des filières aux controverses sur l'élevage. Proceeding of the 12ème Journées de la Recherche Avicole et Palmipèdes à Foie Gras, 5-6 april 2007, Tours, France, hal-01580518.

Wang, J., Wu, S.G., Zhang, H.J., Yue, H.Y., Xu, L., Ji, F., Xu, L., Qi, G.H., 2013. Trimethylamine deposition in the egg yolk from laying hens with different FMO3 genotypes. Poultry Science 92, 746–752.

Yadav, N.K., Vadehra, D.V., 1977. Mechanism of egg-white resistance to bacterial-growth. Journal of Food Science 42, 97–99.

Yanagisawa, T., Watanuki, C., Ariizumi, M., Shigematsu, Y., Kobayashi, H., Hasegawa, M., Watanabe, K., 2009. Super Chilling Enhances Preservation of the Freshness of Salted Egg Yolk During Long-Term Storage. Journal of Food Science 74, E62–E69.

Yannakopoulos, A.L., 2007. Egg enrichment in omega-3 fatty acids. In Bioactive egg compounds. In: Huopalahti, R., Lopez-Fandiño, R., Anton, M., Shade, R. (Eds.), Bioactive egg compounds. Springer-Verlag, Berlin-Heidelberg, Germany, pp. 159–170.